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How Birds Hear Birdsong

Why Omicron Spread across the World

Life Lessons from the Amazon

THE KEY TO QUANTUM COMPUTING

New techniques aim to fix physics errors fast


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MAY 2022

VOLUME 326, NUMBER 5

SCIENTIFIC AMERICAN

ON THE COVER
Quantum computers aim to outclass classical machines, but they can only do that if scientists can keep errors in check. Enter quantum error correction codes. These connect quantum bits, or qubits, with "helper" qubits, which keep noise away from where data are stored. The strategy is promising but presents many challenges. **Photograph by IBM Research.**

Photograph by André Dib

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FROM THE EDITOR

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

New Perceptions

Science is all about expanding the realm of human perception. Sometimes that means making the invisible visible, like when Galileo turned a telescope toward Jupiter, discovered moons around another planet and changed our literal worldview. We now know that flowers, as beautiful as they are to us, are communicating with birds and bees using ultraviolet patterns we can't see and that elephants can feel vibrations travel through the ground from miles away.

People have been observing birds singing and calling since there were people. Birds vocalize to attract mates, defend territory, find one another, and more. Many birds' songs sound musical to us, with distinct notes that are repeated in pleasing patterns at a steady speed—melody, rhythm and tempo, basically. But as Adam Fishbein and other bird researchers have discovered recently (*page 36*), what sounds so entrancing to us isn't that meaningful to them. Birds don't seem to listen to the melody so much as to fine details within each note that humans can't detect.

Most parasites are invisible, although some are not (like tapeworms, yikes). Beauty is in the bird's ear or the scientist's eye of the beholder, and there's a growing movement to recognize that parasites can and do go extinct and should be protected. As science journalist Rachel Nuwer writes on page 62, as many as 40 to 50 percent of all animal species are parasites, and almost every other species has at least one parasite that has evolved to parasitize it.

Parasites are one of the problems plaguing fish farms. When you concentrate fish in huge pens, parasites and diseases spread rapidly and can escape to wild-living animals. Now scientists and science-informed aquaculturists are experimenting with environmentally and financially sustainable fish-farming practices. On page 44, author Ellen Ruppel Shell takes us to Maine, where the commercial fisheries of cod, shrimp and mussels have crashed, and the climate emergency is pushing lobsters to cooler Canadian waters. Farmed shellfish and even enormous finfish operations being developed there could be the future of seafood.

The future of computing is the subject of our fascinating cover story this month, by quantum theorist Zaira Nazario. Quantum computing uses basic units called qubits (analogous to the bits in classical computers but in the form of waves rather than 1s and 0s) that are linked together through quantum entanglement. Quantum computers can store and manipulate information at scales and speeds far beyond anything classical computers can do, but they also suffer from errors unlike anything in classical computers. Nazario specializes in fixing these errors, and on page 28 she narrates the challenges and discoveries and delights of this important and mind-bending work, with graphics that help make invisible quantum quirks visible.

The Ashaninka people have a different sort of vision for what's possible. They have seen parts of the Amazon destroyed by loggers, miners and drug runners, and they've been exploring sophisticated and creative methods for protecting their homeland. In an unusual (for us) collaboration, anthropologist Carolina Schneider Comandulli and the Apiwtxa Association share one community's worldview and how it has inspired them to create a sustainable, self-sufficient way of life and empowered other Indigenous people in the Amazon and their allies to protect and rebuild habitat. Turn to page 70 to enjoy the stunning accompanying photography.

We have just witnessed what is almost certainly the fastest-spreading human virus in history, the Omicron variant of SARS-CoV-2. On page 58, science journalist Megan Scudellari and graphic artist Veronica Falconieri Hays show why this variant is so good at what it does. Omicron has more genetic mutations than previous variants of concern, starting with mutations that allow it to hide from the human immune system. And more variants are coming. We hope you're able to stay as safe and healthy and well informed as possible, as science helps us see and hear and fix things that we can't easily perceive. SA

Illustration by Nick Higgins

> **“Asking individuals to take responsibility for climate change does not distract us from pressuring larger entities to do the same.”**
>
> SAMUEL BENNETT *VIA E-MAIL*

January 2022

MECHANICAL MYSTERY

“Wonder of the Ancient World,” by Tony Freeth, describes the Antikythera mechanism, a Greek astronomical calculation machine. As a biologist with an interest in engineering, I was amazed by the device’s construction. Just how did the ancients make it? I doubt they had tools such as lathelike machines to cut the gears, dividing heads to index them, accurately made drills, and so on.

GERALD LEGG *Hurstpierpoint, England*

Now that the design of the Antikythera mechanism is understood, my question is: Did it really work? And if so, how was that feat accomplished? For a device of such complexity to have functioned, the parts would have needed to be incredibly well machined. A working mechanism would seem to require the build quality of a fine watch—a device that only emerged centuries later.

NORMAN L. GILINSKY *Eastsound, Wash.*

FREETH REPLIES: My colleagues and I share Legg’s amazement. In the University College London Antikythera Research Team, our two Ph.D. students are exploring the issues he raises. It is difficult to see how the device’s components—such as gears, arbors and coaxial output tubes—could have been made without a lathe, and we are researching the evidence for lathes in ancient Greece. Its creators must have had some form of drill, as well as files or chisels for cutting gear teeth. The coaxial tubes raise many questions. Our students are part-time, so it may take a while to resolve these issues.

In response to Gilinsky: The Antikythera mechanism must indeed have been made with great precision for its time—it was perhaps not as accurate as a modern watch but very well made for ancient Greece. Friction must have been a huge issue—particularly because many of the parts were in contact with one another in a way that would not happen in a modern instrument.

Did it work? We cannot be sure, but two pieces of evidence suggest it likely did. The first is Roman politician Cicero’s first-century B.C.E. descriptions of Greek devices that sound similar: two made by mathematician Archimedes in the third century B.C.E. and one by philosopher Posidonius in the first century B.C.E. The second comes from modern models—particularly those of Michael Wright, a U.K.-based “historian of mechanism” and a former curator at London’s Science Museum. His models work remarkably smoothly—although he does use 19th-century lathes to make them.

Researchers on our team are exploring whether our latest theoretical model works. First, they are building a model with modern machinery to check whether there are serious design issues. Then they will build one (or parts of one) using techniques we believe were available in ancient Greece.

SECURITY BESEECH

In “Hacking the Ransomware Problem” [Science Agenda], the editors describe strategies for addressing ransomware attacks, in which hackers encrypt data in a target’s computer system and demand payment to free it.

There are multiple issues that allow ransomware to survive. Removing the incentive for criminals to use it is great, but that works only for companies that report the attack. The vast majority seem to feel government involvement is more of a hindrance than a help. Having worked in the security and networking side of companies, I can say the biggest issue that allows ransomware to persist is companies’ reluctance to implement good security architecture and practices. This results from a combination of problems, but in general, the implementors do not know what they are implementing or why. Inevitably one area will be closed off under direction from a security person or audit, but another 50 will remain open. Companies cherry-pick good practices and do not realize that they are exponentially more secure if you implement them in tandem with complementary practices.

BRETT LITTRELL
CTO, Alum Rock Union School District

CLIMATE STRATEGIES

In “Eat to Save the Planet” [Observatory], Naomi Oreskes argues that people can help mitigate the climate emergency by cutting back on red meat consumption but notes that some “have argued that calls for individual action actually distract us from corporate responsibility.”

Asking individuals to take responsibility for climate change does not distract us from pressuring larger entities to do the same. This movement requires everyone to participate to the maximum extent possible. Individuals can fight climate change in many ways that do not require a lot of time or increased expense. The tools are available to change our transportation, the energy used in gases emitted by our homes, our consumer purchases and donations to offset our carbon usage. Next time, don’t tell readers one thing they can do. Tell them the 20 things they can do.

SAMUEL BENNETT *via e-mail*

VIOLENCE AND IDEOLOGY

Kudos to Amy Cooter for “Inside America’s Militias,” her article on a move to more violent extremism among such groups. Down here in rural Alabama, we own an interest in land next to a militia training camp, complete with obstacle courses, firing ranges, and fields for simulated combat and tactical drills. I've dealt with the spectrum of Cooter's well-defined characters countless times over the decades and in as many contexts, from grilling them in jury selections to debates while some work on our farm equipment. As I was ticking off points of agreement with Cooter, I was anxiously awaiting her take on a topic I've found the militia world fixated on: Antifa, which she describes as "the antifa (antifascist) movement."

Militia-speak can't seem to settle on the finest-sounding string of bad words to describe antifa. Having been shot at as a veteran of the Vietnam War, I know fear and see it in the militia world when its members discuss the organization. I'd like to know if that fear is justified. Cooter's piece leaves us with scant tidbits on the subject.

Guy V. Martin, Jr. *Montgomery, Ala.*

COOTER REPLIES: What we do know is that groups that long for a fictional past, especially those with overtly racist motivations, are more organized and more threatening than those on the left. Antifa is not represented by a single organization, and engagement with it is often considered more of a transitory action, in which some people may participate for a single protest or other action rather than necessarily having a meaningful, long-term group affiliation. Strongly ideological individuals of any political persuasion have the potential for violent action. But in my opinion, the fear of antifa in militia communities and beyond is more about the social change its presence represents rather than a real or systematic threat of violence.

ERRATA

"Lemur Rhythm," by Jack Tamisiea [Advances], should have said that the study on indris showed the first confirmed case of a nonhuman mammal possessing categorical rhythm similar to that in human music, not categorical rhythm in general.

Ian Battaglia's review of *The High House* [Recommended] incorrectly describes Florida as the novel's setting. The character Francesca dies in a hurricane in that state, but the plot centers on the English coast.

In the March 2022 issue, two Advances articles included illustrations that should have been credited to Thomas Fuchs: "Phantom Finger," by Matthew Hutson, and "Unusual Flow," by Rachel Berkowitz.

LETTERS TO THE EDITOR

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Crypto Is Still Too Cryptic

These digital assets are opaque, volatile and prone to scams

By the Editors

Blockchain has gone mainstream. Last year 16 percent of Americans claimed to have speculated in cryptocurrencies based on blockchain technology, and this year's Super Bowl broadcast included several ads for crypto markets. But even as their cheerleaders encourage others to dabble in cryptocurrencies, their worth remains dubious. Their values are quite volatile, and as unregulated assets, they leave average investors vulnerable to crashes and scams. Just as worrisome, creating these digital resources guzzles energy at a prodigious rate, contributing to climate change.

This is a highly unregulated industry in its Wild West era. The Biden administration recently signed an executive order telling federal agencies to study the problem because the crypto market lacks the consumer protections that stabilize this type of investment and deter its use by criminals. If people decide to wade into these uncharted waters, they should do so with the utmost care.

Blockchain, a digital ledger that records transactions, is public, decentralized—spread among the computers in a network—and secure. Theoretically, data stored via blockchain are nearly impossible to modify without leaving signs of fraud. As a result, the technology can support a variety of applications, including secure sharing of medical data and tracking financial transactions.

Cryptocurrencies, such as Bitcoin and Ether, can be used to pay for goods much like legal tender, except that exchanges are recorded via blockchain. Although the technology ostensibly frees crypto users from central authorities such as governments or banks, most people still interact with it through intermediaries. Crypto exchanges allow people to buy and sell cryptocurrencies the way investors trade stocks. Unlike stocks, however, cryptocurrencies do not derive their value from a tangible object or company and cannot be guaranteed by a trusted authority.

As a result, cryptocurrency speculation can be extremely volatile. For example, the value of Bitcoin once dropped by 30 percent in a single day. Although the stock market has weathered similar dips, when this happens, the federal government and other entities can step in to try to stabilize fluctuations. With cryptocurrencies, there are no such backups.

Blockchain also enables users to shield their identities. This anonymity, as well as freedom from official oversight, has made cryptocurrencies popular among ransomware hackers. Anonymity also makes it difficult for buyers to assess the legitimacy of any given cryptocurrency exchange—the person running the exchange can take in money from investors while hiding behind a pseudonym, then steal the loot. In 2021 scammers nabbed $14 billion worth of cryptocurrencies.

In addition, cryptocurrencies are not minted by a government; instead many must be "mined" by members of the decentralized network performing computing tasks to help validate transactions of that particular cryptocurrency. These tasks require enormous energy: in 2021 mining a single Bitcoin required enough electricity to power an American household for nine years. And the more Bitcoins are mined, the more power is needed to earn new ones. This escalation favors early adopters of the system, who got in when it was easier to earn Bitcoins. Much like in a pyramid scheme, early adopters benefit from bringing newcomers into the fold: additional traders will drive up the value of their existing assets.

Similarly energy-hungry processes are also used to mint NFTs—non-fungible tokens—but the two technologies are not the same. Think of an NFT as a digital receipt that represents ownership of a specific object, with blockchain helping to track that ownership as it transfers from entity to entity. Using NFTs could be a boon for artists: people can often share and download digital art for free, but by selling an NFT of a digital art piece, the artist gets paid while ensuring that the person who purchases the art is acknowledged as the official owner. Like cryptocurrencies, however, NFTs' value can vary wildly.

This type of value-distorting craze is not new—think of the convoluted mortgage-market derivatives that caused the 2008 financial crisis. Unlike those, crypto has become a mass-market product advertised to everyday buyers. But the risk of creating bubbles that could bankrupt untold numbers of people is the same. So, until this industry is better monitored or regulated, investing in crypto or NFTs remains a gamble taken in the dark—buyer beware. SA

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Illustration by Thomas Fuchs


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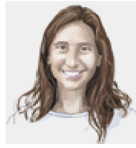


Lauryn Benedict is a professor of biological sciences at the University of Northern Colorado, where she directs the UNCO Behavioral Ecology Lab. **Matt Wilkins** is founder and CEO of the Galactic Polymath Education Studio.

Female Birds Sing, Too

Science is better when it is inclusive

By Lauryn Benedict and Matt Wilkins

Female birds sing. That is one conclusion of our 2020 study on one of the most abundant, widespread, well-studied bird species in the world: the barn swallow. Despite the well over 1,000 scientific publications about this species, female barn swallow song had never previously been the focus of a research article.

Why does it matter that female song has been ignored in this bird that breeds across most of North America? It highlights a long-standing scientific bias and helps us think about why that bias persists.

Since the beginning of modern birdsong research, the field has focused on the conspicuous songs of male songbirds. Conventional evolutionary theory assumes that across the animal kingdom, males compete for access to females, leading male animals to evolve exaggerated traits (like antlers) that help them fight off other males, as well as features (like the fabulous feathers of peacocks) that attract females. Birdsongs can function in both these contexts, and although males may have more elaborate songs than females, this is far from universal. In fact, females sing in at least 64 percent of songbird species, and their songs can serve the same functions as male songs.

Yet many researchers still assume that "the male bird sings, and the female chooses," with field studies overwhelmingly focused on the more abundant male signals. The most frequent song, however, might not always be the most important, just as a debate can be settled by who had the last word rather than who spoke the most. Our study suggests that the evolution of female barn swallow songs is more important than the evolution of male songs for explaining why the two sexes sound different.

A second reason for the neglect of female birdsong stems from geographic bias. Any ornithologist or serious birder working in the tropics could tell you that females do sing, sometimes as frequently as males. But early researchers tended to study species near their universities in the Northern Hemisphere. In a large proportion of North American birds, females have lost or reduced their songs, which may represent evolutionary adaptations to conserve energy for migration or to focus on breeding during a short season.

A final reason for female birdsong being understudied could be gender. Men have dominated birdsong research from its inception. As more women enter the field, however, they are spurring an exuberant surge in the study of female song. Women are much more likely than men to be first authors on papers on female birdsong. The historical lack of diverse participation in science may have contributed to researchers forming self-reinforcing assumptions that impeded a full understanding of the world around us.

To combat such biases in the scientific canon, we need to make science more accessible to all. For example, if we can make people aware that female birds sing, we will enhance their experience of nature and improve their ability to observe it. In many species, including barn swallows, males and females look similar from a distance but can be distinguished by ear. Female barn swallows primarily sing just before they begin breeding—knowing that can help observers track the timing of barn swallow nesting, for example. Initiatives such as xeno-canto and eBird collect millions of public observations and audio recordings of birds every year. People who understand the latest science will create better global data sets, which, in turn, will generate better science.


Barn swallows in courtship display

Duncan Usher/Minden Pictures

Nonscientists make better observers because they lack preconceived notions. One of us (Benedict) often talks to public groups and finds that birders ("experts") tend to assume female birds don't sing, whereas nonbirders tend to assume female birds might sing. Lessons about authentic science are ideal for engaging children, in particular, who have yet to absorb existing biases. One of us (Wilkins) adapted our female songbird research into a free interdisciplinary lesson for grades 5–12 (available at galacticpolymath.com). Wilkins once told a fifth grade math class they were among the first people in the world to explore a data set from a study on how bird vocal pitch decreases with body size, and they spontaneously broke into applause.

Female birds sing! We need to declare that truth so emphatically because it reflects the constant adjustments to the scientific consensus as new facts become available and new voices are added to the conversation. We welcome a future where research, communication and education combine to deepen our connections to one another and the natural world. SA

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ADVANCES

Artificial intelligence learned to share the road—and win—in Gran Turismo Sport.

Jon Feingersh/Getty Images

INSIDE

ARTIFICIAL INTELLIGENCE

AI Champions

Digital drivers triumph in ultrarealistic racing game

To hurtle around a corner along the fastest "racing line" without losing control, race car drivers must brake, steer and accelerate in precisely timed sequences. The process depends on the limits of friction, which are governed by known physical laws—and self-driving cars can be programmed to use these laws to drive as quickly as possible. But this challenge becomes much trickier when the automated driver has to share space with other cars. Now scientists have unraveled the problem virtually by training an artificial-intelligence program to outpace human competitors in the ultrarealistic racing game Gran Turismo Sport. The results could provide insights useful for designing self-driving cars.

Artificial intelligence has already defeated human players within certain video games, such as Starcraft II and Dota 2. But Gran Turismo differs significantly, says Peter Wurman, director of Sony AI America and co-author of the new study in *Nature*. "In most games, the environment defines the rules and protects the users from each other," he explains. "But in racing, the cars are very close to each other, and there's a very refined sense of etiquette that has to be learned and deployed by the [AI] agents. To win, they have to be respectful of their oppo-

Cars in Gran Turismo Sport

nents, but they also have to preserve their own driving lines and make sure that they don't just give way."

To teach the program the ropes, Sony AI researchers used a technique called deep reinforcement learning. They "rewarded" the AI algorithm for certain behaviors such as staying on the track, remaining in control of the vehicle and respecting racing etiquette—avoiding collisions, for example. Then they turned the program loose to try to achieve those goals. Multiple versions of the AI, dubbed Gran Turismo Sophy (GT Sophy), each learned to drive one specific car on one particular track. Next, the researchers pitted several versions of the program against human Gran Turismo champions.

In the first test, conducted last July, humans achieved the highest overall team score. On the second run, in October 2021, the AI versions broke through. They achieved the fastest lap times and beat their human foes as a team—plus, an AI won every race.

The human players seem to have taken their losses in stride, and some enjoyed pitting their wits against the AI. "Some of the things that we also heard from the drivers was that they learned new things from Sophy's maneuvers as well," says Erica Kato Marcus, director of strategies and partnerships at Sony AI.

"The lines the AI was using were so tricky. I could probably do them once, but it was so, so difficult—I would never attempt it in a race," says Emily Jones, who was a world finalist at the FIA-Certified Gran Turismo Championships 2020 and later raced against GT Sophy. Although Jones says competing against the AI made her feel a little powerless, she describes the experience as impressive. "Racing, like a lot of sports, is all about getting as close to the perfect lap as possible, but you can never actually get there," Jones says. "With Sophy, it was crazy to see something that was the *perfect* lap. There was no way to go any faster."

The Sony team is now developing the AI further, including aiming for one version that can race any car on any track in the game. They also hope to work with Gran Turismo's developer to incorporate a less invincible version of the AI into a future game update.

Because Gran Turismo provides a realistic approximation of specific real-world cars and racetracks—and of the unique physics parameters that govern each—this research might also have applications outside of video games. "I think one of the pieces that's interesting, which does differentiate this from the Dota game, is to be in a physics-based environment," says Brooke Chan, a software engineer at the AI research company OpenAI and co-author of the OpenAI Five project, which beat humans at Dota 2. An AI training on Gran Turismo is learning to understand more about the physical world, adds Chan, who was not involved with the GT Sophy study.

"Gran Turismo is a very good simulator—it's gamified in a few ways, but it really does faithfully represent a lot of the differences that you would get with different cars and different tracks," says Stanford University mechanical engineer J. Christian Gerdes, who was not involved in the new study. "This is, in my mind, the closest thing out there to anybody publishing a paper that says AI can go toe to toe with humans in a racing environment."

Big differences remain when it comes to physical roadways, though. "In the real world, you have to deal with things like bicyclists, pedestrians, animals, things that fall off trucks and drop in the road that you have to be able to avoid, bad weather [and] vehicle breakdowns," says Steven Shladover, a vehicle-automation researcher at the University of California, Berkeley, who was also not involved with the study. "None of that stuff shows up in the gaming world."

Gerdes says that because GT Sophy orchestrates the fastest possible path while interacting smoothly with often unpredictable humans, its achievement could have lessons for other fields in which humans and automated systems work together. Beyond automated driving, this capability might one day aid interactions such as robot-assisted surgery or machines helping out around the home.

GT Sophy's success also upends certain assumptions about the way self-driving cars must be programmed, Gerdes adds. Many automated vehicles optimize their movements—such as taking turns quickly without spinning out—based on programmed-in physics, but GT Sophy optimized through AI training.

"I think the lesson for automated-car developers is there's a data point here that maybe some of our preconceived notions—that certain parts of this problem are best done in physics—need to be revisited," Gerdes says. "AI might be able to play there as well." *—Sophie Bushwick*

Sony Interactive Entertainment

ECOLOGY

Hidden Forests

Thousands of tree species remain unknown to science

The world's forests may hold more secrets than previously thought: a new global estimate of tree biodiversity suggests that there are about 9,200 tree species yet to be documented. Most are likely in the tropics, according to the new research published in the *Proceedings of the National Academy of Sciences USA.*

Although trees are hard to miss, they are also hard to quantify—and sometimes even to identify. "Their crowns are hundreds of feet up; they're in between other things; they look like similar [species]," says Wake Forest University conservation biologist Miles Silman, who was not involved in the new study. "It's a rare breed of person who sits out in the wild for months on end and looks at every single tree."

The new research drew on the efforts of hundreds among that rare breed from around the world. These contributors have catalogued trees in two huge data sets: One, the Global Forest Biodiversity Initiative, records every species found in extensively documented forest plots worldwide. The other, TREECHANGE, compiles sightings of individual species. Together they suggest there are approximately 64,100 recorded tree species on the planet—up from previous estimates of around 60,000.

To arrive at their estimate of an additional 9,200 yet undocumented species, the researchers extrapolated from the number of rare ones already in the databases. Most unknown species are likely to be defined as rare, found in limited numbers in small geographical areas, says study co-author and Purdue University quantitative forest ecologist Jingjing Liang. The team's result is "a rather conservative estimate," Liang says, because scientists know less about the preponderance of uncommon trees in places such as the Amazon, where out-of-the-way spots could host pockets of unusual species found nowhere else. "If we can focus the resources, the forest inventory expertise and money, on those rain forests in the Amazon and Borneo," Liang adds, "then we would be able to estimate it with higher confidence."

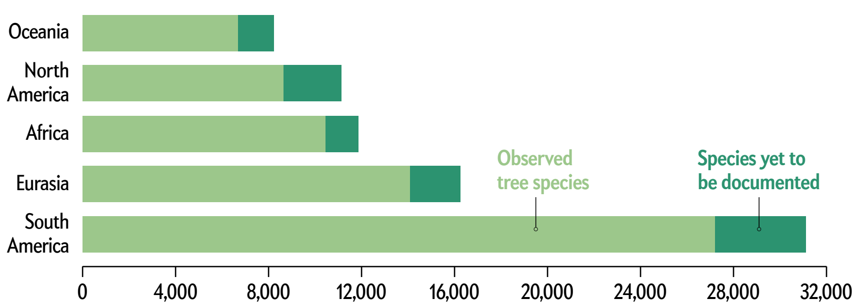
Silman says the study result is likely an underestimate. His and his colleagues' local surveys suggest there are at least 3,000 and possibly more than 6,000 unknown tree species in the Amazon basin alone. Tree species often get lumped together based on appearance, he notes, so new genetic analysis techniques will likely lead to the discovery of even more biodiversity.

Kenyon College biologist Drew Kerkhoff, who was also not involved in the study, wonders how many species will go extinct before scientists describe them. "Conversely," he says, "how many are already known to Indigenous peoples in the Amazon or Congo basins—or were known to peoples or cultures who have themselves been rendered extinct through colonization, disease, genocide or assimilation? How many [species] already have dried samples sitting in an herbarium cabinet?"

Searching for the new species will inform not only conservation but the basic evolutionary science of how and why species diversify and die out, Kerkhoff says. "Just the fact that there are thousands of species of something as common as trees out there that are still left to be discovered," he adds, "I find pretty inspirational."

—Stephanie Pappas

Estimated Tree Species per Continent



Source: "The Number of Tree Species on Earth," by Roberto Cazzolla Gatti et al., in *Proceedings of the National Academy of Sciences USA*, Vol. 119; January 31, 2022

Graphic by Amanda Montañez

BIOLOGY

Hunt for Color

Mosquitoes target red tones after smelling CO_2

A hungry mosquito can sense the carbon dioxide a person exhales from 100 feet away, and a new study reveals that the gas triggers the insect's visual system to pinpoint human skin tones.

"The odor is just telling them that something is out there, but their vision is telling them where it could be located," says University of Washington neurobiologist Jeff Riffell, lead author of the study in *Nature Communications.* Tracking 1.3 million mosquito trajectories, his team found that the insects are drawn to red and orange light (which human skin prominently reflects, regardless of race) and avoid most greens and blues—but only in the presence of CO_2.

Observing mosquitoes is hard; they dart through the air in quick, chaotic patterns. Researchers typically examine them in small boxes, but that "doesn't recapitulate their natural behaviors," Riffell says. To simulate a more realistic environment, Riffell's team built a seven-foot-long mosquito wind tunnel that could control wind speed, odors and visual stimuli with exquisite precision. Along the tunnel's edge, 16 cameras captured live video that was stitched together to reveal each insect's flight path.

Aedes aegypti can carry dengue and Zika virus.

When *Aedes aegypti* mosquitoes were released into the tunnel, they did not investigate objects colored to match human skin until carbon dioxide was added. When it was, the mosquitoes flocked to the objects. Filtering out orange and red light halted the attraction. In another experiment, the researchers introduced mutations in the mosquitoes' photoreceptors to suppress their vision for longer light wavelengths like red. This also stopped their swarming toward human skin tones, as did mutating a CO_2-sensing receptor.

"Given that mosquitoes do not have a separate red-sensitive receptor," says Almut Kelber, a sensory biologist at Sweden's Lund University who was not involved in the research, it seems likely "that orange, red and black are all seen as dark and that the choice is not for 'red' but for 'not green or blue.'"

Other insects also use smell to cue visual preference. Female Asian swallowtail butterflies, for instance, "make color choices depending on the odor," Kelber says. In a laboratory setting without scents, they preferentially land on blue objects. But when swallowtails smell a larval host plant to lay eggs on, she adds, they move toward green. Smelling oranges or lilies shifts their preference to red.

Riffell plans to extend his findings to develop better mosquito traps. Many traps have white components, he says: "And mosquitoes do not like white at all." —*Niko McCarty*

Joao Paulo Burini/Getty Images

BIOENGINEERING

Inside Edit

A tool from bacteria informs a new gene-tweaking technique

Deep in a bacterium's gelatinous matrix dwell little "cellular machines" called retrons, which produce single strands of DNA to detect certain viral infections. Now for the first time, researchers have used these natural DNA scriptwriters to modify genes in human cells. A new study, published in *Nature Chemical Biology,* suggests this technique can enhance gene editing across diverse animal groups.

Although the well-known CRISPR process has made gene editing much easier in recent years, it "has its own limitations," says the study's senior author Seth Shipman, a bioengineer at the University of California, San Francisco. This process introduces an enzyme called Cas9 to cut DNA segments and provides templates of desired DNA, designed by researchers, for cells to incorporate during the repair process. But this template DNA is created in the laboratory and must be inserted separately from CRISPR's components—and it does not always penetrate the cellular membrane.

Shipman and his colleagues instead used retrons to manufacture that DNA inside the cell itself, where the CRISPR process can readily use it. Retrons carry an enzyme called reverse transcriptase that builds DNA strands based on RNA. They also feature "some strangely overlapping loops of RNA" that help them function, says Santiago Lopez, a graduate student at U.C.S.F. and lead author on the study.

The researchers modified retrons in the lab so they would produce the desired template DNA. Additionally, they elongated the RNA loops, a change that turned out to let each retron produce more DNA copies. Finally, they inserted the retrons into cells along with CRISPR's components.

Using this process, retrons produced from 10 to 100 times more template DNA in yeast cells than in human cells. The retrons also achieved better editing precision in yeast than in human cells, possibly because of the differing number of strands or the way each cell type repairs DNA. "But frankly, we are not that worried right now," Shipman says, "since this is only a foot in the door." He says more adjustments and optimization will likely yield highly accurate editing in human cells.

"If we can repurpose retrons to produce DNA as 'donors' within a patient cell, it can be used for gene therapy applications for diseases such as sickle cell anemia, which require repair of only small stretches of faulty genetic sequences," says University of Nebraska molecular biologist Channabasavaiah B. Gurumurthy, who was not involved in the study.

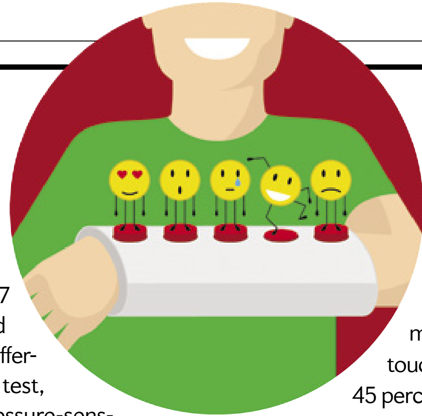
But introducing foreign DNA into human tissue cells can also "elicit adverse immune responses that limit genetic modifications," says Jin-Soo Kim, director of South Korea's IBS Center for Genome Engineering, who was also not involved in the work. Researchers who are using CRISPR alone have developed processes to suppress such responses, Kim adds, but it remains to be seen how to accommodate retrons.

—*Saugat Bolakhe*

HAPTICS

Touching Emoji

New tech conveys emotion through a virtual touch



Distancing amid the COVID-19 pandemic has made both physical and social connections a touch more difficult to maintain. For Stanford University graduate student Millie Salvato, being apart from her girlfriend on the opposite coast has proved challenging.

Sometimes a text or video call is not enough, and people in Salvato's situation often long for a way to send a loving caress or comforting squeeze from afar. For a new study detailed in *IEEE Transactions on Haptics*, she and her colleagues demonstrated a wearable sleeve that can simulate human touch—and convey abstract social messages sent electronically.

"It's a unique work that looks at how our social touch is delivered and then … how to reproduce it," says Gregory Gerling, a touch researcher at the University of Virginia who was not involved in the study.

Salvato and her team measured how 37 participants expressed social information in different situations. In each test, one person wore a pressure-sensing device on an arm, and another touched it to respond to scenarios involving six intended meanings: attention seeking, gratitude, happiness, calming, love and sadness.

After collecting 661 touch movements—squeezes, strokes, shakes, pokes, and the like—Salvato and her colleagues mapped the location and pressure of each. Next, they used a machine-learning algorithm to select the movements that were most reliably part of each response. Finally, they programmed a wearable sleeve to simulate these movements using eight embedded disks that vibrate when electronically signaled.

"It doesn't feel like an actual human hand … but it doesn't feel like these discrete motions either," Salvato says, as one might expect from large moving disks. "It feels nice, honestly."

Even with no training, 30 new study participants correctly matched the simulated touches to the six scenarios 45 percent of the time—about 2.7 times more than by chance. For comparison, a previous study from Gerling's laboratory found participants could match scenarios for touches from real human hands 57 percent of the time.

In the new study, "I think it's interesting that participants can reliably understand what touch has been delivered to them at a pretty high rate, given the sparse amount of information that they have available to them," Gerling says.

Previous research has found that social touch is important for physical and mental health. In the future, instead of just sending a <3 to a loved one by phone or computer, adding a "touch emoji" might help us feel just a little bit closer. —*Richard Sima*

Illustrations by Thomas Fuchs

COGNITION

Don't Overthink It

Reducing reasoning may help to learn language

Children often learn new languages more easily than adults do, but it's unclear why. Some hypothesize that grasping a language requires absorbing subtle patterns unconsciously and that adults' superior conscious reasoning interferes. New research suggests that, indeed, grown-ups might just be too smart for their own good.

For a recent study in the *Journal of Experimental Psychology: General*, a group of Belgian adults simultaneously read and heard strings of four made-up words (such as "kieng nief siet hiem"). Specific consonants always appeared at the beginning or end of a word if the word contained a certain vowel. Participants next read the sequences aloud quickly. Their ability to avoid mistakes doing so indicated how well they absorbed the consonant-vowel patterns.

But before exposure to the new words, the participants had carried out a separate test: pressing keys to react to letters and numbers. Some got a much faster, more mentally draining version of this test. Those who tackled the difficult version claimed greater cognitive fatigue afterward—but performed *better* on the subsequent language task. The researchers hypothesize that tired learners used less conscious analysis on the word rules: they were free to learn like a child.

For a related paper, in the *Proceedings of the National Academy of Sciences USA*, the team had English-speaking adults listen to streams of syllables secretly clustered into three-syllable "words." Later, they played pairs of three-syllable clusters; one word in the pair came from the stream, and one was a new combination. The participants guessed which word was familiar, then rated their confidence.

In one participant group, some had first done the original mentally draining test. In another, some had received magnetic pulses to disrupt activity in a brain area that previous research has linked to executive control. In both groups, these interventions improved participants' performance on the syllable task when they were unsure about their answers, indicating unconscious parsing of speech. (Confident answers suggested conscious recall instead.)

Georgetown University neuroscientist Michael Ullman, who was not involved in either paper, likes that the studies taxed cognitive control differently and measured different skills. "That's really good in science because you've got converging evidence," he says, adding that he would like to see higher language skills such as grammar studied this way.

Ghent University psychologist Eleonore Smalle, who spearheaded both papers, offers advice based on her team's findings. When beginning to learn a language, she says, immerse yourself in its sounds, even—or especially—while distracted. "Have a good glass of wine while listening to a podcast in Italian," she suggests with a laugh. "Why not? It could help." —*Matthew Hutson*

Honeybee visits a California golden poppy.

Sumiko Scott/Getty Images

VIROLOGY

Pollen Passengers

Hundreds of viruses travel through plant pollination

There's more than just pollen riding on a springtime breeze. Just as some human viruses spread when humans reproduce, plant viruses can use pollen to hitch a ride from flower to flower. A study in *Nature Communications* shows how plentiful pollen-borne viruses are—and suggests that human activity may help them spread.

University of Pittsburgh evolutionary ecologist Tia-Lynn Ashman and her colleagues used genetic sequencing to catalog viruses on wildflower pollen from four different environments: California grasslands, the California coast, an agricultural area in Pennsylvania and the Appalachian Mountains. The team found 22 known viruses—some of which have serious effects on crops. They also found evidence of hundreds of viruses scientists had never seen.

The findings match results across microbiology, says University of Florida plant virologist Amit Levy, who was not part of the study: "There's just way more viruses everywhere than we expected."

The team also discovered an interesting correlation. Flowers from the agricultural site carried genome snippets from more than 100 different viruses, whereas flowers from the California grasslands (where human activity is lowest among the areas studied) had only around a dozen. The other sites had intermediate viral diversity. The researchers hypothesize that plant homogeneity within crop fields could encourage more viruses to inhabit these areas—once a virus evolves to infect a crop, it finds many compatible hosts.

Although this link is preliminary, Levy says it makes sense that industrial agriculture might breed plant pathogens. With plants packed together, "there's no social distancing between the crops."

Ashman wonders if honeybees, which farmers often breed, could also exacerbate plant virus spread in agricultural areas. Honeybees are less choosy about which plants to visit than most native bees, potentially carrying viruses between wildflowers and crops.

Hernan Garcia-Ruiz, a virologist at the University of Nebraska–Lincoln who was not involved with the new study, says it grabbed his attention because the authors uncovered a plethora of viruses even in plants that did not appear sick. But such microbes may not be as benign if transmitted from wild plants to crops. Garcia-Ruiz cites sugarcane mosaic virus—a serious sugarcane and corn pathogen that hides in wild grasses in between crop seasons. "As soon as the corn is available, insects move the virus back into corn," he says.

Ashman agrees that it is important to understand viruses' effects on a variety of plants, especially if humans are encouraging spread from natural habitats to agriculture and back. As a scientific hypothesis, she finds this prospect "tantalizing"—but "possibly frightening." —*Saima May Sidik*

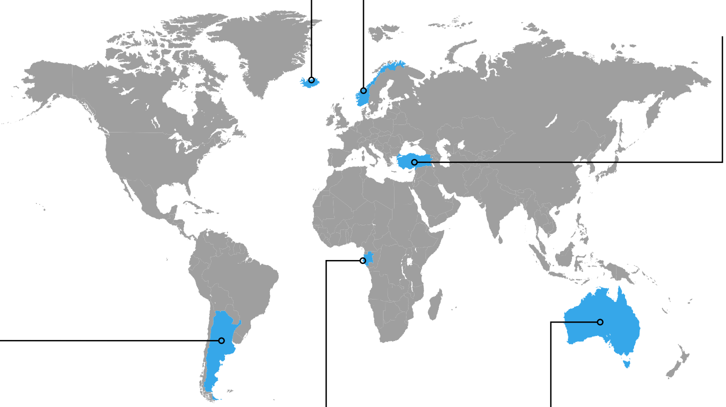
IN THE NEWS

Quick Hits

By Joanna Thompson

ICELAND
The "Blue Blob," a mysterious patch of frigid water in the northern Atlantic Ocean, appears to have slowed the melt rate of Iceland's glaciers by up to 50 percent. But experts warn that unimpeded climate change may overcome this cooling effect by the 2050s.

NORWAY
A 27-year analysis of Norwegian salmon has revealed an abrupt reduction in their body size, beginning in 2005. The decline strongly correlates with a sudden drop in levels of oceanic zooplankton, a crucial food source for the fish.



ARGENTINA
As ice fields in the Patagonian Andes shrink, the tectonic plates underneath them are simultaneously pushing upward. Researchers found that the heavy glaciers weigh down buoyant sections of mantle; when the ice melts, the ground below springs up rapidly.

TURKEY
A dagger forged from meteorite material and found in King Tut's tomb apparently originated outside Egypt. X-ray analysis suggests the dagger's metalwork did not match Egyptian metallurgy of the time but was consistent with techniques used in Mitanni, a region overlapping present-day Turkey.

GABON
Chimpanzees from the Rekambo community were seen applying crushed insects to their wounds and those of others in the troop, suggesting they might be taking advantage of pharmacological properties.

AUSTRALIA
A deluxe version of *Songs of Disappearance*, an album composed of birdsong from endangered or at-risk Australian species, soared to number two on the country's music sales charts. The birds rose above Taylor Swift's latest album, nesting just below the dulcet tones of Korn.

For more details, visit www.ScientificAmerican.com/may2022/advances


Rescue drone

Sophie Linckersdorff/Getty Images

FORENSICS

Remote Rescue

Reflected light can reveal forensic details far below a drone

Volunteers sometimes spend months trudging through remote terrain to search for lost hikers or crime victims. But a new tool could soon pinpoint forensic evidence from the sky instead. By identifying how traces of blood and other human signs reflect light when found on various natural surfaces, the scientists say searchers will be able to quickly scour large areas for clues about missing persons—dead or alive—using images acquired by drones.

Special drone-mounted sensors can record wavelength intensity for the entire electromagnetic spectrum (rather than just the red, green and blue of a typical camera) in each pixel of an image. Geologists routinely use this technology to pinpoint mineral deposits. Mark Krekeler, a mineralogist at Miami University in Ohio, and his colleagues realized that the same approach, supported by the right spectral data library, could potentially detect forensic evidence.

To build their tool, the researchers measured how human-related features, including blood, sweaty clothing and skin tones, reflect different wavelengths of light. Previous studies have examined such reflective "signatures" to identify blood, "but the signature depends on the surface itself and may change over time," Krekeler says. He and his team analyzed thousands of samples, such as bloodstains on different rock types, recording how they changed as the blood dried.

The researchers customized software that mixes the known reflective signatures of various surfaces to reproduce a target of interest. For example, rock and clothing signatures can be combined to seek a hiker lost in the mountains, or a blood signature can be mixed with those of clothing and sand to search for a wounded person in a desert.

The software estimates whether the target exists in any pixel in an image. It can distinguish between an animal and a human in dense forest, search a cityscape for evidence of a specific person in a blue cotton dress, or determine whether soil is stained by blood or diesel fuel, Krekeler says. His team was slated to present its work at the Geological Society of America's meeting of the North-Central Section in April.

Wendy Calvin, a planetary scientist at the University of Nevada, Reno, who was not involved with the study, calls it "an interesting and novel use of spectral data—and the technique looks promising." But she says it could be challenging to use from afar because of how much of a substance would likely be needed to show up in a pixel.

Within months, officials will be able to download and test the tool for themselves. Developing best-practice protocols for search teams could make such technology routine for investigations and forensics, Krekeler says. As drones and sensors become more widespread, he adds, they can transform investigations that are currently costly, labor-intensive or even impossible. *—Rachel Berkowitz*

MICROBIOLOGY

Sponge Gunk

Kitchen scrubbers make ideal homes for many bacteria types

Your kitchen sponge is teeming with microbes. But repeated contact with food waste is not the only reason; a sponge's unique structure plays a role, too. It could even inspire a new way to grow bacteria for research, according to a study in *Nature Chemical Biology*.

One of the biggest challenges microbiologists face is culturing bacteria species that will not readily grow in a laboratory. Some microbes are incredibly finicky, and scientists often have no idea what conditions these organisms need. "It's kind of like trying to make pandas reproduce in the zoo," says bacteriologist Trina McMahon of the University of Wisconsin–Madison, who was not involved in the new study.

Sponges could provide an answer. Bacteria are usually grown on petri dishes' smooth, unpartitioned surfaces. But sponges are riddled with hollow pockets—which, crucially, are not uniform. "Imagine there are tiny rooms and bigger rooms," says Lingchong You, a microbiologist at Duke University and senior author of the study. Some bacteria types depend on many other individuals for survival and need space to form large communities, but others require relative isolation so they are not killed by their neighbors. Sponges' mix of larger and smaller chambers offers an ideal range.

Although a sponge's potential as a bacteria farm might seem intuitive, "actually demonstrating that experimentally is a challenging process," You says. The researchers first modeled spongelike environments on a computer and found that varying chamber sizes would allow many different bacterial strains to thrive. Then they replicated these results in cellulose sponges.

"It's rare to see both [scenarios] combined in such a nice way," McMahon says. But she notes that You's team focused on *Escherichia coli* strains that were lab-engineered to be either dependent on one another or self-sufficient—so she wonders if the sponge technique will work with other sensitive bacteria. "There is a limit, I think, to what you can do with those engineered strains," she says.

Future experiments will show whether You's purpose-built sponges can support wild microbes. In the meantime, he recommends sanitizing your kitchen sponge: "It's probably not the cleanest item." *—Joanna Thompson*

MEDICINE

COVID Gum

A key protein traps SARS-CoV-2 when chewed

Chewing gum mixed with a particular protein could be a low-cost way to help prevent the spread of the virus behind COVID-19, a recent study suggests.

The angiotensin-converting enzyme 2 (ACE2) protein, found on the surface of many human cells, acts as a gateway for the virus to infect them. If delivered to the mouth by chewing gum, however, ACE2 could instead trap the virus by binding to the spike protein it uses to infect cells. The protein in the gum could also bind to receptors on cells themselves, thereby blocking infection sites. This combination could prevent viruses from infecting cells in the oral cavity, researchers report in *Molecular Therapy*.

SARS-CoV-2, the virus that causes COVID-19, typically first infects human cells in the nose and throat. But the mouth is also a key reservoir of the virus in an infected person, scientists have found. The new study contends that inactivating the virus in the mouth's mucous membranes and saliva could reduce infection in the adjoining nasopharyngeal area, too. If additional research bears out these findings, the gum might join face masks and hand sanitizer in the anti-COVID arsenal.

Delmaine Donson/Getty Images

To study this strategy, a team led by University of Pennsylvania pharmaceutical researcher Henry Daniell genetically modified lettuce plants to produce a soluble form of ACE2 (which has been proved safe at high dosages in animals). The lettuce was then powdered and blended with cinnamon-flavored chewing gum.

The researchers tested the protein's effectiveness in hamster cells modified to produce human ACE2 receptors. They found that a relatively small quantity of the protein, coming from the gum, was associated with a 95 percent reduction in the amount of cell penetration by a stand-in virus equipped with SARS-CoV-2 spike proteins. The amount of a similar stand-in virus inside unmodified monkey cells also dropped by 85 percent when exposed to the protein. Adding the gum to saliva samples and swabs of nasal and throat fluid from a handful of people infected with SARS-CoV-2 was associated with a more than 95 percent reduction in the virus amount.

Daniell says his team is awaiting approval from the U.S. Food and Drug Administration to test the gum's effectiveness in humans. Testing with a chewing machine suggests the protein would be released over 10 minutes, and Daniell estimates protection would last four hours. He is also testing the chewing-gum approach against influenza.

A key consideration is whether this strategy works if infection first occurs outside the mouth. "The main entry route for COVID-19 is the nose," says immunologist Danny Altmann of Imperial College London, who was not involved in the new study. "And the gum may have little effect at stopping the virus entering from that opening—unless it is found that it provides protection at the back of the throat."

Even if the gum does not fully defend a chewer against infection, it might reduce spread by cutting down the amount of virus in an infected person's mouth and thus reducing how much is available for transmission, says University of Leicester virologist Julian Tang, who also was not involved in the study.

In a best-case scenario, COVID-busting gum could be on store shelves in about six months, Daniell says. And one day four out of five doctors might recommend virus-busting gum for their patients.

—Abdullah Iqbal

BIOLOGY

Science in Images

By Carolyn Wilke

During their nightly energy-conserving cooldowns, hummingbirds may strategically adjust just how low their body temperatures go. These tiny powerhouses cool off by up to 37 degrees Celsius while roosting, entering a hibernationlike state called deep torpor. This state can save 60 to 90 percent of an individual's energy per hour, says Anusha Shankar, a Cornell University ecologist and lead author of a new study about the phenomenon.

Though crucial for the fleet fliers' way of life, deep torpor comes with trade-offs. For example, torpid birds become stiff and unable to respond to threats. "They're effectively comatose," says University of New Mexico ornithologist Christopher Witt, who was not part of the study.

Now, as detailed in the *Journal of Experimental Biology*, Shankar's team shows that some hummingbirds also chill in a shallower torpor with intermediate temperatures, demonstrating more control over their bodies' thermostats than previously thought.

This capability has gone unnoticed despite 70 years of research on hummingbird torpor, Shankar says. But past research typically examined torpor under laboratory conditions; Shankar, who was then working at Stony Brook University, and her colleagues studied wild hummingbirds in their natural environment in southeastern Arizona.

The scientists captured hummingbirds before nightfall and placed them in outdoor structures. As each night unfolded the team spied on the animals using infrared cameras and charted temperatures around the birds' eyes, where feathers interfere less with such measurements. The three species studied spent five to 35 percent of the night in shallow torpor. The rest of the time was spent at normal temperatures, in deep torpor, or transitioning between states, with variations from bird to bird. This is the first scientific documentation of shallow torpor in hummingbirds, Witt says, "but it's very clearly part of their thermal regulatory strategy."

Shallow torpor may help hummingbirds achieve more of the restorative benefits of sleep while avoiding some potential deep torpor dangers—including reduced immune function—that have been observed in other animals, Shankar says. "And it leads to so many other questions" that she and others are starting to pursue, such as what drives changes in torpor and how the birds accomplish these dramatic temperature shifts.

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

Ignacio Yufera/FLPA/Minden Pictures


Hummingbirds can enter torpor to conserve energy while sleeping.

Poet and novelist **Barbara Quick** lives in northern California. Her 2007 novel, *Vivaldi's Virgins,* has been translated into a dozen languages and is in development as a miniseries. Her fourth novel, *What Disappears,* will be published on May 17. Her 2021 chapbook, *The Light on Sifnos,* won the Blue Light Press Poetry Prize.

The Algorithm

Optimization under uncertainty
is a field of study in which my grown son
will earn his Ph.D. The math, in his case,
concerns the production of wind energy.

He reads his papers aloud on the phone to me
as a way to optimize their clarity,
so that even a layperson, such as myself,
can understand what he's saying,
in between each beautifully made
equation and graph.

For me, it's a matter of optimizing
my time with him, my only child, who lives
so far away and does not get along
with the man I married. I'm looking for
the algorithm that can minimize
the pain entailed for all of us
in this awful situation.

One needs to account for the inconstancy
of the wind's strength and direction,
and how best to cant the rotors' turning blades,
and how the power produced is affected
by the wakes created when lots of turbines
are working in concert together.

We stay on the phone for hours sometimes
while I fill my sails with the sweet sounds
of my son's voice, filled with longing
to hold him close again.

I admire the choice he's made to apply his gifts
in ways that can make the world a better place,
even though uncertainty is omnipresent,
and must be factored in
to every calculation.

Nelli Okhrimenko/Getty Images

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.*

A New Era for Obesity Drugs

Costly medications work well, but are they safe over the long term?

By Claudia Wallis

The people who seek out endocrinologist Domenica Rubino have tried again and again to lose weight. Diets of all kinds. Exercise regimens. Health-tracking apps. Some have turned to gastric bypass surgery, lost scores of pounds but then regained them. Many patients have medical problems related to severe obesity, including diabetes, fatty liver disease, hypertension, polycystic ovary syndrome, sleep apnea and painful arthritic joints. Rubino, director of the Washington Center for Weight Management and Research in Arlington, Va., says that for years she had relatively few tools to help them. That changed with the recent advent of medications directly targeting the brain-gut axis that regulates appetite. "We are finally able to help people lose weight in the ranges that help the complications of obesity," Rubino says.

The medication generating the most excitement is a weekly injectable drug called semaglutide (brand name: Wegovy). It was approved in June 2021 for treating people with a body mass index in the obese range or just under that range but with weight-related health issues. A study involving 1,961 such individuals published last year in the *New England Journal of Medicine* found that, on average, people taking semaglutide lost 14.9 percent of their initial body weight over 68 weeks compared with just 2.4 percent for a group receiving placebo injections. Such results are about double what older weight-loss drugs achieve, says Robert Kushner of Northwestern University, one of the study's principal investigators. Evidence from the trial suggests that along with weight loss come reductions in blood pressure, blood glucose and unhealthy lipids, as well as C-reactive protein (a measure of inflammation).

Kushner emphasizes the drug is not just for weight loss but to reduce the associated risk of chronic illnesses. "We want to be sure our patients are getting healthier, not just thinner," he says.

Semaglutide is widely seen as a breakthrough—"a new paradigm for the hormonal treatment of obesity," as Kushner puts it. The medicine mimics a gut hormone called glucagon-like peptide-1 (GLP-1) that acts on the pancreas to increase insulin production, on the stomach to slow emptying, and on the brain to turn down appetite and signal satiety. Patients can eat less and not be bothered by hunger and cravings. Other medications are in development that combine two or three hormones involved in appetite.

The hitch is that these drugs must be used throughout life, much like diabetes medications, or else the benefits are lost. In fact, a 2021 study led by Rubino found that people on semaglutide regain weight when the drug is stopped. The premise of such treatments is that serious obesity is not a transitory condition related mainly to behavior and environmental factors, as many people see it. Rather, in the view of the National Institutes of Health and the American Medical Association, it is a chronic, relapsing disease—one that disrupts multiple physiological systems.

Still, the prospect of a lifetime of weekly injections to maintain weight loss raises a number of questions, beginning with safety. Anything that alters functions as fundamental as metabolism and energy balance can have significant side effects. The diet pill Fen-Phen, now banned, caused heart valve damage, for instance. Most people on semaglutide experience nausea and diarrhea, but these are usually mitigated by starting them on a low dose. In the *New England Journal of Medicine* study, only 4.5 percent of semaglutide recipients dropped out because of gastrointestinal symptoms. Kushner also points out that a lower-dose version of semaglutide, marketed as Ozempic, has been used for type 2 diabetes for more than four years, "and the safety profile is good." But a higher dose taken over many decades could be another matter.

Cost is also an issue for the weight-loss drug and will likely be a problem for similar medications. The price is $1,349 a month. Insurance coverage is spotty, and Medicare does not pay for it. Yet demand is so strong the drugmaker, Novo Nordisk, can't keep up. "We've been asked to hold off starting new patients," Kushner says.

The rush to embrace a lifelong injectable drug makes some obesity researchers nervous. "As someone who studies lifestyle interventions, I feel that our health-care system is just focused on treatment and not prevention," says Krista Varady, a professor of nutrition at the University of Illinois, Chicago. "We just wait for people to get sick so we can sell them things like drugs."

Prevention would undoubtedly be better, Rubino agrees, but many of her patients are already ill. Her team always promotes a healthier diet and more exercise, she says, and "the medicines provide physiological support for those changes." SA

Illustration by Fatinha Ramos

Meet the Beauty in the Beast

Discover this spectacular 6½-carat green treasure from Mount St. Helens!

For almost a hundred years it lay dormant. Silently building strength. At 10,000 feet high, it was truly a sleeping giant. Until May 18, 1980, when the beast awoke with violent force and revealed its greatest secret. Mount St. Helens erupted, sending up a 80,000-foot column of ash and smoke. From that chaos, something beautiful emerged… our spectacular ***Helenite Necklace***.

EXCLUSIVE
FREE
Helenite Earrings
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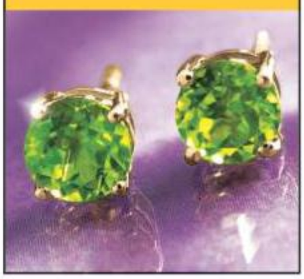
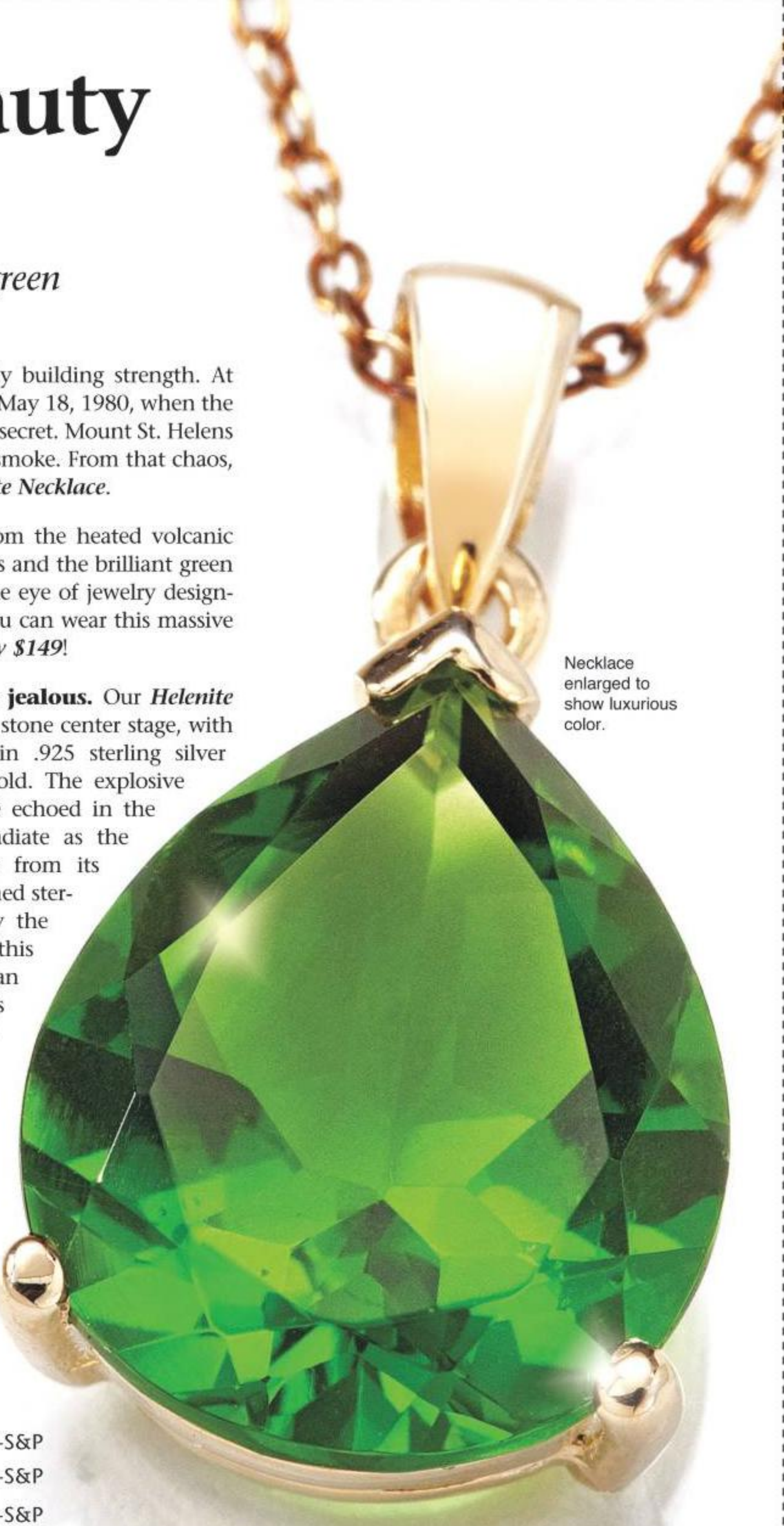


Helenite is produced from the heated volcanic rock of Mount St. Helens and the brilliant green creation has captured the eye of jewelry designers worldwide. Today you can wear this massive 6½-carat stunner for ***only $149***!

Make your emeralds jealous. Our *Helenite Necklace* puts the green stone center stage, with a faceted pear-cut set in .925 sterling silver finished in luxurious gold. The explosive origins of the stone are echoed in the flashes of light that radiate as the piece swings gracefully from its 18″ luxurious gold-finished sterling silver chain. Today the volcano sits quiet, but this unique piece of American natural history continues to erupt with gorgeous green fire.



Necklace enlarged to show luxurious color.

Your satisfaction is guaranteed. Bring home the ***Helenite Necklace*** and see for yourself. If you are not completely blown away by the rare beauty of this exceptional stone, simply return the necklace within 30 days for a full refund of your purchase price.

JEWELRY SPECS:

- 6 ½ ctw Helenite in gold-finished sterling silver setting
- 18″ gold-finished sterling silver chain

Limited to the first 2200 orders from this ad only

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QUANTUM COMPUTING

Errors in the Machine

The same physics that makes quantum computers powerful also makes them finicky. New techniques aim to correct errors faster than they can build up

By Zaira Nazario

Illustration by Alice Mollon

Zaira Nazario is a quantum theorist at the IBM Watson Research Center in Yorktown Heights, N.Y.

IT IS A LAW OF PHYSICS THAT EVERYTHING THAT IS NOT PROHIBITED IS MANDATORY. ERRORS ARE thus unavoidable. They are everywhere: in language, cooking, communication, image processing and, of course, computation. Mitigating and correcting them keeps society running. You can scratch a DVD yet still play it. QR codes can be blurred or torn yet are still readable. Images from space probes can travel hundreds of millions of miles yet still look crisp. Error correction is one of the most fundamental concepts in information technology. Errors may be inevitable, but they are also fixable.

This law of inevitability applies equally to quantum computers. These emerging machines exploit the fundamental rules of physics to solve problems that classical computers find intractable. The implications for science and business could be profound. But with great power comes great vulnerability. Quantum computers suffer types of errors that are unknown to classical computers and that our standard correction techniques cannot fix.

I am a physicist working in quantum computing at IBM, but my career didn't start there. I began as a condensed-matter theorist investigating materials' quantum-mechanical behavior, such as superconductivity; at the time I was oblivious to how that would eventually lead me to quantum computation. That came later when I took a hiatus to work on science policy at the U.S. Department of State, which next led me to the Defense Advanced Research Projects Agency (DARPA) and the Intelligence Advanced Research Projects Activity (IARPA). There I sought to employ the fundamentals of nature to develop new technology.

Quantum computers were in their earliest stages then. Although Paul Benioff of Argonne National Laboratories had proposed them in 1980, it took physicists nearly two decades to build the first one. Another decade later, in 2007, they invented the basic data unit that underlies the quantum computers of IBM, Google and others, known as the superconducting transmon qubit. My experience with superconductivity was suddenly in demand. I helped run several quantum-computing research programs at IARPA and later joined IBM.

There I devoted myself to improving operations among multiple linked qubits and exploring how to correct errors. By combining qubits through a quantum phenomenon called entanglement, we can store vast amounts of information collectively, much more than the same number of ordinary computer bits can. Because qubit states are in the form of waves, they can interfere, just as light waves do, leading to a much richer landscape for computation than just flipping bits. These capabilities give quantum computers their power to perform certain functions extremely efficiently and potentially speed up a wide range of applications: simulating nature, investigating and engineering new materials, uncovering hidden features in data to improve machine learning, or finding more energy-efficient catalysts for industrial chemical processes.

The trouble is that many proposals to solve useful problems require quantum computers to perform billions of logical operations, or "gates," on hundreds to thousands of qubits. That feat demands they make at most a single error every billion gates. Yet today's best machines make an error every 1,000 gates. Faced with the huge gap between theory and practice, physicists in the early days worried that quantum computing would remain a scientific curiosity.

CORRECTING ERRORS

THE GAME CHANGED in 1995, when Peter Shor of Bell Labs and, independently, Andrew Steane of the University of Oxford developed quantum error correction. They showed how physicists can spread a single qubit's worth of information over multiple physical qubits, to build reliable quantum computers out of unreliable components. So long as the physical qubits are of high-enough quality that their error rate is below some threshold, we can remove errors faster than they accumulate.

To see why Shor's and Steane's work was such a breakthrough, consider how ordinary error correction typically works. A simple error correction code makes backup copies of information—for example, representing 0 by 000 and 1 by 111. That way, if your computer reads out a 010, it knows the original value was probably 0. Such a code succeeds when the error rate is low enough that at most one copy of the bit is corrupted. Engineers make the hardware as reliable as they can, then add a layer of redundancy to clean up any remaining errors.

It was not clear, however, how to adapt classical methods of error correction to quantum computers. Quantum information cannot be copied; to correct errors, we need to collect information about them through measurement. The problem is, if you check the qubits, you can collapse their state—that is, you can destroy the quantum information encoded in them. Furthermore, besides having errors in flipped bits, in a quantum computer you also have errors in the phases of the waves describing the states of the qubits.

To get around all these issues, quantum error correction strategies use helper qubits. A series of gates entangles the helpers with the original qubits, which effectively transfers noise from the system to the helpers. You then measure the helpers, which gives you enough information to identify the errors without touching the system you care about, therefore letting you fix them.

As with classical error correction, success depends on the physics of the noise. For quantum computers, errors arise when the device gets entangled with the environment. To keep a computer working, the physical error rate must be small enough. There is a critical value for this error rate. Below this threshold you can correct errors to make the probability that a computation will fail arbitrarily low. Above this point, the hardware introduces errors faster than we can correct them. This shift in behavior is essentially a phase transition between an ordered and a disordered state. This fascinated me as a theoretical condensed-matter physicist who spent most of her career studying quantum phase transitions.

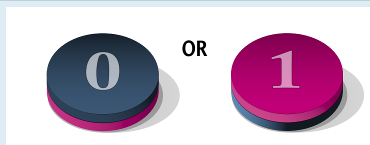
We are continuing to investigate ways to improve error correction codes so that they can handle higher error rates, a wider variety of errors, and the constraints of hardware. The most popular error correction codes are called topological quantum codes. Their origins go back to 1982, when Frank Wilczek of the Massachusetts Institute of Technology proposed that the universe might contain an entirely new category of particles. Unlike the known types, which have either integer or half-odd-integer values of angular momentum, the new breed could have fractional values in between. He called them "anyons"

Bits vs. Qubits

Quantum computers harness the rules of quantum mechanics to surpass the capabilities of classical machines. Qubits can be in a "superposition" of multiple states. A quantum phenomenon called entanglement causes qubits to be inextricably correlated—if you have two entangled qubits and measure them individually, you get random results, but when you look at both as a whole, the state of one is dependent on that of the other. Entangled qubits contain more information than the two qubits separately.

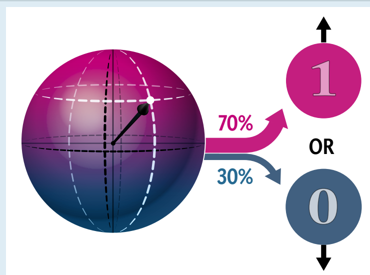
FROM BIT …

A classical bit can have one of two states: 0 or 1, like two sides of a coin.



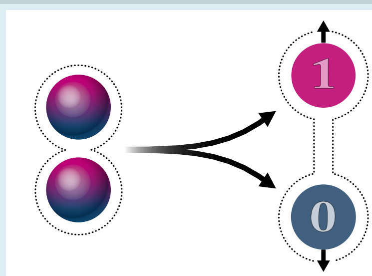
… TO QUBIT …

A qubit, on the other hand, has many more possible states. These can be thought of as points on a sphere, each with different coordinates. One point of many is shown here. When a qubit is in a superposition state, it can have an infinite number of possible coordinates. If scientists directly measure that qubit, however, these possibilities "collapse" to a single state.



… TO ENTANGLED QUBITS

If two qubits are entangled, their states are no longer separate; rather, they depend on one another. When a scientist measures the state of an entangled qubit, she immediately knows the state of its partner without measuring. The effect persists no matter how far the qubits are physically separated.



Graphics by Jen Christiansen

and cautioned that “practical applications of these phenomena seem remote.”

But soon physicists discovered that anyons were not so esoteric after all; in fact they have connections to real-world phenomena. To complete their migration from theory to the practical needs of technology, Alexei Kitaev of the California Institute of Technology realized that anyons are a useful formulation for quantum computation. He further proposed using certain systems of many particles as quantum error correction codes.

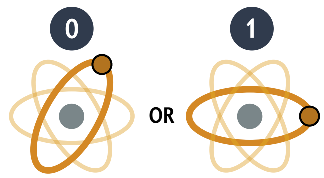
In these systems, the particles are connected in a lattice structure where their lowest energy state is highly entangled. The errors correspond to the sys-

Quantum Circuits

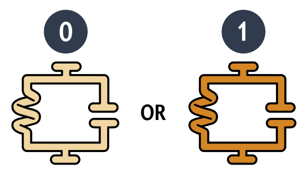
Quantum circuits are abstract representations of quantum computation, analogous to circuits in classical computational theory. With these diagrams, we set aside the physical details—whether the qubits are superconducting transmons or some other technology—and focus on the operations they perform.

A quantum computer can be built in a variety of ways, with different items playing the role of qubit. Three popular approaches are listed here.

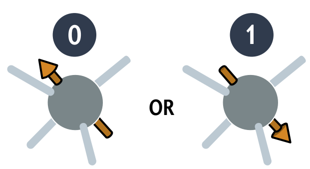
Atomic Ion Qubits
Electron orbit defines quantum state



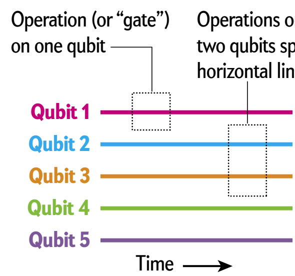
Superconducting Qubits
Different superpositions of electric charge define quantum state



Solid-State Spin Qubits
Spin of an atom of interest in a lattice defines quantum state

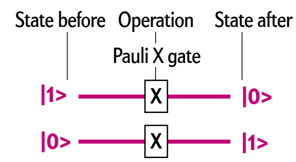


Regardless of the physical form, the operations of each of these types can be represented by the same quantum circuit diagrams, which look like sheet music. Parallel horizontal lines depict the individual qubits. The notes represent the operations, or “gates.” Like music notation, the circuit diagram is meant to be read across in time. It shows the sequences of operations that you perform on each of the qubits.

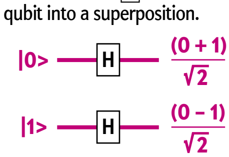


Different gate symbols represent different operations.

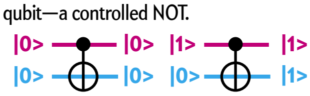
A bit flip, or so-called Pauli X, gate (X) inverts the qubit: If it is 1, it flips to 0, and vice versa.



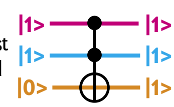
A Hadamard gate (H) places the qubit into a superposition.



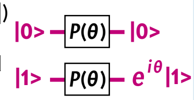
If a symbol is connected by a vertical line to another qubit, the inversion is contingent on the value of another qubit—a controlled NOT.



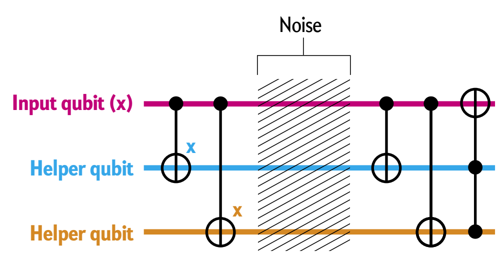
A controlled NOT that connects at least three qubits is called a Toffoli gate.



A phase gate (P(θ)) rotates the qubit at an angle around the Z axis.



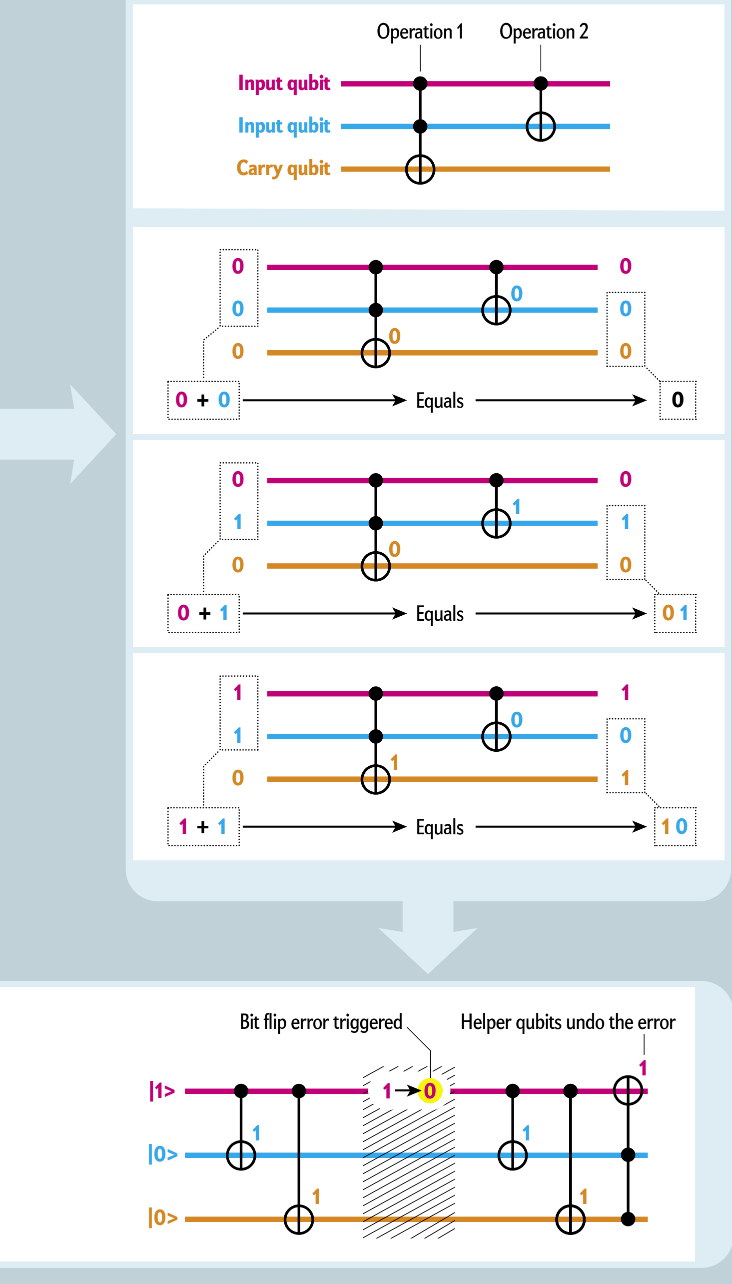
Each gate has an error rate—a probability that the hardware implementing the gate will return the wrong value, like the odds of a musician playing the wrong note. Without error correction, circuits fail with a probability that is linearly proportional to the gates’ error rate: you would soon have so many wrong notes that the piece is unrecognizable. But by using helper qubits, a quantum circuit can catch and correct glitches. Here’s one example of a simple error-correcting circuit. It works by encoding a single qubit worth of information in three qubits and determining if two different pairs of qubits are the same or different—one pair tells you if an error occurred, two pairs identify where it occurred, with the Toffoli gate applying the correction. In this way, you extract information about the error without touching or knowing anything about the quantum information.

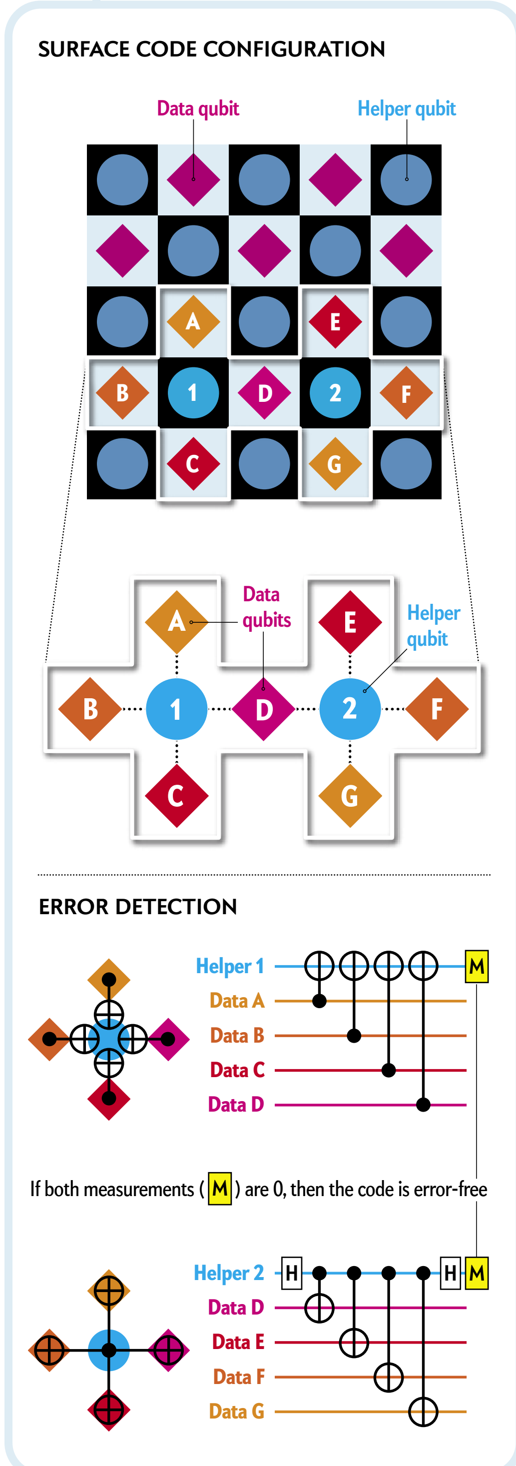


tem being in a higher energy state, called an excitation. These excitations are anyons. This system marks the birth of topological codes—and with it, another connection between condensed matter physics and quantum error correction. Because noise is expected to act locally on the lattice, and topological codes have localized excitations, they quickly became the favorite scheme to protect quantum information.

Two examples of topological codes are called the surface code and the color code. The surface code was created by Kitaev and my IBM colleague Sergey Bravyi. It features data and helper qubits alternating on a two-dimensional square grid like black and white squares on a chessboard.

Here is a simple circuit example, representing an addition problem. It takes two input qubits and calculates their sum, with an additional carry qubit to carry over digits. The circuit consists of a Toffoli (controlled-controlled-NOT) gate and a CNOT gate. Three sample calculations show how it works.



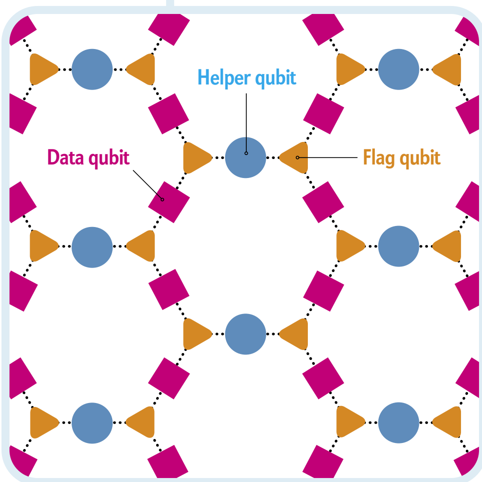


FROM CHESSBOARDS TO SETTLERS OF CATAN

THE THEORY BEHIND SURFACE CODES is compelling, but when we started to explore them at IBM, we ran into challenges. Understanding these requires a little more knowledge of how transmon qubits work.

A transmon qubit relies on oscillating currents traveling around an electrical circuit of superconducting wire. The qubit 0 and 1 values correspond to different superpositions of electric charge. To perform operations on the qubit, we apply pulses of microwave energy at a specific frequency. We have some flexibility in what frequency we choose, and we set it when we fabricate the qubit, choosing different frequencies for different qubits to be able to address them individually. The trouble is that the frequency may deviate from the intended value, or pulses may overlap in frequency, so that a pulse meant for one qubit could change the value of a neighbor. The surface code's dense grid, where each qubit connects with four other qubits, was causing too many of these frequency collisions.

Our team decided to solve the problem by connecting each qubit to fewer neighbors. The resulting lattice consisted of hexagons—we call it the "heavy hex" layout—and looks like the Settlers of Catan game board rather than a chessboard. The good news was that the heavy hex layout reduced the frequency of collisions. But for this layout to be valuable, the IBM theory team had to develop a new error correction code.



The new code, called the heavy hexagon code, combined features of the surface code and of another lattice-based code called the Bacon-Shor code. The lower qubit connectivity in our code means that some qubits, called flag qubits, must serve as intermediaries to identify which errors have occurred, leading to slightly more complex circuits and therefore a slightly lower error threshold for success. But we have found the trade-off is worth it.

There is another problem yet to solve. Codes living on two-dimensional planes and incorporating only nearest-neighbor connections have a large overhead. Correcting more errors means building a larger code, which employs more physical qubits to create a single logical qubit. The setup requires more physical hardware to represent the same amount of data—and more hardware makes it more difficult to build qubits good enough to beat the error threshold.

Quantum engineers have two options. We could make peace with the large overhead—the extra qubits and gates—as the cost of a simpler architecture and work to understand and optimize the different factors contributing to the cost. Alternatively, we could continue to seek better codes. For instance, to encode more logical qubits into fewer physical qubits, perhaps we should allow qubits to interact with more distant qubits than just their nearest neighbors or go beyond a two-dimensional grid to a three- or higher-dimensional lattice. Our theory team is pursuing both options.

THE IMPORTANCE OF UNIVERSALITY

A USEFUL QUANTUM COMPUTER must be able to carry out any possible computational operation. Neglecting this requirement is the root of many common misconceptions and misleading messages about quantum computation. Put simply, not all the devices that people call quantum "computers" are actually computers—many are more like calculating machines that can perform only certain tasks.

Overlooking the need for universal computation is also the root of misconceptions and misleading messages about logical qubits and quantum error correction. Protecting information in memory from error is a start, but it is not enough. We need a universal set of quantum gates, one that is sufficiently rich to perform any gate that is allowed by quantum physics. Then we need to make those gates robust to errors. This is where things get difficult.

Some gates are easy to protect against errors—they fall into a category called transversal gates. To understand these gates, consider two levels of description: the logical qubit (the error-protected unit of information) and the physical qubits (the hardware-level devices that, working together, encode and protect the logical qubit). To perform an error-protected one-qubit transversal gate, you perform the gate on all the physical qubits encoding the logical qubit. To operate an error-protected transversal gate between multiple logical qubits, you operate the gate between corresponding physical qubits in the logical qubits. You can think of the logical qubits as two blocks of physical qubits, called block A and block B. To implement a logical (that is, error-protected) transversal gate, you perform the gate between qubit 1 of block A and qubit 1 of block B, qubit 2 of block A and qubit 2 of block B, and so on for all qubits in the blocks. Because only corresponding qubits are interacting, transversal gates leave the number of errors per block unchanged and therefore under control.

If the entire universal set of quantum gates were transversal, life would be easy. But a fundamental theorem states that no quantum error correction code can perform universal computation using only transversal gates. We can't have everything in life—or in quantum error correction.

This tells us something important about quantum computers. If you hear anyone say that what is special about quantum computing is that you have superposition and entanglement, beware! Not all superposition and entangled states are special. Some are implemented by a group of transversal gates that we call the Clifford group. A classical computer can efficiently simulate quantum computations using only Clifford gates. What you need are non-Clifford gates, which tend to not be transversal and are difficult to simulate classically.

The best trick we have to implement non-Clifford gates that are protected from noise is called magic state distillation, developed by Kitaev and Bravyi. You can implement non-Clifford gates using only Clifford gates if you have access to a special resource called magic states. Those magic states, however, must be very pure—in other words, have very few errors. Kitaev and Bravyi realized that in some cases, you can start from a collection of noisy magic states and distill them to end up with fewer but purer magic states by using only perfect Clifford gates (here you assume that the Clifford gates are already error-corrected) and measurements to detect and correct errors. Repeating the distillation procedure many times gives you a pure magic state out of the many noisy ones.

Once you have the pure magic state, you can make it interact with the data qubit using a process called teleportation that transfers the data qubit's state into the new state that the non-Clifford gate would have produced. The magic state is consumed in the process.

Clever though this approach is, it is also extremely costly. For a standard surface code, magic-state distillation consumes 99 percent of the overall computation. Clearly, we need methods to improve or circumvent the need for magic-state distillation. Meanwhile, we can advance what we can do with noisy quantum computers using error mitigation. Instead of trying to design a quantum circuit to fix errors in computations in real-time (requiring extra qubits), error mitigation uses a classical computer to learn the contribution of noise from the outcome of noisy experiments and cancel it. You do not need additional qubits, but you pay the price in having to run more quantum circuits and introduce more classical processing.

For example, if you can characterize the noise in the quantum processor or learn it from a training set of noisy circuits that can be efficiently simulated in a classical computer, you can use that knowledge to approximate the output of the ideal quantum circuit. Think of that circuit as a sum of noisy circuits, each with a weight you calculate from the knowledge of noise. Or run the circuit multiple times, changing the value of the noise each time. You can then take the results, connect the dots, and extrapolate to the result you would expect if the system was error-free.

These techniques have limitations. They do not apply to all algorithms, and even when they apply, they get you only so far. But combining error mitigation with error correction produces a powerful union. Our theory team recently showed that this method could, by using error correction for Clifford gates and error mitigation for non-Clifford gates, allow us to simulate universal quantum circuits without needing magic state distillation. This outcome may also allow us to achieve an advantage over classical computers with smaller quantum computers. The team estimated that the particular combination of error mitigation and error correction lets you simulate circuits involving up to 40 times more non-Clifford gates than what a classical computer can handle.

If you hear anyone say that what is special about quantum computing is that you have superposition and entanglement, beware! Not all superposition and entangled states are special.

To move forward and design more efficient ways of dealing with errors, there must be a tight feedback loop between hardware and theory. Theorists need to adapt quantum circuits and error correction codes to the engineering constraints of the machines. Engineers should design systems around the demands of error correction codes. The success of quantum computers hinges on navigating these theory and engineering trade-offs.

I'm proud to have played a role in shaping quantum computing from a field of lab-based demonstrations of one- and two-qubit devices to a field where anyone can access quantum systems with dozens of qubits via the cloud. But we have much to do. Reaping the benefits of quantum computing will require hardware that operates below the error threshold, error correction codes that can fix the remaining mishaps with as few additional qubits and gates as possible, and better ways to combine error correction and mitigation. We must press on because we haven't finished writing the history of computation yet. SA

FROM OUR ARCHIVES

The Limits of Quantum Computers. Scott Aaronson; March 2008.

Quantum Connections. Christopher R. Monroe, Robert J. Schoelkopf and Mikhail D. Lukin; May 2016.

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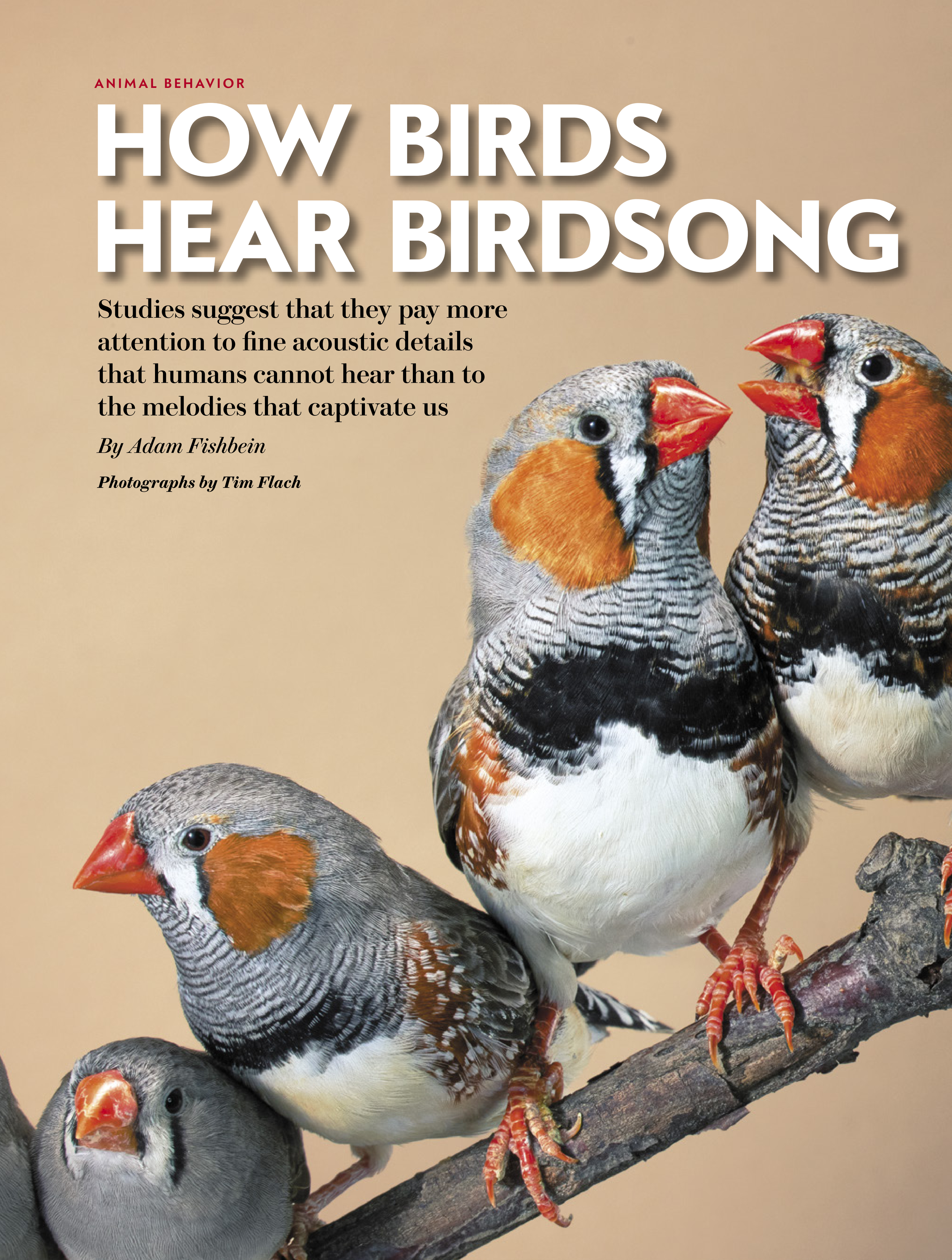
ANIMAL BEHAVIOR

HOW BIRDS HEAR BIRDSONG

Studies suggest that they pay more attention to fine acoustic details that humans cannot hear than to the melodies that captivate us

By Adam Fishbein

Photographs by Tim Flach



AUSTRALIAN ZEBRA FINCHES

Adam Fishbein is a postdoctoral researcher at the University of California, San Diego. He studies the cognitive and neural bases of animal social interactions.

WHEN WE HUMANS HEAR BIRDSONG, WHICH MANY HAVE APPRECIATED more than ever during the pandemic, we can't help but think about parallels to human music and language. We discern distinct melodies linking the clanks and buzzes of Song Sparrow songs, sentencelike structure in the Red-winged Blackbird's pronouncement of *conk-la-ree!* and a cheery whistle in the wide-open-beaked songs of the White-throated Sparrow.

Birdsong, which has intrigued scientists since Aristotle's time, is traditionally defined as the long, often complex learned vocalizations birds produce to attract mates and defend their territories. Modern researchers categorize it in contrast to bird calls, which are usually shorter, simpler, innately known and used for a more diverse set of functions, such as signaling about predators and food. These definitions are by no means clear-cut. For instance, some species have songs that are simpler than their calls. But when I refer to birdsong, I mean those longer, more complicated sounds as opposed to the short cheeps and peeps.

The very terminology researchers and laypeople alike use to talk about birdsong reflects the musical and languagelike way it strikes our ears. Getting deeper into the lingo for a moment, when researchers analyze birdsong, we usually break it down into smaller units, termed notes or syllables. We then group the syllables into sequences called phrases or motifs that have characteristic rhythms and tempos. In this way, we can measure potentially important aspects of song, such as the number of syllable types in a bird's repertoire or the patterns in which phrases are arranged. These descriptions also parallel the ways we mark the relations among words in human syntax or among notes in musical compositions.

But what do the birds think about all these features? How does birdsong sound to them? Recent research that my colleagues and I have conducted, along with work from a growing number of other scientists around the world, has revealed that birdsong sequences do not sound to birds like they do to us. Moreover, birds appear to listen most closely not to the melodies that catch our ears but rather to fine acoustic details in the chips and twangs of their songs that lie beyond the range of human perception.

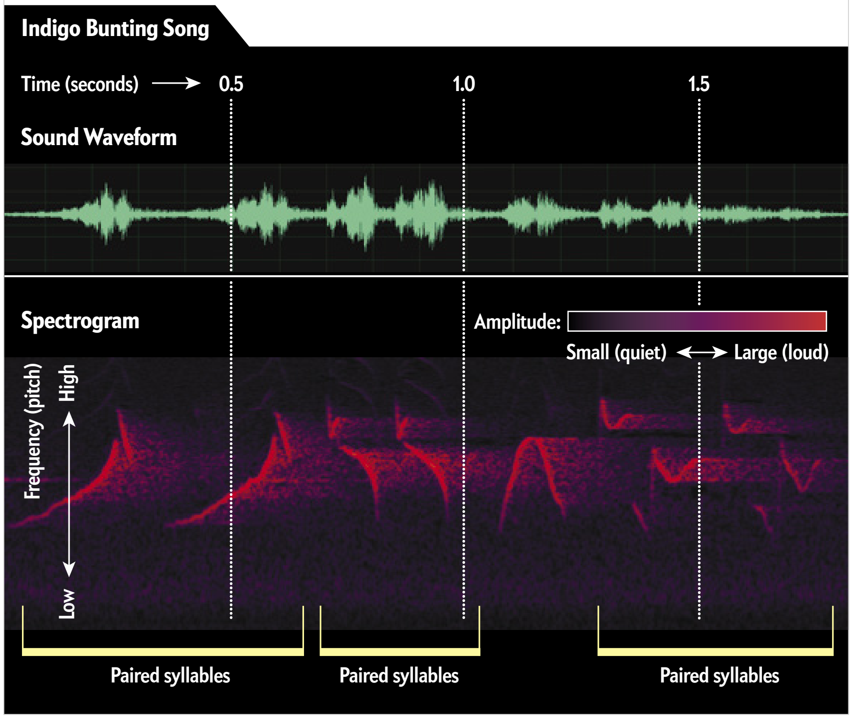
BEYOND MELODY

BIRDSONG RESEARCHERS have known since at least the 1960s that birds hear song differently than we might expect. One of the classic ways to test perception in birds in the wild is through so-called playback experiments, in which investigators play songs to birds and measure their behavioral response. Many birds respond to playback of a typical song of their species as if a territorial intrusion were occurring—they approach the speaker from which the song is playing, fly around the sound's source to look for the intruder, and emit their own threatening calls or songs. By comparing responses to natural and manipulated songs, researchers can learn which features are important in perception. In the predigital age, they would capture song on tape recorders and literally splice together the magnetic tape to create manipulated songs with, for example, rearranged syllables or shorter silent intervals between notes. Today digital recording equipment and sound-editing software make such manipulations much easier to create.

In one classic playback study in the 1970s, Stephen T. Emlen of Cornell University studied song perception in the Indigo Bunting. The vibrantly blue males of this species deliver songs consisting of syllables that they almost always utter two at a time. Ornithological field guides often call attention to this pattern of paired syllables when describing the song, and it is easily seen in a spectrogram, a visual depiction of song that shows the frequency and amplitude of its signal over time. (The perceptual equivalent of frequency is pitch, and that of amplitude is loudness.) Despite the prominence of the paired pattern to human ears and eyes, when Emlen played a modified song with unpaired syllables to the birds, they reacted with the same intensity of territorial response they exhibited when they heard the natural paired song. This result

Paired Syllables

A sound waveform (*top*) and a spectrogram (*below*) show the Indigo Bunting's song. The spectrogram depicts time on the *x*-axis, the frequency or "pitch" of the sound on the *y*-axis, and the amplitude or "loudness" of the signal in the redness of the lines (the redder they are, the greater the amplitude). The brackets mark paired syllables in the song. To human ears, the paired syllables are defining characteristics of the bunting's song. But the birds respond similarly to modified versions of their song in which the syllables are unpaired, which suggests that they are focusing on different features of the song than humans are.



means that, despite its salience to us, the pattern of paired notes is not significant for the birds in terms of recognizing fellow species members. If the Indigo Bunting were to write a field guide description of its own song, it would differ considerably from our assessment.

Testing how birds perceive song in the wild is important, but it has its limits. A bird could be out of earshot looking for food when you want to start your experiment, for instance. In the laboratory, researchers can test hearing in birds with more precision and control. When you go to the doctor's office and have your hearing checked, you are instructed to raise your hand or push a button to indicate that you've heard a sound. Researchers use a similar approach to probe auditory perception in birds. Because we can't explicitly ask the birds, "Did you hear that?," we train them to peck a button on the side of their cage if they detect a sound or if the sound they hear fits into a particular category or differs from another sound.

Lab studies have found many similarities in auditory sensitivities between songbirds and humans, including the thresholds for hearing differences in pitch or detecting gaps between sounds. But they have also revealed surprising differences between the abilities of birds and humans to hear sequences of sounds and acoustic details.

One pivotal finding from such work is that birds perform surprisingly poorly on recognizing a melody shifted up or down in pitch. This is something humans do naturally: we still recognize the tune of "Happy Birthday to You" if it is played in higher or lower registers on a piano. Classic lab experiments in the 1980s and 1990s by Stewart H. Hulse and his colleagues at Johns Hopkins University showed that for birds, when the pitch of a sequence changes, the tune sounds different, even though the underlying pattern remains the same. Thus, the melodies we hear when we listen to birdsong may be very different from the birds' perceptual experiences.

Subsequent studies have bolstered that hypothesis. In 2016 a team led by Micah Bregman, then at the University of California, San Diego, reported that European Starlings can recognize transposed sequences but only when all the fine details in the sounds are removed. That work highlights the importance of those fine details to birds when listening to song.

AN EAR FOR DETAIL

YOU CAN BREAK a sound waveform down into two levels of description: envelope and fine structure. The envelope is made up of slow fluctuations in the amplitude of the waveform, whereas the fine structure consists of the rapid fluctuations in frequency and amplitude within the waveform. In other words, a sound's fine structure is how it changes at the millisecond level. Historically, many birdsong researchers overlooked fine structure, in part because it is not readily visible in sonograms or spectrograms, which have been useful in helping people visualize song. But zooming in on the waveform of an individual song syllable can reveal these fine acoustic details.

Robert Dooling of the University of Maryland helped to pioneer the study of fine structure in birdsong. For decades he and his colleagues have been working to assess birds' ability to detect it. In a pivotal study published in 2002, they tested birds and humans on distinguishing sounds that differed only in fine structure. All the bird species they tested—Zebra Finches, Domestic Canaries and Budgerigars—performed much better than the humans did. The birds were able to hear differences in fine structure two to three times smaller than those the human subjects could detect. The

Adam Fishbein (*waveform and spectrogram*)

Illustration by Liz Wahid (Indigo Bunting) exact physiological mechanism underlying the birds' superhuman sensitivity remains unknown, but it may be related to features of their inner ears, which differ from our inner ears in having a relatively shorter cochlea that is slightly curved rather than coiled.

When I began studying how birdsong compares with human language in 2015, when I was in graduate school at the University of Maryland, I wasn't thinking much about fine structure. Instead I was looking to uncover languagelike grammatical abilities in birds. But as I dug deeper into this question and conducted many experiments with birds, I came to realize that the key to understanding what they are communicating in song may lie in these fine acoustic details rather than the sequences in which they occur.

The grand champion of the birds tested in Dooling's 2002 study was the Zebra Finch. This small, lively songbird native to Australia is the most popular species for lab-based modern birdsong research, largely because it both sings and breeds prolifically in captivity. Its song, produced only by males, is also relatively simple, consisting of a single motif of three to eight syllables repeated over and over again, usually in the same order. The simplicity of the song makes it more straightforward to study than others. Because the males learn both the syllables and the sequence in which they occur from a tutor, typically their father, one might think that both levels of the song are important in perception.

We tested that notion in a 2018 study that examined how well Zebra Finches hear the difference between natural song motifs and motifs where syllables are either temporally reversed or shuffled in sequence. We trained birds to report whether they could hear the difference between sounds. They listened to a repeated sound and then pushed a button to initiate a trial where the sound either changed or remained the same. If a bird pecked a certain button when the sound was different, it counted as a correct hit, and the bird got a food reward. If it pecked that button when the sound was the same, the lights in the chamber went off, and it counted as a guess. Using this method, we evaluated the birds' ability to discriminate between the repeating sound (the natural song motif) and novel sounds (motifs whose syllables we had temporally reversed or shuffled). From the birds' perspective, they were simply trying to earn tasty food.

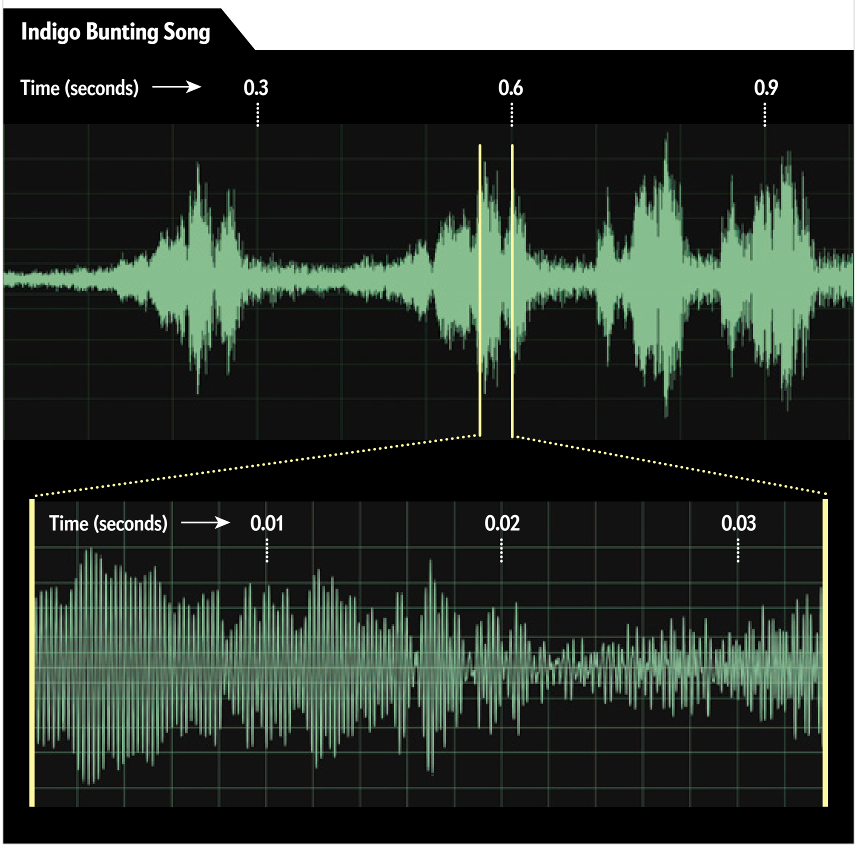
Interestingly, the Zebra Finches performed nearly perfectly at discriminating reversed syllables, which can be difficult for our human ears to detect, but they did poorly at discriminating shuffled syllables, which are more salient to us. When you reverse a syllable, one of the main things that changes is fine structure, so it is not surprising that the birds knocked it out of the park on that exercise. Yet their difficulty with sequence differences is unexpected, not only because those changes are easy for humans to hear but also because the males learn to produce song syllables in particular sequences. Their difficulty in perceiving shuffled syllables may mean that for these songbirds, sequence matters in the learning process but does not carry much information for communication.

Given the results of these experiments with artificially modified songs, my colleagues and I began to wonder how fine-structure perception is relevant for natural song communication. Hearing reversed syllables is impressive, but the birds never actually produce such sounds. So the next question we asked was how well birds hear subtle natural acoustic changes in song.

My colleagues had already shown in another 2018 paper that Zebra Finches can hear tiny differences in the fine structure of one another's calls, which can carry information about sex and individual identity. To examine their perception of fine structure in song, we took advantage of the fact that Zebra Finch song bouts consist of a single motif repeated over and over with the same syllables in the same order—or at

Fine Structure

A closer look at the Indigo Bunting's song reveals finer details that the bird may be listening to rather than the paired syllables. Here we see the sound waveform of the beginning of the song depicted in the first infographic (*top*). Zooming in on the highlighted portion of the second syllable reveals the rapid fluctuations in frequency and amplitude that occur at the millisecond time scale within a song syllable (*bottom*).

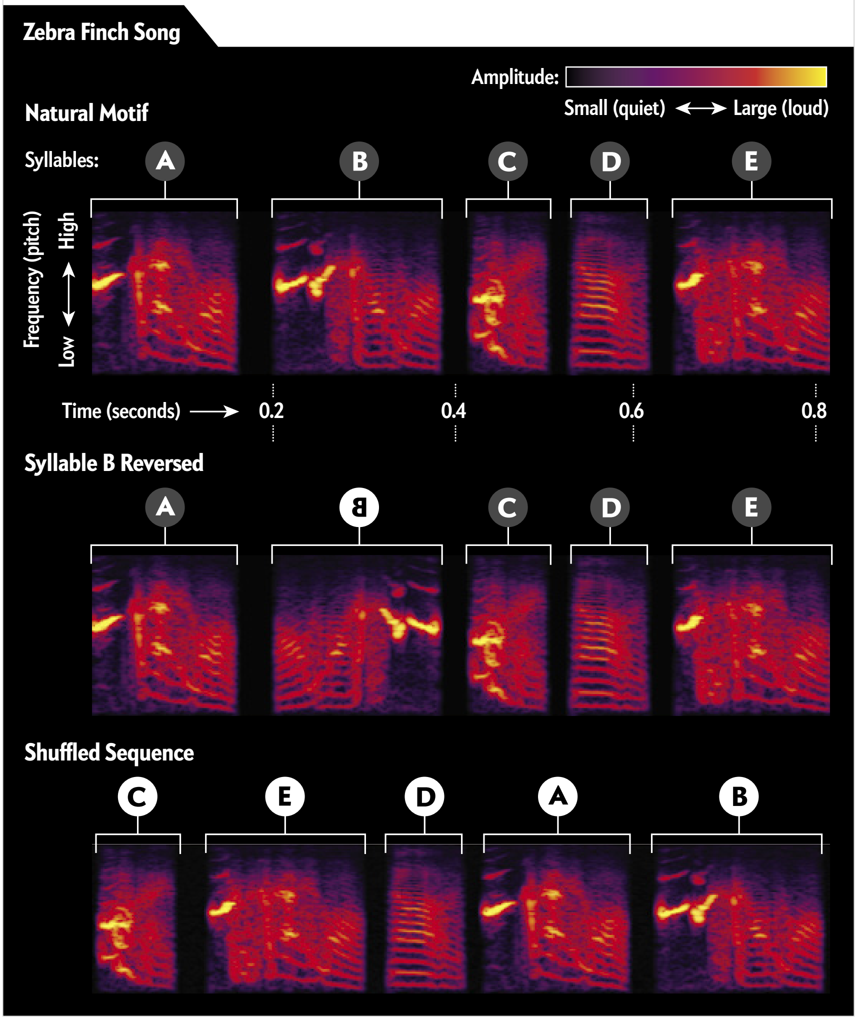


Adam Fishbein (*waveform and spectrogram*)

EUROPEAN
STARLING

Sound Discrimination

The Zebra Finch song consists of what sounds to humans like a string of identical motifs, each containing several distinct syllables. But the motifs actually differ considerably in their fine structure, and the birds can discriminate between different renditions of the same motif. In the spectrograms shown, the natural motif is repeated as the "background sound" (*top*). The same motif but with the second syllable reversed in structure was one of the "novel sounds" (*middle*) presented to the birds. The same motif but with the syllables shuffled around in order served as another novel sound. The white circles mark syllables that have either been reversed or shuffled.



least researchers think of them as the same. In truth, there are small differences in how a given syllable is uttered in each rendition of the motif. We tested the finches' ability to discriminate between different renditions of motif syllables and found that the birds can hear the differences easily.

This result means that although to us the Zebra Finch song sounds like the same motif on repeat, to the birds it does not. We suspect that instead they could be perceiving a rich trove of information about emotion, health, age, individual identity, and more in the fine structure of song beyond what our ears can detect. It is reasonable to expect that other birds with songs that sound repetitive to human ears share the Zebra Finch's powers of perception.

You might be wondering whether these small acoustic fluctuations in song are just accidental or random, like variations in the trajectory of a pitcher's curveball toward home plate. In fact, the key to fine structure may be the avian voice box. Humans produce the sounds that we shape into speech with our mouths and tongues using a single source at the top of our neck, the organ known as the larynx. Birds, in contrast, produce sound using a unique two-branched structure that sits atop the lungs called the syrinx. It carries two sources of sound, one from each branch, that can be controlled independently. On top of that, muscles in the songbird syrinx contract faster than any other vertebrate muscle, enabling millisecond-level temporal control. Thus, the birds aren't producing fine acoustic variation by a slip of the beak—they can control it in addition to perceiving it.

DANCE OF THE SYRINX

TOGETHER THESE STUDIES show that birds listen to song differently than we have traditionally imagined. Melodies and sentence structure are essential to us when we listen to music and speech. We can't help but project them onto birdsong when we hear it. But differences in sequence don't seem to matter much to birds. Some species have difficulty hearing even simple changes. For humans, when these kinds of manipulations occur in speech or music, they totally disrupt the message or melody. But birds seem to be listening most closely to the acoustic details of individual song elements, independent of the sequence in which they occur. And they hear details beyond what our ears can discern.

In thinking about how birdsong sounds to the birds, a better analogy than human language or music might be dance. When we learn a dance routine, getting the sequence right is necessary for getting the moves right—like when I learned to follow a Lindy Circle with a Charleston in my swing dance class. Screwing up a transition can cause the structure of an individual move to fall apart. But someone watching a dance does not extract much

Adam Fishbein (*waveform and spectrogram*)

Illustration by Liz Wahid (Zebra Finch)

information from the order of the moves. Instead the audience is focused on the acrobatics, rhythm and variety of the movements rather than the sequences in which they occur. It may be the same for birdsong. From the perspective of the bird producing the song, getting the sequence right can be essential for getting the "moves" right. But for the bird listening, what is most important may be the individual moves themselves.

This is not to say there aren't certain significant parallels between birdsong and human speech or music. The ability to take heard sounds and reproduce them as humans do in speech and birds do in song, a feat termed vocal learning, is actually quite rare in the animal kingdom. Our closest living relatives, chimpanzees, do not appear to be vocal learners, nor do any other primates. Even those mammals that do show some vocal-learning ability—bats, whales, elephants, seals and sea lions—do not achieve the same level of vocal mimicry as humans and some birds (songbirds, parrots and hummingbirds, to be specific; other groups, including pigeons, chickens and owls, are not vocal learners). Even more amazingly, researchers such as Erich Jarvis of the Rockefeller University have shown that similar neural pathways and molecular mechanisms control vocal learning and production in songbirds and humans, a product of convergent evolution. In this way, we can learn a lot about human vocal communication from studying birds. But the songs they produce do not appear to be the music or language to their ears that we might imagine.

We still have a lot to learn about how birds perceive birdsong. Several studies have shown evidence that bird calls convey specific information about things in their environment such as food or predators, but we do not yet know whether anything similarly meaningful exists in birdsong, perhaps carried in the fine structure. Neither do we know how birds perceive the fine structure of song in natural environments, where sound can bounce off trees and buildings and has to compete with a cacophony of environmental noise.

Additionally, recent work has shown that, contrary to traditional views of birdsong as a strictly male behavior, female birds commonly sing, too. This discovery raises the question of whether male and female birds may listen to song differently. Moreover, in many tropical species, male and female partners sing highly intertwined duets that can even sound to human ears like a single continuous song. How do birds manage to listen for their turn to sing while making sure to produce the correct notes?

The next time you hear a birdsong, try thinking of it less like a catchy melody or a simple sentence and more like a fast-moving, precisely coordinated dance of the syrinx—one that's potentially as rich in emotion and meaning as human language or music but expressed in a different way. SA

FROM OUR ARCHIVES

Birds Can Tell Us a Lot about Human Language. Adam Fishbein; ScientificAmerican.com, February 2, 2018.

The Quantum Nature of Bird Migration. Peter J. Hore and Henrik Mouritsen; April 2022.

scientificamerican.com/magazine/sa

ECOLOGY

BOLD EXPERIMENTS IN FISH FARMING

In coastal Maine, scientists and seafood workers are cleaning up aquaculture's dirty reputation and trying to save a threatened economy—but not without controversy

By Ellen Ruppel Shell

Photographs by Peter Essick

Ellen Ruppel Shell wrote about Alzheimer's disease and air pollution in our May 2020 issue. She is author of four books, including *Cheap: The High Cost of Discount Culture* (2009) and *The Job: Work and Its Future in a Time of Radical Change* (2018). She is currently working on *Slippery Beast,* a book about the eels of Maine.

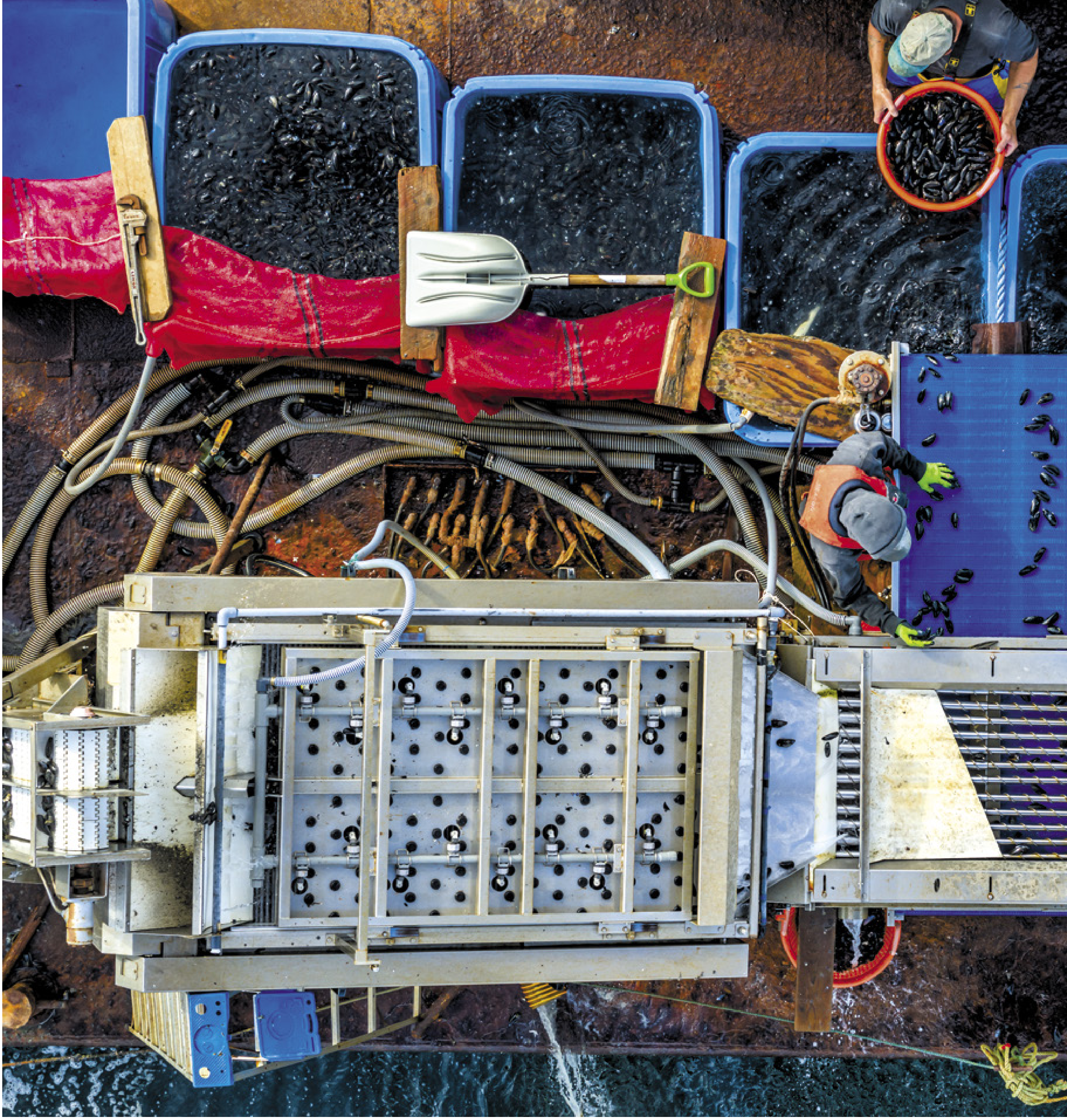
CARTER NEWELL OWNS AND OPERATES ONE OF THE MOST PRODUCTIVE mussel farms in the state of Maine. One frigid spring morning I joined him and his two-person crew on a short boat ride to the barge he calls *Mumbles,* a 60-by-24-foot vessel anchored that day in a quiet cove in the brackish Damariscotta River. Named for the Welsh seaside town where Newell once did research, *Mumbles* was tethered to a steel-framed raft hung with hundreds of 45-foot ropes, each thick with thousands of mussels in various stages of development.

I shivered in the piercing wind as a crew member stepped from *Mumbles* onto the shifting raft to identify mussel ropes ready for harvest. Newell remained on the barge to helm a 16-foot crane that hauled up the designated ropes, each heavy with a Christmas tree–shaped aggregation of roughly 3,000 mussels. An outsized brush then swept the bivalves off the ropes and into an enormous stainless steel bucket. Another machine funneled them into a heavy polyethylene bag the size of a baby elephant, from which they were poured onto a conveyor-belt apparatus to be scrubbed, sorted and bagged. Newell designed this ungainly Willy Wonka–esque apparatus over decades in a costly process of trial and error that faced—and ultimately overcame—several challenges, including protecting the mussels from turbulent seas and voracious eider ducks.

As he oversaw the morning harvest, Newell, who has a Ph.D. in marine biology, talked some science—the dynamics of phytoplankton, why nitrate chemical concentrations increase in the winter, how chlorophyll levels for the entire coast of Maine can be mapped with just three satellite images. Mostly, though, he talked about mussels: their life cycle, their geographic distribution, how to prepare them (don't spare the garlic) and—critically—how best to farm them without going broke. "Fish farming is no way to make a quick buck," he told me.

The truth is that soon fish farming may be the only way for Maine's struggling seafood workers to make any bucks at all. Thanks to overfishing, parasites and rising

MUSSEL HARVESTING at Pemaquid Mussel Farms in Bar Harbor, Maine, is overseen by farm owner and marine biologist Carter Newell (*pages 32 and 33*). The shellfish are grown on long ropes dangling into the water from a raft (*top*). The ropes are hoisted onboard (*left*), and Newell cuts a mussel open to check for health (*far left*).



ocean temperatures, among other threats, nearly all of Maine's commercial fisheries are in free fall. Maine cod is crashing, as are local shrimp. The wild mussel catch declined from 25 million pounds to a mere nine million over the past two decades. And lobsters, by far the state's most profitable catch, are scuttling north to cooler Canadian waters. None of this bodes well for the state's once robust seafaring economy: the average age of a Maine commercial fisher hovers above 50, suggesting that many young people have lost faith in the work.

AFTER THE MUSSEL ROPES are raised by Pemaquid operators, a machine scrapes off the shellfish, and they are sorted into bins.

As one wild fishery after another falters, the future of Maine—and, some say, the future of seafood—may lie in aquaculture, the cultivation of aquatic plants and animals. Historically, intensive fish farms have been linked to a lot of bad things: declines in biodiversity, habitat loss, the overuse of antibiotics, and animal welfare abuses, especially in Asia and Latin America. And in recent years fish die-offs and other problems have plagued North American sites. But Newell represents a new breed of scientist with innovative approaches to growing fish that are both economically and environmentally sustainable. His kludgy mussel-growing apparatus generates three times as much seafood as traditional mussel farms. And because free-floating mussel larvae seed the ropes naturally and eat whatever phytoplankton drifts their way, Newell's farms require no

human-generated feed or energy, a boon for the environment as well as for his bottom line.

A far more controversial experiment in Maine involves cultivating finfish such as salmon and yellowtail either in immense net pens in the ocean or, more recently, in land-based operations where thousands of metric tons of fish circle gigantic tanks like felons pacing around a prison yard. Fish in these recirculating aquaculture systems (RAS) consume a steady diet of scientifically designed feed and, if need be, infection-fighting drugs. The current they swim against is artificially generated, as is the LED light that bathes them up to 24 hours a day to hasten their growth. It is a surreal scenario, but proponents claim RAS are well positioned to bolster Maine's economy while serving the nation's growing demand. "The U.S. runs an enormous seafood deficit," says microbiologist Deborah Bouchard, director of Maine's Aquaculture Research Network, noting the country relies heavily on fish imported from other nations. "Maine is building on the opportunity to fill the gap."

Oceanographer David Townsend, director of the School of Marine Sciences at the University of Maine, says the state has two important attributes for fish cultivation: cold, nutrient-rich water and extremely vigorous tides that distribute those nutrients throughout the water column. "Our coastal waters are very productive," he says.

But the farming of large, carnivorous fish makes some scientists uneasy. Recirculating tanks require huge amounts of energy to move and filter millions of gallons of water daily, and that water still holds waste that can pollute nearby rivers and estuaries. Also, there's a matter of the fish and their welfare. "Farming finfish on an industrial scale is like farming livestock on land on an industrial scale," says economist Rosamond L. Naylor, who directs the Center on Food Security and the Environment at Stanford University. "There are ways to minimize risks, but they are costly, and not everyone is taking the steps they should be taking."

The question of whether industrial aquaculture will enrich Maine's economy without damaging its fragile ecosystems haunts scientists, politicians and residents. The Gulf of Maine is the least alkaline body of water on the Atlantic coast between Mexico and Canada, and its delicate chemistry is particularly vulnerable to disruptions both natural and human caused. Whatever their outcomes, Maine's experiments will set an important precedent for seafood production around the globe.

SCIENTISTS AGREE THAT THE FOOD SUPPLY must increase substantially to feed the world's growing population and that cultivated fish, shellfish and algae will play a major role in that expansion. Aquaculture is already the world's fastest-growing sector of food production, churning out more than half of all fisheries products, and seafood is the most traded commodity on the planet. But although Americans eat a lot of seafood, relatively little is homegrown: an estimated 65 to 85 percent of fish bought for consumption in the U.S. is imported, most of it from China. The U.S. does not export much farmed fish, either, because it grows so little of it. According to the most recent data, from 2019, the U.S. produced 490,000 tons of farmed fish, barely a rounding error compared with the roughly 49 million tons produced by China.

Maine's Atlantic salmon could help the U.S. compete. Often called the "king of fish," salmon are sleek, shiny and beautiful. They are also an extremely popular menu item, ranking second only to shrimp as America's favorite seafood. The cold-water fish were once plentiful in Maine, but dams, overfishing, parasites and pollution all led to the closing of the state's wild Atlantic salmon fishery in 1948, and today it is illegal to catch or sell

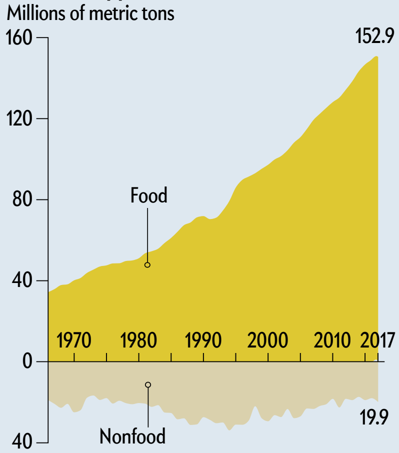
A World of Seafood

Fish, shellfish and crustaceans have become a gigantic global harvest. More than 177 million metric tons of seafood (excluding plants) came from oceans and fresh water in 2019, the latest year for which data are available. These charts show the regions and countries that produce and use the most. The charts also show how much comes from fish farming—or aquaculture—and from wild-catch fisheries, as well as trends in consumption over time.

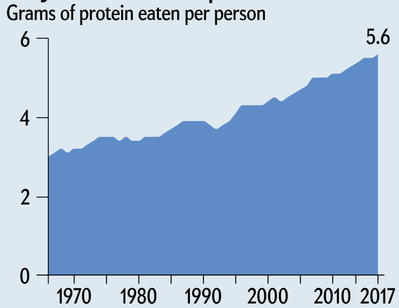
DEMAND ON THE RISE

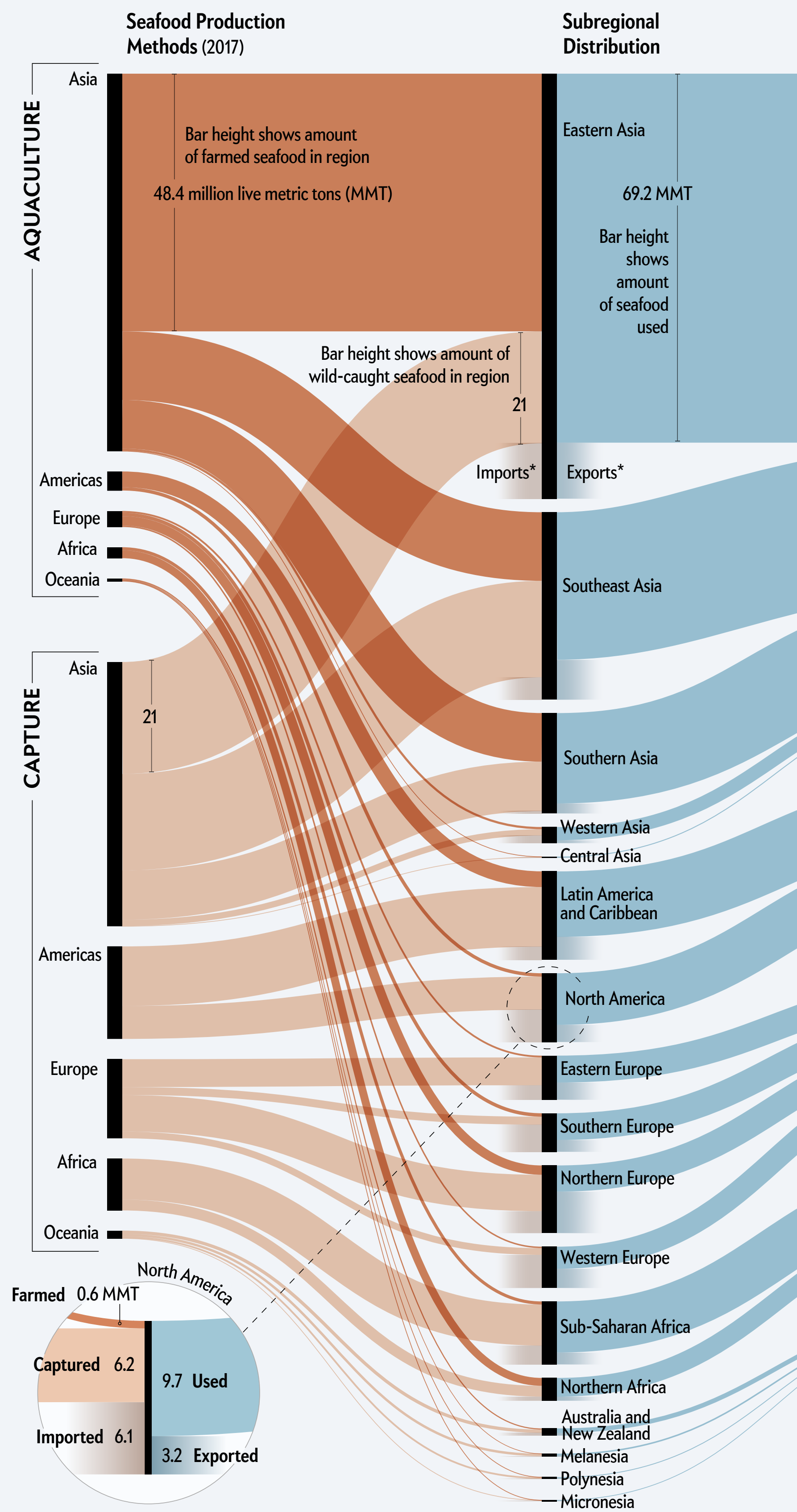
The amount of seafood that people use has been climbing since the 1970s. Most of the growth is in food products, whereas nonhuman food uses (animal feed, for instance, or bait to catch other fish) have fluctuated. On average, our daily diet of seafood protein has also increased.

Seafood Supply
Millions of metric tons



Daily Seafood Consumption
Grams of protein eaten per person



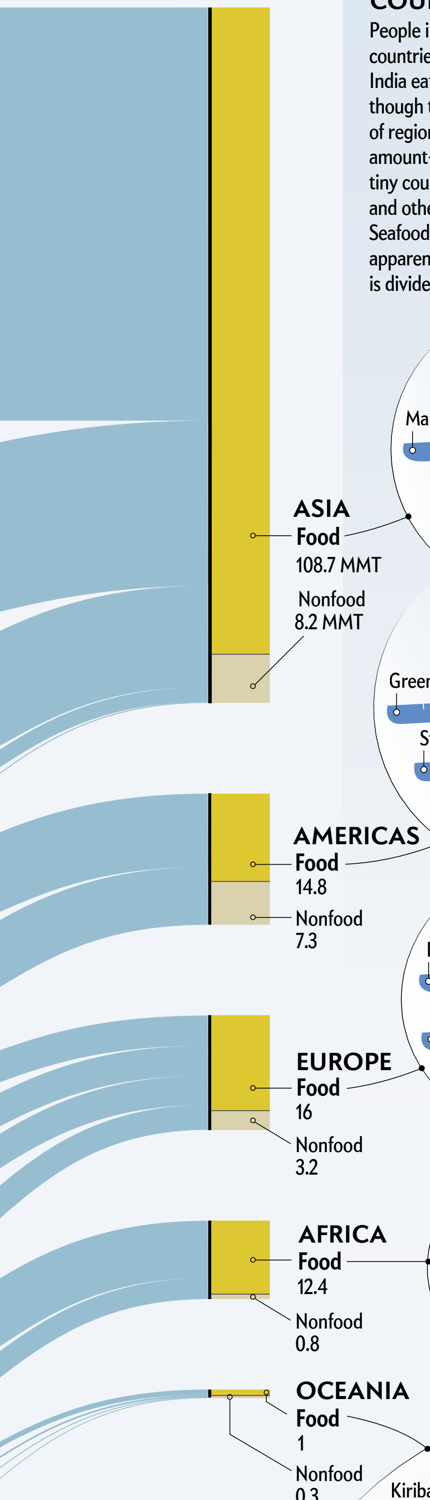


Sources: FishStatJ, Food and Agriculture Organization of the United Nations (https://www.fao.org/fishery/en/statistics/software/fishstatj), accessed March 2022; FishStatJ, Food Balance Sheets of Fish and Fishery Products (*2017 import, export, food and nonfood country-level data*); FishStatJ, FAO Fisheries and Aquaculture Production Statistics (*aquaculture, capture and species data*); FAO Yearbook of Fishery and Aquaculture Statistics 2019. FAO, 2021, accessed March 2022 (*1966–2017 data; 2017 country-level fish protein data*)

These charts do not include data for marine mammals, crocodiles, corals, pearls, mother-of-pearl, sponges and aquatic plants.

Graphic by Accurat (Alessandro Zotta and Alessandra Facchin)

Total Supply per Region



HOW MUCH A COUNTRY EATS

People in highly populous countries such as the U.S. and India eat relatively little seafood—though these nations are part of regions that produce a fair amount—when compared with tiny countries such as Kiribati and other nations in Oceania. Seafood reliance becomes apparent when production is divided by population size.

Daily Consumption of Seafood Protein

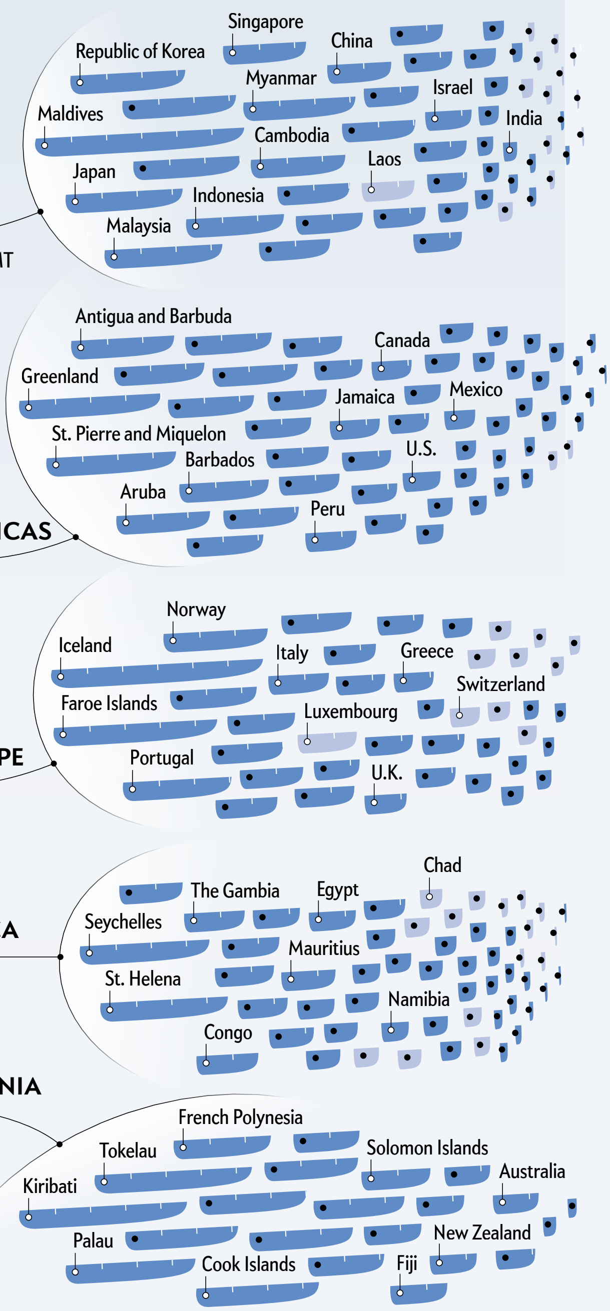
Grams per person (2017)

0 5 15 30 g

Country Name

Country has coastlines

Country is landlocked



*Production methods—and cross-region connection details—are not available for imports and exports.

WHAT WE EAT AND USE

Seafood species differ in popularity, depending on whether they are farmed or wild-caught.

Top Three Species, by Group (2017)

Group	Species	MMT
AQUACULTURE		
Freshwater fish	Grass carp	5.7
	Silver carp	4.8
	Nile tilapia	4.6
Mollusks	Cupped oysters	5.3
	Japanese carpet shell	4.0
	Constricted tagelus	0.9
Crustaceans	Whiteleg shrimp	5.4
	Red swamp crawfish	2.2
	Chinese mitten crab	0.8
Saltwater/freshwater fish	Atlantic salmon	2.6
	Milkfish	1.5
	Rainbow trout	0.9
Saltwater fish	European seabass	0.3
	Gilthead seabream	0.3
	Large yellow croaker	0.2
CAPTURE		
Saltwater fish	Anchoveta	4.3
	Alaska pollock	3.5
	Skipjack tuna	3.4
Freshwater fish	Silver cyprinid	0.3
	Nile tilapia	0.3
	Nile perch	0.3
Mollusks	Jumbo flying squid	0.9
	Yesso scallop	0.4
	American sea scallop	0.3
Crustaceans	Gazami crab	0.5
	Akiami paste shrimp	0.4
	Antarctic krill	0.4
Saltwater/freshwater fish	Hilsa shad	0.6
	Pink salmon	0.5
	Chum salmon	0.3

SALMON NET PENS off Black Island, Maine, run by Cooke Aquaculture, were the scene of a massive salmon die-off in 2021. More than 100,000 fish perished. The company placed the blame on unusually low oxygen levels in the pens.

them. Today more than 95 percent of Atlantic salmon sold in the U.S. is foreign-grown, most in net pens anchored just below the surface in coastal waters.

Open fish pens have been used in Norway since the 1960s and are still in use in Canada and Chile, but environmental concerns have led to bans in most U.S. coastal states. A ban in Washington, which goes into effect in 2025, will leave Maine as the only state that still sanctions their use. Despite rigorous regulations, every year net-pen operations are cited for environmental and labor-related malfeasance, infestation by sea lice and other parasites, and infectious disease. Scientists say an equally vexing challenge is posed by renegade fish that escape the pens and mate with wild salmon to produce offspring that are genetically ill-equipped to survive. This last threat is especially concerning in Maine, home of the nation's last remaining wild Atlantic salmon population.

Feed is another major problem. Salmon farmers sometimes inadvertently overfeed their stock, and the uneaten feed promotes the growth of algal blooms that deoxygenate the water as they decompose. This can lead to "dead zones," wide swaths of ocean that can no longer sustain life. Another often cited concern is that until quite recently, a high proportion of fish feed consisted of small wild-caught "forage fish" such as anchovies, herring and sardines, all rich in the long-chain omega-3 fatty acids necessary for the growth of larger fish. From 1950 to 2010 roughly 27 percent of all wild-caught fish was used in fish meal. Many observers saw this as a terrible waste: they argued that feeding edible fish to edible fish is unsustainable and ultimately makes little economic or ecological sense.

Food scientists have sought alternatives, but it has not been easy. Carnivorous fish have difficulty digesting carbohydrates, so researchers tried various combinations of plant fats and proteins, including those found in soybeans. "It's like Impossible Burger for fish," Townsend says. Unfortunately, like humans, not all

salmon can tolerate soy, which in large quantities can damage their gut and immune system.

Experimental fish feeds aim to solve this problem and address yet another concern: that waste from fish pens will pollute natural waterways. New "low-polluting" feeds contain far less nitrogen and phosphorus and provide nutrients in a form that is easily digested and absorbed to minimize the amount of these elements excreted by fish. Emerging feeds include algae oil, yeast protein and black soldier fly larvae, commonly known as maggots. Scientists are also designing proteins with amino acid compositions similar to those in feed made of fish but created from sawdust and other forest residue plentiful in the sylvan state of Maine. Whether algae, maggots or reconstituted sawdust will ultimately replace fish in the aquaculture food chain is unclear, but scientists agree that these experimental feeds show substantial promise. Still, growing fish in pens in the open sea poses risks that some believe outweigh the benefit.

Giant RAS tanks are meant to minimize several of the environmental threats posed by net pens. The approach dates back to the 1950s, but recently scientists and engineers have supercharged the technology into a mind-bogglingly efficient protein-generation machine capable of growing more fish in less time and space than is possible in nature. In contrast to offshore net pens, land-based RAS are designed to maintain tight control over water quality, temperature, circulation and other environmental variables. Bacteria convert ammonia excreted by the fish into typically harmless nitrate; gas-exchange systems add oxygen and remove dissolved carbon dioxide; and wastewater is microfiltered and zapped with ultraviolet light to remove phosphorus, lingering bacteria and viruses. Some of the newest systems feature machine-vision sensors and artificial intelligence to optimize feeding by monitoring fish biomass and behavior in real time.

Several multinational RAS companies are currently vying for a stake in Maine. Notable among these is Nordic Aquafarms, a Norwegian firm that has proposed a major tank facility in the small coastal city of Belfast. Nordic's $500-million plan to generate nearly 73 million pounds a year of Atlantic salmon would make it the second-largest RAS salmon farm in the world. The largest is an operation run by Atlantic Sapphire, another Norwegian-owned firm based in the unlikely location of Homestead, Fla. That facility has suffered a series of crises, including a massive "mortality event"—elevated gas levels that wiped out 500 tons of salmon. In the first half of 2021, the company reported losses of more than $50 million and faced accusations of criminal animal cruelty.

Nordic Aquafarms founder and president Erik Heim insists that his company will avoid these problems, but researchers are cautious. Jon Lewis worked for 23 years as a scientist and diver, and he recently retired as director of the Division of Aquaculture in Maine's Department of Marine Resources. "Land-based systems have real advantages in that they don't rely on Mother Nature for water treatment," he says. But even if the filtration systems remove most of the discharged waste, he adds, some still flows to the bay. "Given the scale of these systems, that's significant."

At the Belfast facility, salmon eggs will be incubated in specially designed hatching cabinets, and the emerging baby fish, known as fry, will spend the first few weeks of their lives eating their yolk sacs before entering a quarantine tank. The young fish will then move to a series of tanks that simulate the natural life cycle of salmon—swimming from fresh water to increasingly salty water over a period of 18 to 20 months, when they reach market size. The system circulates 5,200 gallons of water a minute: 4,700 gallons of salt water sucked from the Gulf of Maine and 800 gallons of fresh water pumped from groundwater wells and aquifers. Filtered waste will be converted into animal feed or fertilizer—in theory enough to fertilize about seven and a half pounds of vegetables per pound of fish produced.

Unfortunately, pumping and filtering all that water requires a lot of power, as does heating the water in winter and cooling it in summer—all of which can contribute to the climate crisis. "We really don't have data on the energy use in these systems compared to other approaches, but it's clearly very high," Lewis says. A review sponsored by Maine's Department of Environmental Protection concluded that the plant will release as much as 759,000 metric tons of carbon dioxide equivalents into the atmosphere every year, roughly equal to the annual CO_2 contributions of 47,000 Americans.

There are also fundamental objections to raising free-ranging creatures such as salmon in crowded captivity. The animals we lump together and call "fish" represent a staggeringly diverse array of species, some of which have incredibly complex social structures and navigation abilities, says Becca Franks of New York University, a psychologist who researches animal behavior and welfare. Atlantic salmon are a case in point: they migrate 2,000 nautical miles to and from their spawning grounds guided only by Earth's magnetic fields and an acute sense of smell. "Farming salmon is the moral equivalent to farming hawks," Franks says. "We need to think about the stress and suffering of these animals … about how they live their natural lives."

NOT ALL SEA ANIMALS ARE THE AQUATIC equivalent of a hawk, however, and some take well to domestication. Sandra Shumway, a marine scientist at the University of Connecticut, is an internationally recognized expert on the cultivation of sea life. "I do think it's very important that we grow more micronutrients and protein for human consumption," she says. "But let's think about bivalves."

Bivalves require little space, and some—such as mussels and oysters—barely demonstrate an inclination to move. "They're more like potatoes or avocados than salmon," Franks says. Even better, unlike potatoes and avocados, bivalves can be grown without human-supplied fertilizer, water or food. Farmed oysters typically start as larvae, which quickly mature into tiny "seed" oysters that attach to a hard surface such as shell or limestone and are then transferred into estuarine bodies of brackish water to feed on whatever nutrients naturally float their way. These "filter feeders" siphon water through their gills to extract phytoplankton, of which Maine harbors at least 300 species. Waterways inhabited by bivalves are often so clear that sunlight penetrates far below the surface, further promoting the growth of phytoplankton. Some scientists and farmers are hoping to build on this "virtuous cycle" by deliberately planting kelp and other seaweed in close proximity to bivalves. Under this arrangement, the animal waste would provide nutrients for the plants, and the plants would remove CO_2 and generate oxygen for the animals.

Maine's coastline, crenellated with deep estuaries and bays fed by rivers mixing with cold ocean water that pumps nutrients up from below, may seem like a bivalve paradise. But frigid water is a double-edged sword. Oceans store up to 30 percent of the world's output of

CO_2, and cold water, in which the gas is most soluble, absorbs far more than its share, making it more acidic. The rising acidity of Maine's rivers and estuaries threatens to erode the shells of soft-bodied invertebrates such as bivalves left to their own devices.

Bill Mook has had painful experience with this problem. Founding owner of Mook Sea Farm and Hatchery on Maine's Damariscotta River, one of the two largest oyster producers in the state, he grows both mature and seed oysters. A few years ago he noticed that his oyster larvae were not developing normally, a problem he traced to increased acidity of the river water flowing through his hatchery. The water also softened the shells of mature oysters, especially during hard rains, when the river ran highest. Mook found a way to buffer seawater to protect the oysters growing in the indoor hatchery, a remarkable innovation that—though highly labor-intensive—may well catch on with other Maine bivalve farmers if acid levels continue to rise.

Housed in a pair of Quonset huts, Mook's oyster-growing facility looks more like a laboratory than a farm. In the spring of 2021 Meredith White, director of

research and development at the company, ushered me into the hatchery, a moist, cavernous space that reeked of the sea. White first met Mook while she was a research scientist at Bigelow Laboratory for Ocean Sciences in East Boothbay, Maine, and her knowledge of bivalves is exhaustive. Mook's oysters, she says, are bred for certain traits—size, shape, disease resistance—in shellfish labs in Virginia and New Jersey and shipped to Mook's as brood stock. "Some are male, some are female, but you can't tell which without opening them, and that would kill them," she says.

Workers need to wait for the oysters to declare their own sex: both females and males clap their shells before a spawning session, during which females release a cloud of as many as 20 million eggs and males emit a stream of sperm. Technicians carefully combine the eggs and sperm in small white bowls to begin a process of in vitro fertilization. The resulting embryos are transferred to tanks holding 3,000 to 6,000 liters of water, which is gradually warmed to optimize growth. "We check them under a microscope every day," White says. "We can see the cells divide, and in 24 hours, they have a shell."

In about two weeks the oysters form a pigmented eyespot (interestingly, mature oysters have eyes all over their bodies), a sign that they are approaching the pediveliger stage, when they will sprout the bivalve equivalent of a foot. White pulled out trays of ground oyster shell on which tiny oysters "set" this foot, glomming on to the hard surface with a kind of natural glue, much as they would in the wild. "We sell 140 million seed oysters a year," she says. Those oysters, sold to oyster farmers around the state, will eventually grow into mature oysters that go for about $15 a dozen in local markets or $25 a dozen at restaurants.

In Maine the oyster-growing season lasts only five months, from April to October. But Mook's success derives in part from his ability to extend this period by growing them indoors in the colder months, beginning in January. Like cats and dogs and chickens, indoor oysters need to be fed. Mook has developed proprietary growth and processing techniques for algae, and the details are a company secret. He notes the minute organisms are heterotrophic, meaning they can extract energy from sugar, and they do not require light, which helps

BILL MOOK, founder of Mook Sea Farm in Walpole, Maine (*above*), grows algae in special tanks as oyster food. The small-scale operation is housed in two huts (*bottom left*), and oysters are sometimes moved to land (*top left*) from a nearby river so they can be protected from the water's rising acid levels.

to reduce his electricity costs. This money-saving innovation was a game changer.

"Bill's system is ingenious and entirely scalable," Lewis says. It is the first time food has been created specifically for bivalves with this technology, he says, and "it could revolutionize the industry." It also demands a very exacting manufacturing process. "We feed the algae glucose and grow it in a clean room under negative pressure to avoid contamination," Mook tells me as I watched a technician scrub and suit up like a surgeon in paper cap and booties before entering the pristine space. "We harvest the cells every seven days, spin them down in a special centrifuge to preserve their structure, squeeze out the water and freeze the paste in one-kilogram blocks." Mook opened a freezer and pulled out a Ziploc plastic bag of icy green slime. "It took us 10 years to develop this," he said, then hustled us off to the "growing room" filled with lab beakers, each containing a different variety of algae in shades of green, yellow and orange.

OYSTERS from Mook Sea Farm grow in bags, reinforced by cages, that are submerged in the Damariscotta River.

Mook says oysters are more finicky than mussels, another creature he has tinkered with. "Growing oysters versus mussels is like growing orchids versus tulips," he tells me. "Mussels bring less money per pound, but once you've got the infrastructure in place, they are a lot cheaper to grow because, unlike oysters, the seed is wild and free." Townsend agrees. "Mussels grow at very high density, they contain a lot of protein, and they are a good source of omega-3 fatty acids and other nutrients," he says. "If we could get the whole world to eat more mussels, we'd be in much better shape."

Newell has spent decades trying to make that dream a reality. Decades ago, when he got his start, mussel

rafts were not a thing in Maine. Rather farmed mussels were grown on a single long line threaded through buoys bobbing on the surface of open water. In many places, this method is cheap, efficient and effective. But not in Maine. The state is swimming with sea ducks, including six-pound eiders that eat their weight in mussels every day. The duck problem foiled Maine's would-be mussel farmers for decades, until Newell and a handful of other enthusiasts learned about a Spanish method of dropping lines into the sea from an anchored raft, which they figured could be duck-proofed with nets. They built 35 rafts and anchored them in various waterways throughout the state. And "we installed nets around the raft—60 feet deep," Newell says.

That solved the duck problem, but they soon faced another. The rafts were built for calmer waters, but on Maine's stormy coast, winds raging at 60 or 70 knots dislodged mussels and destroyed the rafts.

With the help of government grants, Newell designed and patented a submersible raft that minimized perturbations when lowered 10 to 12 feet under the waves, even in gale winds. The raft tethered to the barge at Newell's Pemaquid Mussel Farms is one of these remarkable contraptions, and it makes growing mussels in Maine far more viable. Using rafts that floated at the surface, Newell says, he harvested about 150 pounds of mussels per rope each season. "With submersibles, it's consistently 300 to 400 pounds. That's about 100,000 pounds of mussels a year on every raft." It's also a far more profitable proposition that makes growing mussels an attractive option for former fishers.

NAYLOR, THE STANFORD ECONOMIST, THINKS these shellfish could play an important role in a healthy diet. "Bivalves are an incredibly rich source of protein," she says, adding that we do not need a huge amount of it on our plates; Americans tend to overconsume protein and underconsume vital micronutrients. Bivalves contain significant quantities of micronutrients, including minerals such as zinc, iron and magnesium, in addition to omega-3 fatty acids. Fast-food eateries have yet to add mussels to their menus, but perhaps they should: a four-ounce serving contains nearly as much protein as a McDonald's Quarter Pounder, with more iron and far fewer calories and saturated fat, and at a lower cost. And although the thought of mussels as fast food might sound a bit far-fetched, given the popularity of these bivalves in France, Belgium, Turkey, Thailand, China and other nations, is it not possible that they would take off in the U.S., much as sushi did in the 1960s?

For decades the U.S. fishing industry has struggled to harvest enough wild fish to meet the growing demand—we want cheap fish, and we want it now. The shocking decline of Maine's commercial wild fisheries shows that this approach no longer serves us. Farmed finfish is generally cheaper than wild, and many restaurateurs consider farmed bivalves tastier than a lot of wild varieties. Farmed versions of all fish are generally more widely available, regardless of the season.

It is too soon to say whether aquaculture can bolster Maine's fragile seafaring sector or contribute significantly to its economy without disrupting the state's iconic shoreline; large finfish facilities, such as RAS, create additional concerns about energy use and animal well-being. But to many scientists, economists and policy makers, one thing is becoming clear: farming fish sustainably in concert with other animals and plants will likely be the best approach to feeding the world's population in the years and decades ahead. SA

FROM OUR ARCHIVES

The Blue Food Revolution. Sarah Simpson; February 2011.

scientificamerican.com/magazine/sa

Megan Scudellari is a Boston-based science journalist specializing in the life sciences.

VIROLOGY

EVASIVE ANATOMY

The Omicron coronavirus variant had specific mutations that hid it from the immune system. That helped make it wildly contagious

By Megan Scudellari

Graphics by Veronica Falconieri Hays

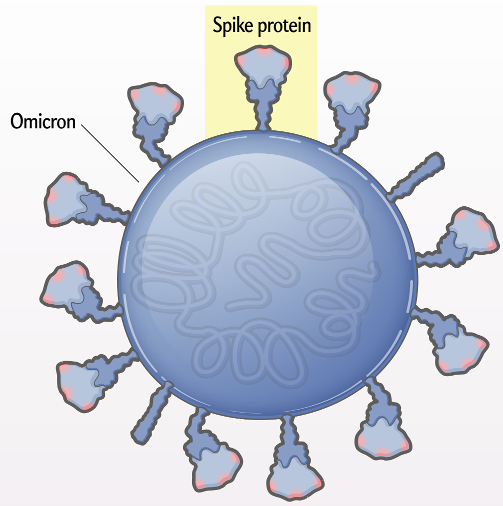
THE OMICRON CORONAVIRUS VARIANT WAS LIKELY THE FASTEST-SPREADING VIRUS IN HUMAN history. One person with the measles virus—a standout among infectious microbes—might infect 15 others within 12 days. But when Omicron suddenly arrived this past winter, it jumped from person to person so quickly that a single case could give rise to six cases after four days, 36 cases after eight days, and 216 cases after 12 days. By the end of February the variant accounted for almost all new COVID infections in the U.S.

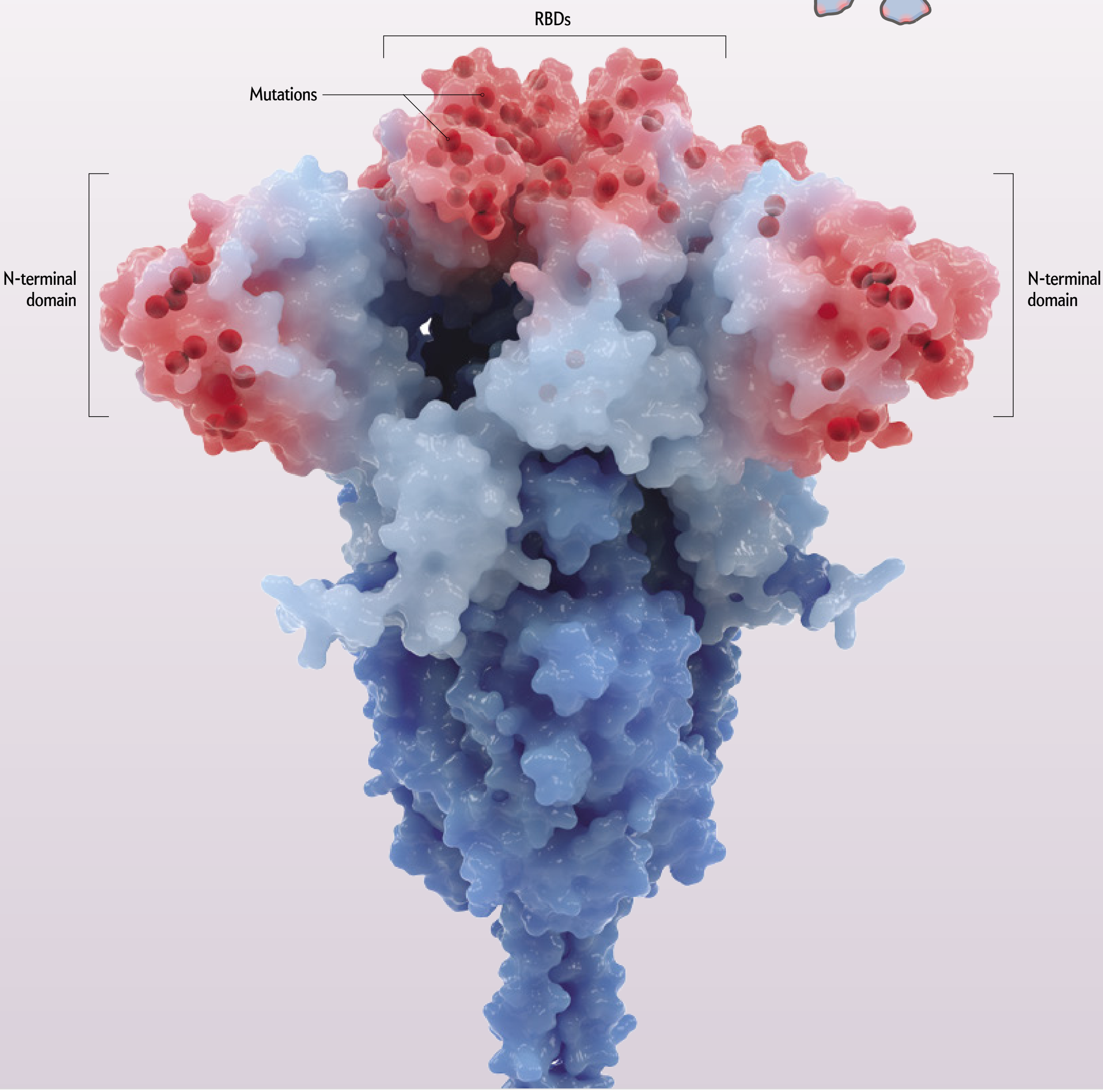
Back when the Alpha variant was spotted in November 2020, scientists knew little about how its few mutations would affect its behavior. Now, with a year's worth of knowledge and data, researchers have been able to link some of Omicron's 50 or so mutations to mechanisms that have helped it spread so quickly and effectively. That investigative process typically takes a lot longer, says Sriram Subramaniam, a biochemist at the University of British Columbia. "But we've been looking at these variants for a year, so we were prepared," he adds.

Omicron hosts twice as many mutations as other variants of concern, and its BA.2 sublineage may have even more. There are 13 mutations on Omicron's spike protein that are rarely seen

Immune System Avoidance

Antibodies try to attack the novel coronavirus, or SARS-CoV-2, by binding to areas on its spike protein. But the Omicron variant has many mutations (*red balls*) to amino acids in two important spike regions (*red tinted areas*): the receptor-binding domains (RBDs) and the N-terminal domain. As a result, antibodies that would ordinarily neutralize the intruder do not.





among other variants. Those changes to its anatomy gave it new and surprising abilities. If Delta is the brute-force Hulk variant, think of Omicron as the Flash—masked and wicked fast.

Here we explore four ways that the variant has physically changed. Three of those alterations helped this version of the virus evade our immune systems and become more infectious, whereas the fourth may have led it to produce more mild disease.

It wore a disguise. What made Omicron so transmissible, most evidence indicates, is a single, potent mechanism: among the variants, Omicron had an unparalleled ability to hide from the immune system.

During infection, fist-shaped clumps of amino acids atop the coronavirus spike called receptor-binding domains (RBDs) grab onto a protein on the outside of some human cells: the ACE2 receptor. To prevent that ill-fated attachment, the immune system creates antibodies—Y-shaped proteins induced by prior infection or vaccination—that recognize an RBD and stick to it like Velcro, getting in the way so the virus cannot link up with ACE2.

In previous variants, one, two or maybe three amino acids on RBDs were mutated, altering each RBD just enough to prevent some but not all antibodies from recognizing it. But Omicron harbored 15 RBD mutations, many on prime antibody-binding sites, forming an elaborate disguise to avoid many more antibodies. It was as if the virus donned a full-blown *Mission: Impossible*–style latex mask to change its face. “There are just so many mutations and so many new ones,” says Matthew McCallum, a biochemist at the University of Washington.

In an analysis published in the journal *Science,* McCallum, with his laboratory head David Veesler and their colleagues, showed a consequence of this dramatic transformation: only one of eight antibody treatments for COVID used in hospitals—which are based on natural antibodies—still bound effectively to RBDs. Other research has shown that mutations on RBDs and a second site called the N-terminal domain enable the virus to avoid antibodies gained by vaccination or infection. Thanks to Omicron’s convincing disguise, the variant had little to slow it down, and it spread with lightning-fast speed. Vaccines, however, still warded off serious illness, especially with booster shots.

It stabilized. When Omicron drastically altered its spike to hide from the immune system, those changes eliminated some chemical residues the spike needed to attach to ACE2. But other mutations compensated: RBDs formed new chemical bridges to still effectively bind to the protein, according to another study in *Science*. “It clearly lost some residues important for binding, but it made them up with other interactions,” says Subramaniam, who was the senior author of the paper.

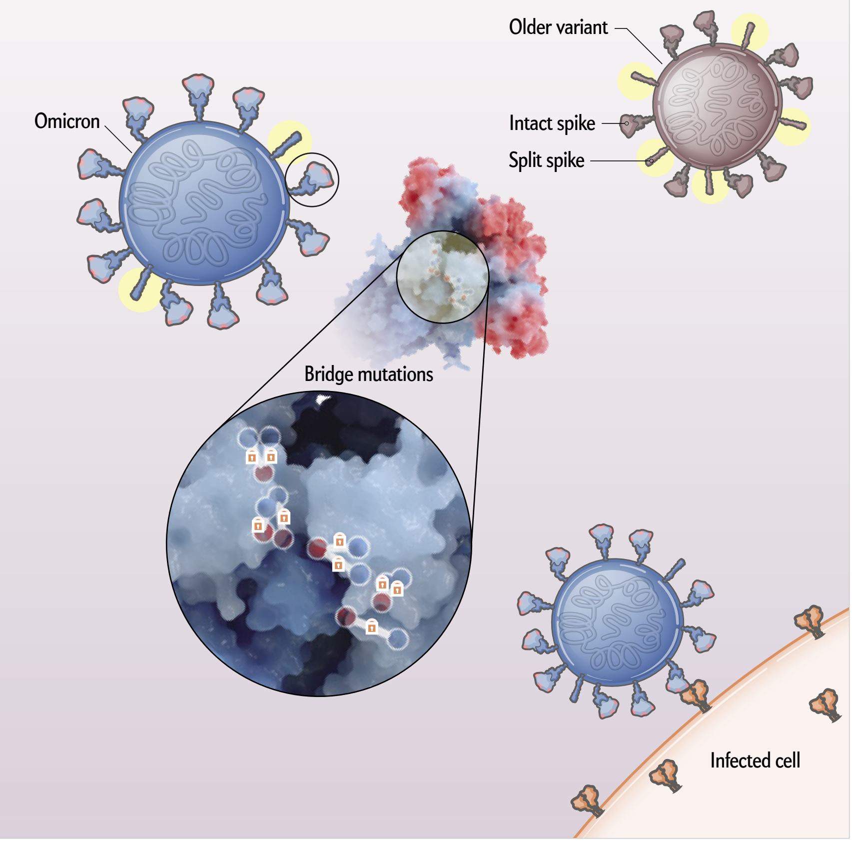
The spike protein also became sturdier. In other variants, two subunits within the spike, S1 and S2, are loosely connected. This allows them to split apart quickly so the spike can bury itself in a human cell when the virus encounters one. The downside of this delicate arrangement, however, is that many spikes split prematurely, before getting close to a cell. Once asunder, the spikes can no longer help the virus attach.

Mutations in Omicron led to slim molecular bridges that hold the subunits together better, according to several studies. One was published in the *Journal of Medical Virology,* and the others were released as preprint papers that have not yet been formally reviewed by other scientists. “This virus has really protected itself from prematurely triggering,” says Shan-Lu Liu, author of one of the papers and director of the Viruses and Emerging Pathogens program at the Ohio State University. “When the virus is in the right place at the right time, it can be triggered and get into the cell, but not prior to that.”

It slipped in the side door. Across previous variants, there was one con-

Spike Stability

The spike protein has two subunits that need to separate as the virus infects a cell. In earlier variants, they were delicately attached and frequently split too early. Some of Omicron’s mutations form extra molecular bridges between the two spike subunits, known as S1 (*light blue*) and S2 (*dark blue*). The bridges keep the subunits from separating prematurely. A greater number of intact spikes make it easier for Omicron to infect more cells.



stant: the virus relies on a protein on the surface of human cells called TMPRSS2 (pronounced "tempress two") to help it break through the cell membrane. But Omicron did not use TMPRSS2. It took a wholly different route into the cell. Instead of breaking down the front door, it slipped in through the side.

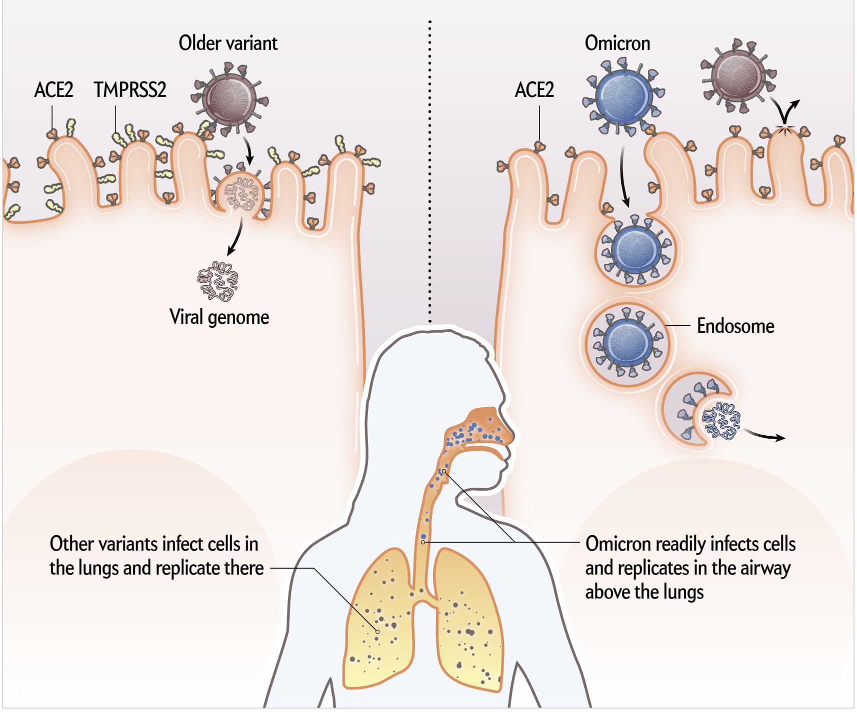
While other variants require both the ACE2 and TMPRSS2 proteins to inject their genome into a cell, Omicron bound only to ACE2. Then it was engulfed in a hollow bubble called an endosome. The bubble drifted into the cell, where the virus broke out and began a takeover.

Scientists speculate that Omicron gained two possible advantages this way. First, many cells do not have TMPRSS2 on their exterior, so if the virus does not need the surface protein, it has a wider buffet of cells to infect. "The current hypothesis is that there should be maybe seven or even 10 times more cells available to the virus if it goes through endosomes and isn't reliant on TMPRSS2," says Wendy Barclay, a virologist at Imperial College London, whose team, among others, detected the new entry pathway, which they described in a preprint.

Second, while the Delta variant often dove down to infect TMPRSS2-rich lung cells, Omicron replicated quickly in the airway above the lungs, which probably helped it spread from person to person. "We may be seeing a switch to the upper airway, which is promoting spread of the virus through coughing, sneezing, and such," says Joe Grove, a virologist at the University of Glasgow and co-author of a preprint that also detected the entry change.

Alternative Cell Entry

Older variants of the virus used two proteins, called ACE2 and TMPRSS2, to get inside a cell. Those variants fused with the cell membrane and injected viral genetic material into the cell. Omicron needs only ACE2 to get inside, making cells without TMPRSS2 available for infection. The variant is encapsulated in a bubble called an endosome, drifts into cells and then breaks out.



It dropped its defenses. A final, fourth change to Omicron did not help to make the variant more infectious, unlike the first three. Instead the alteration created a surprising weakness, rendering the variant more vulnerable to a part of our bodily defenses known as the innate immune system.

Scientists examined the responses from Omicron and Delta to interferons, small proteins that act like highway flares and alert innate immune cells to invaders. Delta was masterful at subduing the interferon response—but Omicron was terrible. It actually activated interferon signaling.

Researchers do not yet know how this change came about. At least 11 of the coronavirus's 26 proteins interact with the interferon system, and many of those were mutated in Omicron. But even without knowing the exact mechanism, scientists can see hints of the consequences of this change.

Because the lungs have a more pronounced interferon response than the upper respiratory tract does, Omicron's vulnerability to that reaction may have prevented it from spreading to the deeper organ. "It makes biological sense for what we see," says Martin Michaelis, a biologist at the University of Kent in England, who analyzed how Omicron interacts with interferon in a paper published in *Cell Research*. "Omicron seems to be less capable of making it further into the body and into the lungs to cause severe disease."

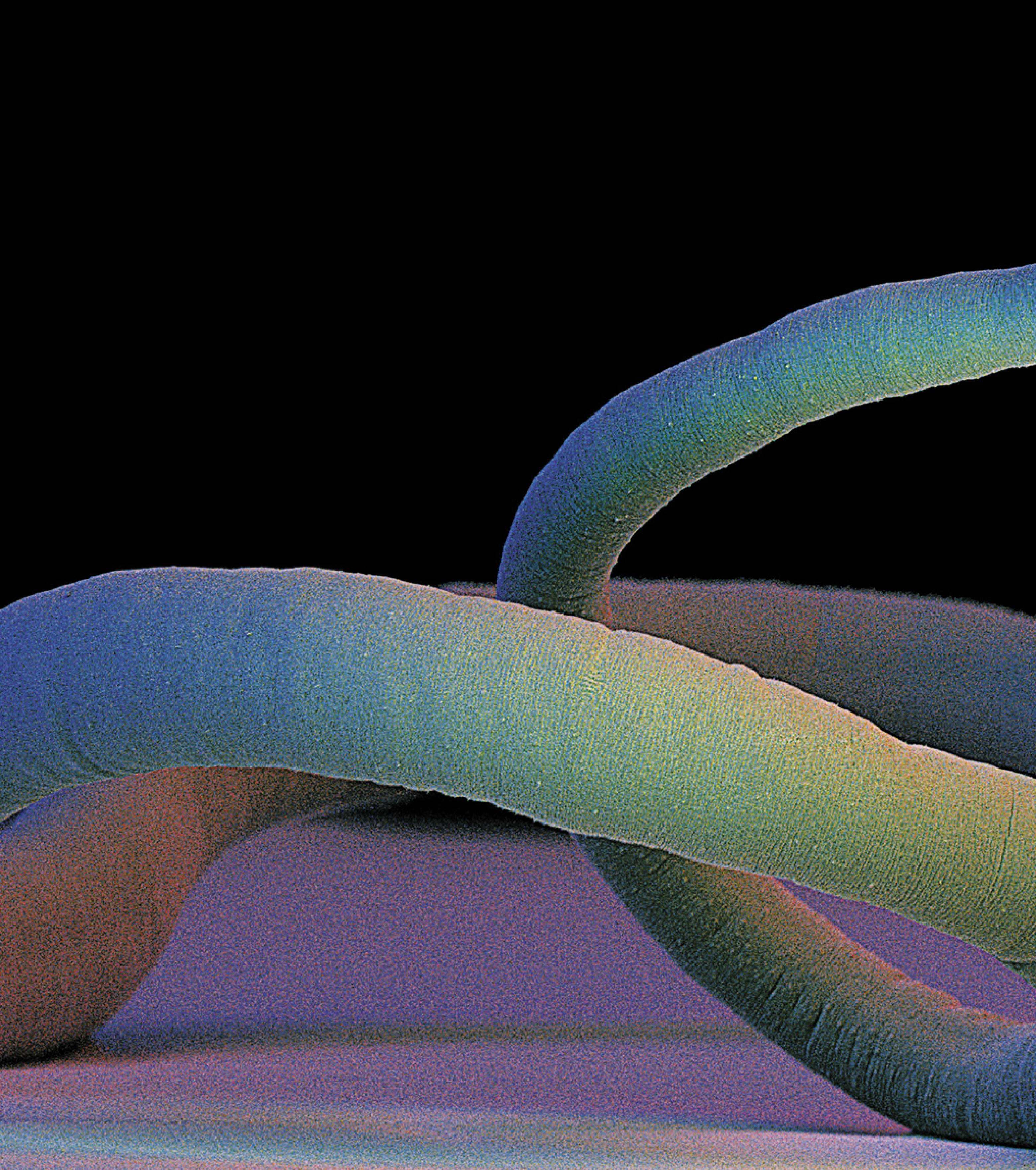
Although Omicron's impact on our whole population was not mild—it led to a giant surge in hospitalizations and deaths and a record number of hospitalized children—the variant did appear to cause less severe disease in some infected people, as well as in animal models. Those who were unvaccinated or had other risk factors were still at greatly heightened risk for severe illness and death, however.

Future variants, if and when they appear, may have yet other modifications to their structures and abilities. "I'm not confident that we can rest on our laurels and say this is all over," Barclay says. With infections continuing to spread and evolve among many populations around the world, the virus is going to come up with more ways to transmit—including ones that scientists haven't even thought of yet. SA

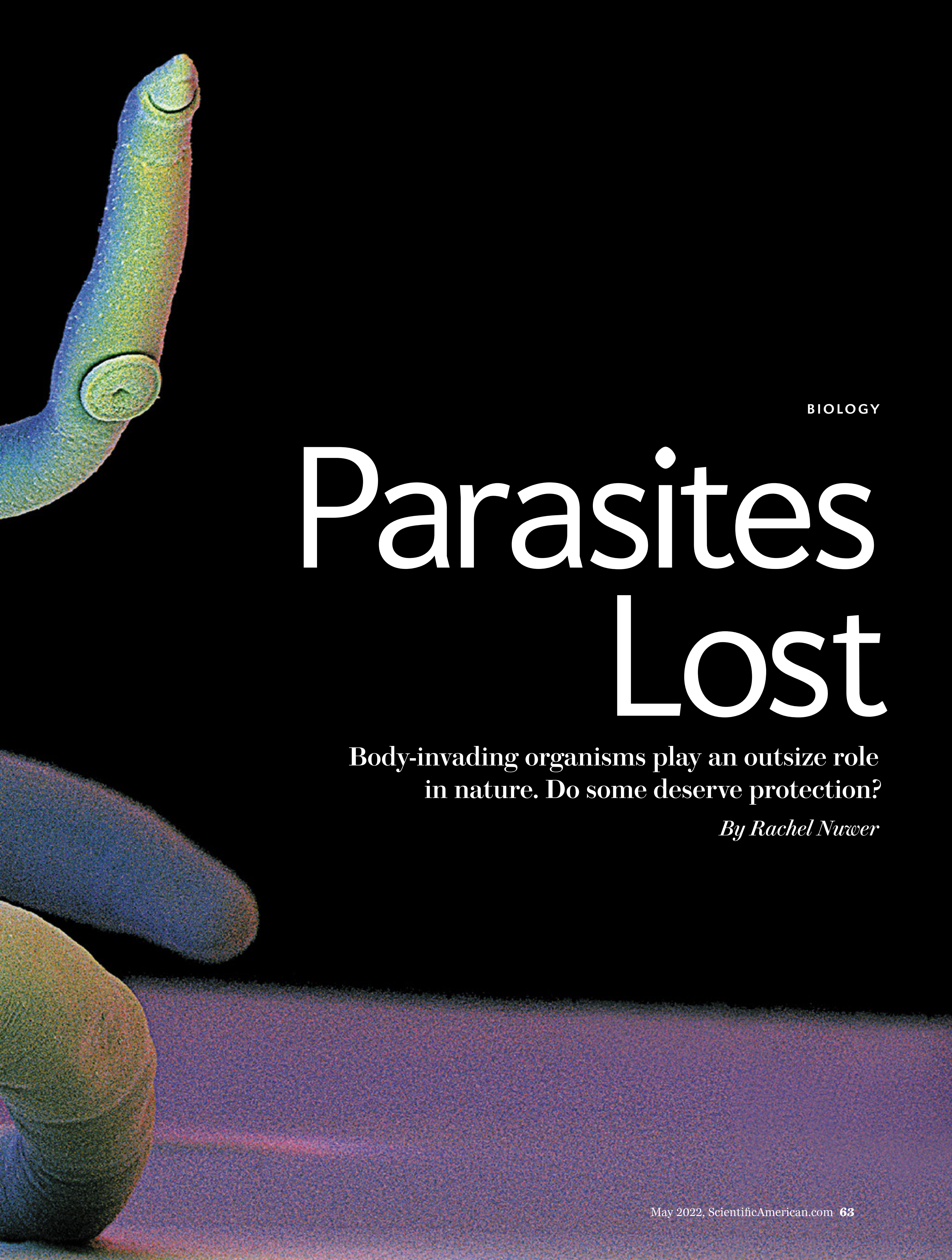
FROM OUR ARCHIVES

Data Captured COVID's Uneven Toll. Amanda Montañez et al.; March 2022.

scientificamerican.com/magazine/sa



CLOSE-UP of a female blood fluke, a parasitic worm that causes schistosomiasis in humans.



BIOLOGY

Parasites Lost

Body-invading organisms play an outsize role in nature. Do some deserve protection?

By Rachel Nuwer

Rachel Nuwer is a freelance science journalist and author who regularly contributes to *Scientific American,* the *New York Times* and *National Geographic,* among other publications.

I WAS PREPARING DINNER, PORTIONING A PIECE OF COD, WHEN A SMALL, PINK BLEMISH APPEARED in the pristine white muscle of fish. Removing the splotch with a knife tip, I realized something was very wrong. What had looked like a bulbous vein began unfurling into a thin squiggle the length of my pinky finger—and it was *moving.*

Like a scene from a horror movie, I watched, entranced, as the serpentine creature swayed its body, dismayed, it seemed, at finding itself ripped from the embrace of fish flesh. Before putting it in the compost bin, I snapped a few photos. I knew exactly who to send them to for identification help: Chelsea Wood, a parasite ecologist at the University of Washington—and perhaps the world's only person who uses words like "beautiful" to describe bloodsucking worms.

Wood's answer arrived the next morning: Anisakidae, she wrote—probably *Anisakis simplex* or *Pseudoterranova decipiens*—a common nematode that spends its larval stage in fish or squid. Wood went on to congratulate me: "What better way to start off the new year than to find a real live worm in your cod fillet?"

Given that Wood had told me about the abdominal pain, vomiting, diarrhea and bloody stool I would have experienced had the live worm managed to find its way into my esophagus, stomach wall or intestines, the congratulations seemed odd. In her enthusiastic manner she explained why such a discovery was positive: the typical hosts of this parasite are whales, dolphins, seals and sea lions—animals at the top of the food chain. "The presence of the worms in the fish is actually a sign that the ecosystem it came from is healthy and that there is a healthy population of marine mammals nearby," Wood wrote. "Celebrate that squirmy harbinger of good news!"

Parasites are organisms that live in an intimate, lasting and costly relationship with their hosts, and scientists estimate that fully 40 to 50 percent of all animal species fall into this group. Just about every free-living species on the planet has at least one parasite specially evolved to exploit it. The broadest definition of "parasite" includes pathogens such as bacteria, viruses, fungi and protozoans. But many parasitologists like Wood focus on multicellular metazoans: animals that encompass hundreds of thousands of species, including up to 300,000 different types of worms that parasitize vertebrates alone.

Metazoan parasites are as diverse as they are abundant. They span 15 phyla, ranging from microscopic, barely multicellular blobs to 130-foot-long tapeworms snuggly coiled inside whale guts—species as phylogenetically different from one another as humans are from insects and jellyfish. They live in every habitat on every continent and in every orifice, organ and body part of their hosts. And they are some of the world's most extreme specialists, with wildly intricate life cycles sometimes requiring up to five different hosts to allow them to get from egg to larva to adult. "It's just such a beautiful expression of the complexity of nature and its interconnectedness," Wood says.

Yet relatively few biologists—and hardly anyone else—are more than faintly aware of parasites beyond the tiny sliver of species such as tapeworms, pinworms and hookworms that are irksome or harmful to humans. As a result, nearly everything we know about parasites today comes from studying how to kill them. "The depth of our ignorance is really unforgivable," Wood says.

That's beginning to change. "Disease ecology and parasite ecology is the now fastest-growing subset of the ecological sciences," says Skylar Hopkins, a parasite ecologist at North Carolina State University. With a recent influx of early-career researchers, "we have this critical mass of scientists and practitioners." As the field grows, more evidence is emerging that points to parasites playing an outsized role in nature. One new study

David Scharf/Science Source (*preceding pages*)

PARASITE ecologist Chelsea Wood stands among the specimens at the University of Washington Fish Collection, part of the Burke Museum of Natural History and Culture.

Jovelle Tamayo

reveals that parasites account for 75 percent of the links in food webs; another study shows that they provide us with valuable ecosystem services, including pest control estimated to be worth billions of dollars.

Like predators, parasites can exert an effect on populations of other organisms in their habitat, which shapes everything from nutrient cycling to the types of plants that grow there to the abundance of top predators. In other words, parasites "play a major role in the natural world that was previously just overlooked," says Armand Kuris, a parasite ecologist at the University of California, Santa Barbara. "Their top-down control of populations operates differently than predation—it's slower—but their effect can, frankly, be just as massive."

Just as parasites' critical roles are being revealed, pioneering work conducted by Wood and others is beginning to show that many of these important animals are in trouble. They are contending with the same threats as better-known species: climate change, habitat destruction, pollution, and more. Because their fate is tied to their hosts—many of which are also in decline—they are often doubly vulnerable, particularly if they are specialists that live on or in only one species. "Every species you can think of that's endangered has parasites that rely on it," Hopkins explains. "If those species go extinct, then their parasites can also go extinct."

But parasite conservation is a hard sell. Saving certain parasites—and, in turn, preserving their roles in nature—will depend on convincing policy makers, the public and a wider community of scientists that protecting them is worthwhile.

NOT ALL BODY INVADERS ARE BAD

ASK A PARASITE ECOLOGIST how they got into parasites, and they'll likely tell you it was by accident. Wood grew up on New York's Long Island and dreamed of becoming a marine biologist. She imagined a career spent swimming with dolphins. In college, however, there were no opportunities for undergraduate marine biology research. The closest thing she could find to get on the water was an internship collecting marine snails infected with trematodes in New Hampshire and Maine. The parasites interested her "in no way, shape or form," she says. "I wasn't there for them."

Wood's mindset shifted slowly, then completely. In parasites, she began to discover an unseen world operating in parallel to the one of free-living species. Her undergraduate courses had hardly mentioned those animals. "It's possible to get a degree in biology and never learn anything about parasites," she says, citing a 2011 study that found that 72 percent of 77 conservation biology textbooks either did not mention parasites at all or only portrayed them as threats to the hosts they occupy. As Wood learned more, she felt as though she were waking up out of the Matrix: she could suddenly see a hidden layer of intricacy and connection

UNDER a stereomicroscope, the skin of a preserved fish is examined for ectoparasites.

sis infection for people in West Africa. But what excites Wood most is investigating the ways that parasites have changed over time.

Understanding the past tells ecologists what was normal before humans started meddling with the environment and what baseline conditions conservationists should aspire to preserve or restore. Unlike well-studied, charismatic animals such as elephants or tigers, wildlife parasites represent a data void: scientists have no idea how, if at all, their populations have changed over time. Yet Wood had observed that both scientists and the media tended to promote the idea that parasite populations are growing out of control, driven by human impacts to the environment.

Wood refers to this as the "sky is falling" narrative. In a 2015 paper published in the *Proceedings of the National Academy of Sciences USA,* for example, researchers wrote that because "host diversity inhibits parasite abundance … anthropogenic declines in biodiversity could increase human and wildlife diseases." This is based on an assumption, however, that parasites are always bad. "The knee-jerk expectation is that as environments have degraded, parasites will increase because they are seen as yet another stress on the system," says Kevin Lafferty, a disease ecologist at the U.S. Geological Survey. That prediction, he says, belies "a strong ignorance" of parasite ecology in general.

Wood agrees that the story is probably more complex. Like any other wildlife facing environmental change, she hypothesizes, over time there would be parasite winners and parasite losers. The only way to test this hypothesis would be to compare present parasitism rates with those from the past.

in every part of life. She also sensed an opportunity for scientific exploration. Fewer than 10 percent of parasite species have even been given names, much less studied in any detail.

Wood now leads her own parasitology laboratory at the University of Washington—"a 24-hour dissection machine," as she calls it. Her team of technicians, graduate students and postdoctoral researchers are all women. "I can't explain why women like parasites so much," Wood says. "There was no gender selection on my part, other than picking the very best people."

Wood's lab tackles a single question from different angles: How do the things people do to ecosystems influence parasites? One project is comparing parasite transmission in coral reefs that experience varying levels of human impacts. Another is looking into how the ecology of rivers, lakes and ponds that serve as access points for water collection affect the burden of schistosomia-

For nearly a decade Wood pondered unconventional resources that might help fill the void of historical data. She eventually found a portal to the past in an unlikely and convenient place: the University of Washington Fish Collection at the Burke Museum of Natural History and Culture, located just one building over from her office. In this unexceptional basement room, the remains of some 13 million marine specimens are preserved and suspended in 40,000 ethanol-filled jars. It is the largest fish collection in North America. But the scaly souls stored here are vastly outnumbered by parasites, tens of millions of which are clamped to the fishes' skin, gills, muscles and guts. The fish are like "parasite time capsules," Wood says. All she needed to do was peek inside.

Katherine Maslenikov, the museum's ichthyology collections manager, was hesitant when Wood first approached her with the idea. "We were sort of nervous,

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like, 'You want to do *what* to our specimens?'" Maslenikov recalls. Many conversations later, she came around. Wood's project, Maslenikov realized, "is a whole new avenue of research"—a chance to fulfill the museum's mission of aiding cutting-edge scientific studies. As Maslenikov put it, "This is not dead storage. A collection is meant to be used."

HISTORICAL ECOLOGY

KATIE LESLIE IS SORTING through ribbons of intestines belonging to a rockfish that's been dead for 41 years. So far Leslie, a research technologist in Wood's lab, has found only the remnants of the animal's last meal. Rockfish are notoriously wormy, but this specimen is proving to be exceptionally parasite-free, until—

"Oh, wait, yes!" Leslie calls out. "Here's an acanthocephalan!"

Under the microscope is the first parasite of the day, a thorny-headed worm. Leslie goes on to tally seven more parasites, including flatworms and nematodes. She then carefully places the fish, along with its neatly labeled vial of organs, back into its jar, and reaches for the next one.

To begin investigating the question of winners and losers, Wood chose eight common Puget Sound fish species from the collection. Maslenikov helped her identify up to 15 specimens per species per decade, starting as far back as the 1880s. In the lab, each fish undergoes a full physical, inside and out, first for sea lice attached to the animal's skin and then for parasitic worms in its organs and gills. Technologically speaking, the method, Wood admits, is "like banging two rocks together."

Finding the parasites is just the first step. Worms can be incredibly difficult to tell apart, with visual differences coming down to the number of teensy spines or hooks on a microscopic appendage. Species identification is therefore an exercise in patience and meticulous taxonomic expertise. "Our work supports the value of morphological taxonomy," says Rachel Welicky, a former postdoctoral researcher in Wood's lab, now working as an assistant professor at Neumann University in Pennsylvania. "It's really becoming a lost art form."

In July 2021 the Wood lab reported findings in *Frontiers in Ecology and the Environment* from its first analysis, on English sole collected from 1930 to 2019. In more than 100 specimens, the researchers identified nearly 2,500 parasites representing at least 23 taxa, of which 12 were prevalent enough to analyze their population trends over time. Of those 12, nine did not change in abundance across the decades; two, a trematode and a thorny-headed worm, decreased; and another, a trematode, increased. In another study that spun out from the same analysis of English sole, published in 2018 in the *Journal of Applied Ecology,* the team also found that a nematode called *Clavinema mariae*—a bloodworm that creates unsightly lesions on its host's skin—underwent an eightfold increase over the 86-year period.

According to Lafferty, who was not involved in the research, those results "demonstrate a new value for the millions of pickled fish in jars on museum shelves across the world." The findings themselves are notable, he continues, because they add an important data point about how parasites respond differently to environmental change. English sole parasites have been surprisingly stable over time, but for those whose populations *did* shift, not all went up. "Just like for free-living species, some parasite species do well under stress, and others don't," Lafferty says. Wood and her colleagues are preparing another study for publication with even greater power to test the "winners and losers" hypothesis.

As the team meticulously works through museum specimens, the scientists are also turning to other resources. Although there are few long-term data sets on any parasite species, there are one-off studies that document the abundance of parasitism at a particular place and time. In a 2020 *Global Change Biology* paper, Wood and her group synthesized these results for two types of common parasites found in raw fish often used in sushi and ceviche. One of the worms, they found, is just as prevalent today as it was in the past, but the other worm underwent an incredible 283-fold increase since the 1970s.

Wormy sushi can lead to a bad case of vomiting and diarrhea when consumed by people, but Wood is concerned about marine mammals—the worm's intended targets. Typically a single worm does not extract much energy from its host. But if the number of worms is skyrocketing, they could pose a problem for marine mammals, especially for populations that are already stressed. The Puget Sound's endangered pod of resident killer whales, for example, suffers from pollution, noisy ships and a lack of Chinook salmon to eat. In 2018 an emaciated killer whale calf turned up in the sound. Authorities launched an unsuccessful effort to save her, and before the calf died, scientists found that her scat was loaded with parasite eggs of the same sushi worm family identified in Wood's study.

This does not prove that parasites played a role in the calf's death. But it does hint at the possibility that parasites might be making life harder for an already beleaguered population, Wood says. To learn more, Natalie Mastick, a doctoral student in Wood's lab, is using several approaches to understand whether whales are facing a greater threat of intestinal parasitism today than they did in the past—such as collecting whale poop found by sniffer dogs on boats and analyzing it for hormones, diet and parasite load. "If parasites turn out to be this huge stressor we didn't know about, at least that's a treatable ailment," Mastick says. Wildlife managers can tuck anthelmintic drugs inside the salmon they feed to worm-stricken marine mammals ("like hiding your dog's pill in a blob of peanut butter," Wood says) or use darts to administer the pharmaceuticals from a distance.

In addition to the possible impacts on health for humans and wildlife, spikes in parasite populations can harm certain industries. The Puget Sound, for

TO SEE whether parasite populations have changed over time, the Wood Lab dissects walleye pollock ranging from four to 116 years old in search of parasitic worms and arthropods.

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example, is famous for producing Pacific oysters with pearly, unblemished shells. But in 2017 a colleague dropped a shell on Wood's desk marked with squiggly canals and dark, ugly spots—signs of a shell-boring oyster pest called *Polydora*. Although the parasites themselves are not dangerous for people to consume, they form blisters on the oyster shells filled with mud and worm feces and scar them with their voracious tunneling. It's not something diners want on their plates. Since the 1860s *Polydora* outbreaks have devastated oyster industries in Australia, Hawaii and the U.S. East Coast, but Washington State—the U.S.'s largest producer of farmed bivalves—had long been spared. In March 2020, however, Julieta Martinelli, one of Wood's postdocs, and her colleagues wrote in the journal *Scientific Reports* that one notorious species, *Polydora websteri,* had indeed invaded the Puget Sound.

Martinelli is now studying the ecology of the parasite in hopes of finding ways to help oyster growers treat and contain it. She and Wood are also trying to untangle the history of *Polydora* and other shell-boring polychaetes. An accidental introduction seems like the obvious answer, but the story may be more complex. Martinelli is turning to oyster middens—essentially, piles of shells left over from ancient oyster feasts—to unravel *Polydora*'s history in the Pacific Northwest. She confirmed that 1,000-year-old native Olympia oyster shells recovered from Jamestown S'Klallam Tribe middens bear signs of some type of burrowing worm. Martinelli guesses that this is a different species—but it could also be that *Polydora* has been lying in wait in very low numbers and only now has been unleashed by some as yet unknown environmental trigger.

Martinelli plans to excavate more recent oyster middens to see if she can pinpoint the parasite's introduction into local bivalve populations. "The tricky thing about paleo work," she says, "is we'll never have the definite answer. But we do have traces of the past that are comparable to the present."

SAVE THE PARASITES

PARASITE INCREASES still get most of the attention—which is why Wood is attuned to parasite decreases and their implications for humans and wildlife. Some are to be celebrated, such as the effort to eradicate the Guinea worm, a spaghettilike parasite that grows up to 2.5 feet long inside an infected person's digestive system before migrating to and eventually breaking through their skin. But for parasites that do not impact humans—the vast majority of species—some of the losses are concerning. One 2017 *Science Advances* paper estimated that up to 30 percent of parasitic worms may go extinct in the coming decades because of climate change and other pressures, and we're only just beginning to learn how such a staggering loss of biodiversity will reverberate.

Take, for instance, the phenomenon of parasitic puppet mastery that occurs in many species. "Parasites shunt energy from lower to higher trophic levels by making prey reckless," Wood says. *Euhaplorchis californiensis,* for one, is a trematode flatworm that, in its larval stage, looks a bit like a sperm, with a big head and long tail. The flatworm begins its life in a snail, then moves into a California killifish, then to its final destination in the gut of a predatory water bird, such as a heron or egret. Killifish typically spend their days hiding, however, which runs counter to the flatworm's agenda. So the parasite creates cysts on its host's brain, causing the hapless killifish to splash around on the surface of the water and flash its shiny belly, baiting the birds. Infected killifish, researchers have found, are 10 to 30 times more likely to be eaten by a bird than noninfected ones. Collectively, trematodes make a significant proportion of killifish populations more readily available as meals for birds—effectively subsidizing those predators' diets. If certain parasite species are in decline or even disappear, it's possible that "it could be way harder to conserve predators," Wood explains.

Likewise, in Japan a 15-inch-long nematomorph worm causes infected crickets to dive into streams, where the adult worms burst out of their hosts to partake in a parasitic orgy. Meanwhile the doomed crickets become food for endangered Japanese char, providing up to 60 percent of the fish's calories. Not only does the nematomorph worm help feed an endangered species, but by relieving pressure on other invertebrate species the fish eat, it also changes the stream's overall ecology.

As scientists learn more about parasites' roles in ecosystems, a small but growing cadre is beginning to think seriously about the need for targeted parasite conservation. In August 2020 parasite ecologist Colin Carlson of Georgetown University, along with Wood, Hopkins and nine others, published a 12-point plan for conserving parasites over the next decade. For starters, they wrote in the journal *Biological Conservation,* we cannot care about or conserve what we do not know exists. They challenged the scientific community to shine a light on parasite diversity by describing more than 50 percent of parasite species by 2030. "We basically have barely scratched the surface," Hopkins says.

Once descriptions and data about each species' ecology and life cycle start rolling in, the authors suggest, parasites in need of conservation could be identified, then integrated into existing species-protection schemes fairly simply. Parasite conservation can simply piggyback on existing efforts to save imperiled free-living species. Threatened parasites can likewise be added to various inventories for tallying and protecting endangered plants and animals. Only one animal parasite, the pygmy hog-sucking louse, is currently included on the International Union for Conservation of Nature's Red List of Threatened Species, and none are included on the U.S. Endangered Species List.

Hopkins, Wood and their peers know that parasites have a serious image problem but are hopeful they can be rebranded. They liken the state of parasite conservation to where the field of predator conservation was just a few decades ago. At the time, many researchers and the public thought of bears, wolves and other meat eaters as damaging to the environment and dangerous to humans and livestock. Those assumptions proved not only false but harmful. Scientists now know that predators are keystone species—ones on which entire ecosystems depend. Removing them can cause cascades of negative impacts, from disease outbreaks and disruption of nutrient cycling to shifts to entirely different habitat types. As researchers realized the importance of predators, the public warmed to them, too.

"My hope is that people are willing to peer into this black box we've put parasites into," Wood says. "Parasites aren't this monolithic threat." SA

FROM OUR ARCHIVES

Surfing Parasites. Stephenie Livingston; November 2020.

scientificamerican.com/magazine/sa

ANTHROPOLOGY

Designing for Life

An Indigenous community in the Amazon basin is showing the world how to live with, rather than off, nature

By Carolina Schneider Comandulli, with the Apiwtxa Association

Photographs by André Dib

ASHANINKA woman by a sacred kapok tree

Carolina Schneider Comandulli has worked with Indigenous peoples in the Amazon and Atlantic rain forests since the early 2000s. She holds a Ph.D. in anthropology from University College London. The **Apiwtxa Association** represents the interests and ideals of the Apiwtxa community in the Kampa do Rio Amônia Indigenous Land in Brazil.

LAST JULY A PREMONITION PERSUADED THE ASHANINKA INDIGENOUS PEOPLE OF the western Amazon basin to undertake a great traditional expedition. Divining that this could be their last chance to enjoy peace and tranquility, more than 200 Ashaninka from the Sawawo and Apiwtxa villages alongside the Amônia River in Peru and Brazil, respectively, boated upstream to pristine headwaters deep in the forest. It was the dry season, when the river waters were clear and safe for the children to splash in and the night sky starry for the spirit to soar in. There, in the manner of their ancestors, the Ashaninka spent a week camping, hunting, fishing, sharing stories, and imbibing all the joy, beauty and serenity they could.

A month later the Ashaninka got the news they had been dreading—a road-building project they'd heard about months earlier was moving forward. Logging companies had moved heavy equipment from mainland Peru to a village at the Amazon forest's edge to cut an illegal road through to the Amônia. Once the road reached the river, loggers would use the waterway to penetrate the rain forest and fell mahogany, cedar and other trees. The birds and animals the workers didn't shoot for food would be scared away by the screech of chain saws. Indigenous peoples would face lethal danger both from violent encounters with the newcomers as well as from casual interactions, which would spread germs to which forest peoples often have little immunity. Drug traffickers would clear swaths of forest, establish coca plantations and try to recruit local youths as drug couriers. The road would bring, in a word, devastation.

This borderland between Brazil and Peru, where the lowland Amazon rain forest slopes gently toward the Andes foothills, is rich with biological and cultural diversity. It is home to the jaguar (*Panthera onca*) and the woolly monkey (genus *Lagothrix*), as well as to several Indigenous groups. Its protected landscapes include two national parks, two reserves for Indigenous people in voluntary isolation and more than 26 Indigenous territories. The nearest large town, Pucallpa in Peru, is more than 200 kilometers away over dense forest as the macaw flies and is almost unreachable; the tiny town of Marechal Thaumaturgo on the Amônia River in Brazil can, however, be accessed by chartered flight from Cruzeiro do Sul, the second-largest city in Acre state, and is a three-hour boat ride downstream of Apiwtxa.

Remote as it is, the region has been threatened for centuries by colonizers who sought its riches. In response, the Ashaninka joined Indigenous alliances to fight off the invaders or fled into ever deeper forests to escape them. In the 1980s, however, technological advances made it far quicker and easier for outsiders to cut through the jungle for logging, ranching, industrial agriculture, and drug production and trafficking.

The Apiwtxa Ashaninka adapted, responding to the intensified assaults with increasingly sophisticated and multifaceted resistance tactics, which included seeking allies from both Indigenous and mainstream society. Most significantly, they devised a strategy for the community's long-term survival. The Apiwtxa designed and achieved a sustainable, enjoyable and largely self-sufficient way of life, maintained and protected by cultural empowerment, Indigenous spirituality and resistance to invasions from the outside world. "We live in the Amazon," said Apiwtxa chief Antônio Piyãko at the July gathering. "If we do not look after it, it will vanish. We have the right to keep looking after this land and prevent it from being invaded and destroyed by people who do not belong here."

The Apiwtxa, along with members of regional nongovernmental organizations, had been working with the Sawawo people, first

Sources: David S. Salisbury, Stephanie A. Spera, Elspeth Collard, Anna Frisbie, M. R. Place, Yunuen Reygadas Langarica and Elizabeth Zizzamia, Amazon Borderlands Spatial Analysis Team, 2021; *Atlas de las Carreteras Propuestas en la Zona Transfronteriza Ucayali Perú-Acre, Brasil*, by Spatial Analysis Lab, University of Richmond (*map reference*)

Map by Mapping Specialists

A LOGGING ROAD from Peru (*left*) cut through the Amazon forest to reach the Amônia River in August 2021. Fearing an assault on the region's biodiversity, Ashaninka Indigenous peoples and their allies halted the loggers' advance with their bodies. They subsequently established a surveillance outpost (*above*) by the illegal road to guard against further attempts by outsiders to extract the region's natural wealth.

in the line of invasion, to prepare to resist the loggers. When they learned that the loggers had finally arrived, members of Sawawo's vigilance committee traveled up the Amônia in their boats. Two and a half hours later they came upon two tractors. Laden with people, food, fuel and equipment for founding a logging base, the vehicles had crossed the river into Ashaninka territory in Peru. The defenders took pictures of the destruction, interviewed the loggers and returned to their village, where they had Internet access. They reported the intrusion to Peruvian authorities through a local Indigenous organization, asking that an environment official visit to survey the damage. They also shared the evidence with the Apiwtxa and other allies and set up camp at the invasion spot, waiting for reinforcements.

Apiwtxa members showed up soon after, by boat, and nine days later supporters from three regional NGOs arrived on foot. That evening they saw two more tractors coming with supplies. More than 20 people, led by a woman carrying her baby, swiftly placed themselves in front of the tractors, preventing the loggers from crossing the Amônia. The Ashaninka, who have a reputation of being fierce warriors, promptly confiscated the keys from the stunned drivers.

The official arrived the next day. He cursorily scanned the environmental damage and demanded the tractor keys, which the Ashaninka handed over. Sawawo's people nonetheless maintained a presence in the camp for months to make sure that the tractors were not used for a fresh assault on the region, and the NGO allies alerted the press to the intrusion.

Eventually the logging companies left the territory. Determined but nonviolent Indigenous resistance, coupled with pressure from global media, had temporarily unnerved them. In November 2021, however, when Apiwtxa village was hosting a gathering of local Indigenous groups to discuss the increasing threats posed by loggers and drug traffickers, the Peruvian government authorized the tractors' retrieval. One of the companies has since resumed its efforts to enter the region, using a tried-and-true tactic—divide and conquer—seeking to convince individual Indigenous leaders to sign logging contracts with them. The struggle the Ashaninka have been waging for decades continues.

CONTEMPORARY, NOT MODERN

SINCE 1992, when a community of Ashaninka people obtained legal title to some 870 square kilometers of partially degraded forest along the Amônia River, they have achieved an astonishing transformation. Once a people undergoing flight, fight or subjugation ever since European missionaries and colonizers arrived in their homeland three centuries ago, the 1,000-odd residents of Apiwtxa village in the Kampa do Rio Amônia Indigenous Land have become an autonomous, self-assured and largely self-sufficient community. They have regenerated the forest, which had been damaged by logging and cattle ranching, restored endangered species, enhanced food security through hunting, gathering, agroforestry and shifting cultivation, and otherwise shaped a way of life they hope will ensure the continuation of their community and principles. These achievements, as well as their support for neighboring communities, have earned them several awards, including the United Nation's Equator Prize in 2017.

The Apiwtxa designs for living, drawn from shamanic visions and informed by interactions with the non-Indigenous world, are predicated on the protection and nurturing of all life in their territory. The Ashaninka hold that their well-being depends on the

THE APIWTXA WAY of living—enjoying a canoe ride on the Amônia River (*opposite page*), weaving palm leaves into the roof of a hut (*center*) or preparing a bird for a meal (*right*)—is predicated on sustainability and self-sufficiency. It involves defending the territory from assaults when necessary as well as implementing norms for protecting biodiversity.

maintenance of the Amazon's incredible biodiversity. This awareness comes largely from their intimate relationships with the plants, animals, celestial bodies and other elements of their landscape, which they regard as their close relatives. These beings, especially the plant ayahuasca (*Banisteriopsis caapi*), which the Ashaninka call *kamarãpi,* help treat their diseases and guide their decisions through visions. "Our life is an enchantment," shaman Moisés Piyãko said to me in July 2015. "What we live in Apiwtxa is all lived beforehand in the world of *kamarãpi."*

As architects of their future rather than passive victims of circumstance, the Apiwtxa are living a concept outlined by development scholar Arturo Escobar in *Designs for the Pluriverse* (2018). Extending design theory into the cultural and political realm, Escobar described social design as a means by which traditional and Indigenous peoples engender innovative solutions to contemporary challenges. In his view, moments of social breakdown, when "the habitual mode of being in the world is interrupted," are important for new ways of living to emerge. Securing a territory, a safe space for the design to flourish, is essential, Escobar adds. Through the struggle to safeguard their land, the Apiwtxa have realized this ideal: the community has fought against social and ecological disintegration to take control of its own fate and that of the creatures they live with and depend on.

I first arrived in Apiwtxa village in 2015 to conduct research for a doctoral degree in anthropology. Getting there required four sets of clearances—from my university, two Brazilian agencies and the Apiwtxa themselves—a commercial flight to Cruzeiro do Sul, a chartered flight to Marechal Thaumaturgo and then a three-hour boat ride. Within days of arrival, I realized that it was no easy task to study the Ashaninka. A centuries-long history of dispossession and exploitation by non-Indigenous people has made them wary of outsiders. It was only after some months of *their* observing *me* that I was allowed to stay. My willingness to collaborate with their projects, my empathy with their principles, and my deep respect for their courage and wisdom all guided their decision. I ended up living and working with the Ashaninka for two and a half years. It was a transformative experience.

I had worked with various Indigenous groups since the early 2000s, as a researcher, consultant on the environmental impact of development projects, and later as an employee with FUNAI, Brazil's National Foundation for Indigenous Affairs. I was well aware of the devastation that the Global North's hunger for oil, minerals, timber and other resources wreaked on forest peoples. I found the Ashaninka remarkable, however, for their penetrating analysis of the assaults they faced, as well as the farsightedness with which they devised responses to them. They were not "modern," in that they did not seek a state of development modeled on a Western ideal of progress and growth that many aspire to but only few can reach. Instead they were exceptionally "contemporary," in the sense of finding their own solutions to present-day problems. As philosopher, anthropologist and sociologist Bruno Latour commented, "Knowing how to become a contemporary, that is, of one's own time, is the most difficult thing there is." And I was awed and

AUTONOMY, a key Apiwtxa principle, requires food and economic self-sufficiency. A child fetches corn from a multicropped field (*left*). A cooperative shop sells handicrafts such as a macaw-feather headdress (*center*); such items help the community earn an income without depleting local resources. Dora Piyãko, the cooperative's president, displays a sling for carrying a baby (*right*).

inspired by the Apiwtxa Ashaninka's ingenuity and resilience.

"We, the Ashaninka, have been massacred by loggers; we have been massacred by rubber dealers; we have been massacred by colonizers.... We were taken as a workforce to serve patrons who told us to cut down the forest and hunt the animals for them so they could live well; we were massacred by the missions who told us that we knew nothing," Benki Piyãko, an Ashaninka leader, told me. "But then we decided to give a different response: we began to study."

The first "student," as Benki tells it, was his grandfather, Samuel Piyãko, who sought to understand the economic imperatives that drove outsiders to exploit nature and Indigenous peoples. Born in Peru, he was a shaman who worked on cotton plantations in conditions of debt peonage, a system by which Indigenous peoples were forced to work for a pittance, purchasing their necessities from their oppressors at extortionate prices, rendering them permanently indebted. Sometime in the 1930s Samuel escaped the plantations and trekked down the Andes slopes to the rain forest in Brazil. There, too, he encountered colonizers who were entering the forest via the great Amazonian rivers.

"I do not have anywhere to escape," Samuel thought, according to Benki. "I will have to adapt here. I will stay here and look with my spirit to see how I will be able to remain connected" to other people and beings. Samuel's descendants say he used his shamanic powers to envision the transformation his people have since achieved. "What is happening here is my grandfather's dream," Moisés, Benki's brother, said. "Here we are, his grandchildren, accomplishing what he thought would guarantee the continuity of the people and build the best path for us all."

Samuel came to be regarded as a *pinkatsari,* or leader, whose sheltering presence induced other Ashaninka families to move to the area. Later, when one of his sons, Antônio, wanted to marry a non-Indigenous, Portuguese-speaking woman from a family of rubber tappers and cattle ranchers, Samuel assented, declaring that she would become an ally. He was right. Her own family initially opposed the marriage, so Francisca Oliveira da Silva, who came to be known as Dona Piti, came to live with her in-laws, bringing along her knowledge of the outside world.

Starting in the 1960s, many of the Ashaninka began working for logging bosses, who used their lack of knowledge about the outside world to exploit them—paying with a box of matches, for example, for a mahogany tree. Piti explained to them the relative values of such goods to traders, helping them understand how they were being cheated in every transaction. Seeking to break the cycle of exploitation and instead trade on their own terms, the community founded a cooperative, a collectively controlled trading enterprise, in the 1980s. "We were being fooled," recalled Bebito Piyãko, one of Piti and Antônio's children. "The cooperative was a way, we thought, to break this dependency." The Ayõpare Cooperative enabled community members to trade what they produced for credit, with which they could get goods from a village shop.

At this time, industrial logging was arriving in the region, cre-

ating destruction of a kind the Ashaninka had never encountered before. In the old days, it might take days to fell a single mahogany tree with an axe; now it took minutes. Swaths of forest fell to chain saws. Tapirs and other game animals fled. Workers brought in from faraway towns invaded Ashaninka celebrations, spreading disease and harassing women. Similar assaults across the Amazon basin sparked a vigorous and prolonged social movement that resulted in Brazil adopting a progressive new constitution in 1988. It recognized the rights of Indigenous peoples to use the natural resources of their territories in traditional ways. With the new constitution in place, the Ashaninka sought FUNAI's help to secure territorial rights to the surrounding forest.

They were besieged by death threats from loggers and cattle ranchers. Ferrying the necessary documents between Apiwtxa and Cruzeiro do Sul required braving ambushes. Nevertheless, Piti, Antônio and their oldest children, Moisés and Francisco, pressed Brazilian authorities for the right to control how their locale's resources should be used. No one was killed, but by the time the land title came through many Ashaninka families had left out of fear. That Samuel died during the struggle, of old age, no doubt increased their sense of insecurity.

STRENGTH IN UNITY

RECOGNIZING THAT UNITY and cooperation were key to survival, the remaining Ashaninka families, led by Antônio, Piti and others, embarked on a process of collective planning to determine their future. What kind of life did they want to live and how would they achieve it? They surveyed their territory and their experiences, looking "inside us at the worst of all the bad moments we had faced, so that we could reflect on the changes we had to make," Benki recalled. Designing their future, devising a set of rules to maintain their cohesive social structure, and developing a management plan to ensure adequate, enduring resources would take three years of exploration and discussion.

During this period the roughly 200 people formed the Apiwtxa Association to represent their interests to civil society and the Brazilian state. And at its end, they began moving the community to the northernmost extremity of their territory, a remote location they deemed strategic: conducive to fending off intruders and to maintaining their social integrity and governance system. Although the Ashaninka traditionally lived as nuclear families scattered across the landscape, they founded a compact village that would be easier to protect, also naming it Apiwtxa.

Roughly translated as "union," the word *apiwtxa* signifies the placing of collective interests above individual ones and is one of the community's key governance principles. The villagers consistently apply it in their struggles, seeking to achieve consensus through gatherings and discussions that can take a single shift or last for days—if that is what it takes for everyone to agree—before embarking on a course of action. These meetings help the Apiwtxa devise ways to overcome threats emanating from outside their territory and plan future projects.

The Apiwtxa constructed the new village by the Amônia River, on two former cattle pastures of around 40 hectares. They reforested the area, mostly with indigenous species, which they nurtured in nurseries. They built the huts in the traditional manner—close to the river, on raised platforms to keep out snakes, and mostly without walls to let in the breeze. Around their homes they planted fruit, palm and timber trees, and medicinal plants. They established banana groves and multicropped fields with corn, manioc and cotton, dug ponds to breed fish and turtles to replenish the fishing resources in the Amônia River, and set up no-go areas, which shifted periodically, to prevent overhunting. And they established a school of their own design, teaching children in the Ashaninka language for the first four years and imparting both traditional skills such as weaving and mainstream knowledge such as arithmetic. A few of the young people went away to attend university and study the outside world—in particular, its economic and political systems—before returning with their skills to the Apiwtxa.

At Apiwtxa, the day revolves around living—bathing in the river, washing clothes, tending crops, fishing, cooking, repairing huts and implements, playing. By the time it draws to a close, everyone is tired. The villagers eat dinner just before sunset, after which the children might enjoy a storytelling session before going to bed. Some of the women spin cotton; the spiritual leaders, mostly men, sit under starry skies to chew coca leaves in silent communion. Among the Ashaninka, a great deal of communication happens without speech, through subtle shifts in expression and posture. We would go to sleep by 7 or 8 P.M., waking up early to birdsong and other forest sounds, feeling deeply rested.

The regulations that the Apiwtxa decided on in the 1990s have since developed into a complex system of governance. The community's leaders, several of whom are Samuel's close relatives, comprise shamans, warriors and hunters who deal with internal issues, alongside people with formal education or experience in building social movements, who serve as interlocutors with the outside world. With such a diversity of skills, the Apiwtxa have also become adept at raising funds from governmental and nongovernmental agencies for projects, such as reforestation.

A second key principle of Ashaninka design is autonomy—independence from systems of oppression and the freedom to determine how to live in their territory. "Not be led by others" is essential, Francisco declared. Autonomy requires a large measure of self-sufficiency, to which end the Apiwtxa have enhanced their food sovereignty and implemented economic and trading practices that minimally impact the environment. The ancient *ayõpare* system of exchange, which goes beyond material exchanges to the creation and nurturing of relationships of mutual support and respect, guides all transactions within and without the community. I experienced it while living there: someone might ask me for, say, batteries, and a few days or months later I would find a bunch of fruit or some other gift on my doorstep.

One manifestation of this system is the Ayõpare Cooperative, which trades only products that do not deplete nature and only with outsiders who support Apiwtxa's objectives. "The forest is our wealth," as Moisés explained. "Our project is to sustain this wealth." The cooperative's most successful products are handicrafts; they help to maintain traditions and protect the forest while providing relative economic autonomy. The cooperative also enables the Apiwtxa to communicate its principles— by, for example, selling native seeds for reforesting other parts of the Amazon.

Reducing physical threats from the outside world enhances autonomy as well. To this end, the Apiwtxa have tried to create a physical and cultural "buffer zone" around their territory by helping neighboring Indigenous communities to also bolster their traditions and protect biodiversity. Prolonged subjugation by mainstream society has led several Ashaninka groups, especially those in Peru, to adopt outsiders' unsustainable modes of living or succumb to market pressures to sell timber or other forest resources, Benki and Moisés observed. Changing this state of affairs requires restoring ancestral ways of interacting with nature, the shamans believe. Indeed, Apiwtxa leaders hold that this ancestral knowledge is a vital resource for all of humankind. "It is not enough to only work on our land," Benki said, "because our land is only a small piece of this big world that is being destroyed."

The Ashaninka reject the idea that humankind is separate from nature and that the latter is subject to the former. According to their creation myth, the original creatures were all human, but Pawa, their Creator, turned many of them into birds, animals, plants, rocks, celestial bodies, and others. Despite being different in form, these beings retained their humanity and are all related to the Ashaninka. Many other Indigenous traditions similarly hold that plants, trees, animals, birds, mountains, waterfalls and rivers, among others, can speak, feel and think and are tied to other beings in reciprocal relationships.

AT A GATHERING by the headwaters of the Amônia River in July 2021, members of the Apiwtxa and Sawawo communities discussed the need to protect the Amazon forest from outsiders who covet its riches.

A SENTIENT WORLD

AYAHUASCA taught them about the intimate connections among beings, the Ashaninka say. In their mythology, the ayahuasca vine sprouted from the place where a wise ancestral woman, Nanata, was buried; it possesses her wisdom. A japo bird (genus *Cacicus*) then explained to the Ashaninka how to unite the ayahuasca vine with a particular leaf (*Psychotria viridis*) to brew the sacred drink, *kamarãpi*. "They drank it and took it to their people, bringing light and conscience to them," Benki said.

Kamarãpi rituals always take place at night, preferably under a clear, starry sky. There is no fire, no talking; the occasion is solemn. When the psychoactive brew starts to take effect, the shaman guiding the ceremony chants, usually to the birds and the spirits in the sky. Soon the others start to sing, too, their voices overlapping to create a rapturous polyphony. At this point, visions ensue. The shaman is attuned to every participant and monitors what they are feeling, intervening when necessary.

When I took part in the ritual, I felt my body dissolving into the surroundings, my self merging with the environment in a way that defies words, giving me a deep sense of the connectedness between other beings and me. In my experience, the *kamarãpi* ceremony establishes powerful bonds among everyone present and between the forest creatures and them, enabling communication to happen in silence even after the ritual is over.

As Moisés sees it, *kamarãpi* helps people develop their conscience by leading them toward self-knowledge and gradually to a deep knowledge of other people and other kinds of beings. Once developed, this wisdom will help guide their actions and relationships. Shamanic rituals have parallels with psychotherapy, anthropologist Claude Lévi-Strauss noted; shamans, like therapists, help people gain insight into themselves and their relationships with others. But psychotherapists are only recently beginning to comprehend the power of psychoactive substances in assisting

THE ASHANINKA BELIEVE that all creatures, as well as features of the landscape such as the Amônia River (*opposite page*), are sentient and connected to one another by reciprocal relationships. Visions induced by a brew from the ayahuasca vine (*left*) reinforce the empathy that the Indigenous people feel for other beings. Francisco Piyãko (*above*) communes with a kapok (*Ceiba pentandra*) tree, believed to have powerful life-giving abilities.

AMÔNIA RIVER meanders through the Kampa do Rio Amônia Indigenous Land in the western Amazon basin.

trauma patients, among others, to come to terms with their suffering and thereby to heal. The *kamarãpi* ritual goes further, creating deep empathy not only for oneself and other human beings but also for other creatures, as well as for rivers and other features of the landscape. All come to be seen as connected, an awareness that has profound implications for how people treat nature.

Apiwtxa's shamans even attribute their capacity to design their society to *kamarãpi* visions. Moisés, Benki and other shamans actively seek guidance from ayahuasca, with whose help they attain, sustain and explore an altered state of consciousness that enables them to envision the future and find solutions to challenges. Dreams are known to be conducive to problem-solving; they enable disparate concepts to link up in ways not normally available to the rational mind. Shamans in Ashaninka and other Indigenous cultures deliberately attain such states of consciousness as a means of seeking foresight and wisdom.

Dreaming is essential but not enough, Benki adds. It is also essential to plan—to think consciously and rationally—and act in the present. When a shaman reports a significant vision, the community discusses it and develops a plan of action. After Benki dreamed about a center for disseminating forest peoples' philosophy—a place that would be rooted in ancestral knowledge while reaching out to the world with a message of caring for all beings—the Apiwtxa acted on it, founding the Yorenka Atame (Knowledge of the Forest) Center in 2007.

They constructed the building on a cattle pasture across the river from Marechal Thaumaturgo, a small town three hours downstream of Apiwtxa. Its creators intended Yorenka Atame as a demonstration to the townspeople of an alternative way of living and turned the pasture into a forest full of fruit trees. Earlier, while serving as environment secretary for the town, Benki had sought to lead its youth away from drug trafficking by training them in agroforestry and inviting them to *kamarãpi* ceremonies. Using aya-

huasca is risky: its impact depends crucially on the brew and the skill and ethics of the person supervising the session. Benki hoped that with his guidance, the ritual would help the young people feel connected to nature—and it did. They helped him plant around Yorenka Atame and went on to establish a settlement called Raio do Sol, or Sunshine, where they grow their own food using agroecology.

Yorenka Atame is a place for exchanging knowledge about the forest and discussing what true development might mean. It has hosted many gatherings of Indigenous peoples and scholars from around the world. "We do not have enemies; we have partners and allies and the ones with whom we disagree," Francisco said—the Apiwtxa wish to engage everyone in dialogue. Exchanges at Yorenka Atame and in the field have helped local rubber tappers to reforest their region and stimulated the cultural revitalization of many Indigenous groups, such as the Puyanawa peoples, who had been enslaved and almost killed off by rubber barons.

Such activities have given the Apiwtxa community a huge presence and influence in the region despite its small size. Isaak Piyãko, another of Antônio and Piti's sons, became the first Indigenous mayor of Marechal Thaumaturgo in 2016. That he is among the leaders of the Apiwtxa, a community whose achievements are widely respected, probably helped his election.

In 2017 Benki and others established a related project, Yorenka Tasori (Knowledge of the Creator), with its own center. It facilitates the diffusion of Indigenous spiritual and medicinal knowledge among forest peoples and beyond. Yorenka Tasori also includes an effort to protect Ashaninka sacred sites, which are often places of great natural beauty but are threatened by roads, dams and extractive industries. As much a political as a spiritual endeavor, Yorenka Tasori seeks to revitalize traditional links among the Ashaninka as a way of restoring their historically powerful cohesiveness. In such manner—by protecting their ancestral knowledge, especially the awareness of interconnectedness with all other beings, and passing these gifts on to younger generations—the Apiwtxa hope to ensure the Ashaninka's continuity as a people.

I accompanied Benki and other Apiwtxa representatives on visits to Ashaninka sacred sites in Peru and was struck by how people were drawn to them. They had an aura of serenity and power that attracted many others, so that our group grew inexorably as we traveled. The Apiwtxa leaders inspired hope wherever they went, to the extent that the chief of one Indigenous community said, "It must have been Pawa who sent you here to open our eyes."

The Apiwtxa hope to open our eyes as well—to reach out to us with their message of unity and interrelatedness of all beings. They believe that a spiritual awareness of the underlying unity of creatures shows a way out of our epoch, marked as it is by ecological and societal crises—a time that is increasingly referred to as the Anthropocene. This geologic era derives from the relentless expansion of humankind's destructive activities on Earth, impacting the atmosphere, oceans and wildlife to the point that they threaten the integrity of the biosphere. The *anthropos* least responsible for the Anthropocene—people inhabiting the land in traditional ways—are suffering its worst consequences, however, in damage to their environments, livelihoods and lives.

The Apiwtxa propose in place of permanent economic growth and extractive industry a social and economic system in which collaboration ranks above competition and where every being has a place and is important to the whole. By looking after human and other-than-human beings and cultivating diversity through protecting, restoring and enriching life, they are pointing to a pathway out of the Anthropocene.

"This message comes from Earth, as a request for humanity to understand that we are transient beings here and one cannot just look at one's own well-being," said Benki in an appeal to the world in 2017. "We have to look toward future generations and what we will leave for them. We have to think of our children and of Earth. We cannot leave the land impoverished and poisoned, as is happening now. Today we can already see great disasters beginning to happen, people emigrating out of their countries in search of water to drink and food to eat. We see a war going on for wealth now, and soon we will see a war for water and for food.

"Shall we wait, or shall we change history? Join us!" SA

FROM OUR ARCHIVES

A Tapestry of Alternatives. Ashish Kothari; June 2021.

scientificamerican.com/magazine/sa

Others Don't Think You're a Mess

People overestimate how harshly others view them. Research shows ways to take a kinder perspective

By Anna Bruk

We all have weaknesses, and we all know hardship. But it's difficult, even on a good day, to admit we are struggling, to ask for help or to apologize when we are out of line.

After two years of overwhelming stress caused by a global pandemic, many of us have become all too familiar with feeling vulnerable, and we have also grown adept at avoiding difficult conversations. We may blow up to let off steam, for instance, and not take responsibility for the harm our actions cause. Or we may sulk when people close to us fail to guess our needs. When setting clear boundaries is in order, many of us may say "yes" to everything only to end up resenting everyone—including ourselves—for having too much on our plates.

Often the best way to break these cycles is to admit to others that we are having a hard time. That step can be excruciating and frightening, but keeping problems to ourselves can create even more long-term complications. Unacknowledged feelings and frustrations rarely stay under the rug. That is why it is important to figure out how to openly articulate one's feelings or thoughts even when that form of expression leaves us feeling exposed or uncomfortable.

Two of my University of Mannheim colleagues—Sabine Scholl and Herbert Bless—and I have investigated these shows of vulnerability: moments of genuine, intentional emotional exposure, done in spite of one's fears. Unlike other forms of self-expression or self-disclosure, these acts always carry risk, such as the possibility that others may perceive someone as weak or even incompetent in consequence. Confessing romantic feelings, for example, could provoke a painful response if these sentiments are not shared, whereas disclosing one's love for pizza is a low-stakes statement.

The good news is that, according to research, our worries about the negative evaluations of others may be exaggerated and frequently do not reflect the way people actually see us in difficult moments. Building on prior pioneering studies of vulnerability by researcher Brené Brown of the University of Houston, my colleagues and I conducted six experiments that revealed consistent results: Across a variety of situations, such as asking for help or admitting to a mistake, people perceived their own displays of vulnerability more negatively than others did. We refer to this pattern of conflicting perceptions as the "beautiful mess effect."

It's important to be aware of this mismatch because it can prevent people from sharing their true feelings and needs. In a safe environment and with a responsive conversation partner, a vulnerable stance in close relationships may have tremendous benefits. For example, studies show that revealing personal information about oneself may increase closeness and trust between partners. An authentic apology, meanwhile, could repair a fractured relationship.

Given these advantages, we next wanted to know how people could overcome the beautiful mess effect, with its differences in perception. Our new experiments suggest that the concept of self-compassion can be of great help when it comes to finding beauty in the mess of one's own shortcomings.

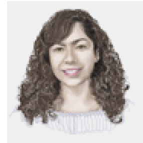
Self-compassion originated from ancient Buddhist teachings. Today's scientists, however, have researcher Kristin Neff of the University of Texas at Austin to thank for defining the concept in detailed psychological terms. According to Neff, self-compassion consists of three components. First, self-kindness entails a caring and understanding response toward one's own suffering. For instance, when someone is struggling with feelings of failure, Neff encourages people to imagine how they might speak supportively to a friend in that position and then apply similar thoughts to themselves. The second component—common humanity—refers to recognizing pain and failures as an unavoidable part of life. Finally, mindfulness entails clear awareness of the present moment—neither ignoring one's difficulties nor exaggerating their magnitude.

My colleagues and I thought that self-compassion could influence how people perceive their own display of vulnerability. After all, vulnerable situations can trigger a lot of shame and fear, and these moments are precisely when self-compassion is most helpful. For instance, consider admitting a mistake. People who treat themselves as they would treat a good friend wouldn't shame themselves for being imperfect. Instead they would remind themselves that imperfection comes with the territory for all mortal creatures. In addition, a mindful approach to the mistake would lessen the need to either exaggerate or deny its significance.

Such a compassionate reaction to one's own vulnerability, in turn, could make it easier to be vulnerable with others. As a result, we expected self-compassionate people to see their own show of vulnerability in a more positive light—closer to the way they perceive the same behavior in others. Thus, we predicted that the beautiful mess effect would be less of an issue for highly self-compassionate people.

To test this prediction, we invited about 340 university students to participate in four experiments that revolved around different vulnerable situations. In one of the experiments, participants read a text that asked them to imagine either themselves or another person of the same gender admitting to their boss that they'd made a substantial mistake while working on a project. After reading the text, participants were asked to evaluate this confession: Did they see it as an act of courage or a sign of weakness? Does showing vulnerability equal revealing

Anna Bruk is a social psychologist and postdoctoral researcher at the University of Mannheim in Germany.



one's strength or inadequacy? At the end of the study, we measured how self-compassionate the participants were using a seven-point scale designed by Neff.

As predicted, people who don't have a lot of compassion for themselves evaluated an admission of their own mistake more negatively than when they imagined others who took the same step. Highly self-compassionate study participants, on the other hand, did not fall prey to this beautiful mess effect. In their evaluations, the difference in how they viewed displays of vulnerability in themselves versus others was significantly smaller than in people lacking self-compassion.

We conducted similar experiments with different situations, such as revealing one's imperfections or confessing love to another person first. We observed the same pattern of results: with higher levels of self-compassion, participants became less likely to judge their own displays of vulnerability harshly. In other words, self-compassionate people may be less likely to fall afoul of the beautiful mess misperception across a spectrum of situations.

Notwithstanding the numerous benefits of showing vulnerability, it is, by definition, a risky business—especially for members of marginalized communities who often bear the extra burden of less psychologically safe environments. People should always be thoughtful about when and where they choose to disclose information about themselves. But without self-compassion, making oneself vulnerable—even in a safe space—can feel like self-destruction, which makes it all the more difficult to take this step. Conversely, being kinder to ourselves may give us a safe place to land, no matter where showing our vulnerability leads us. Then, we don't need to have as much faith in the notion that everything will go smoothly if we share our struggles with others. Instead we can have more trust in ourselves to handle the outcome either way.

Luckily, our level of self-compassion is not set in stone, and it can be intentionally cultivated. For example, journaling exercises can help people change the way they think about their own strengths and weaknesses by writing about one's feelings with awareness and acceptance, offering oneself words of support and reflecting on how others share difficult experiences. By developing a kind, mindful attitude toward ourselves, we can become more comfortable with showing our vulnerabilities. This practice, in turn, can strengthen our close relationships.

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Illustration by Stephanie Shafer

NONFICTION

On Thin Ice

Why do stories about polar science seem stuck in the past?

By Elizabeth Rush

On October 4, 2019, the *Polarstern,* a German icebreaker the length of a football field, sidled up to a thick ice floe above the Arctic Circle and turned off its engines. Soon the sun would set for months. The remaining open ocean around the boat would ice over, and three million square miles of liquid would turn solid in the span of a few short weeks. Were you to have peered down on the ship then, it would have looked like an almond lodged in a bar of white chocolate the size of Australia.

Dig into the fine print of our most complex global climate models, and you'll discover that we have next to no observational data from the high Arctic in winter. We know the region is warming faster than any other place on the planet, but what that means for future weather patterns, sea level, storm intensity, biodiversity (the list goes on and on) remains achingly unclear. There is growing concern, however, that estimates of just how bad it could get, and when, are too conservative. Enter MOSAiC or, as Markus Rex, the mission's leader, calls it (and, no, his tongue is not planted firmly in his cheek), "The Greatest Polar Expedition of All Time."

On the surface, the plan behind MOSAiC is simple enough: allow the Transpolar Drift, a kind of conveyor belt that moves ice across the ice cap, to carry the *Polarstern* straight through the center of the Arctic during the long polar night. By getting "trapped" in the floe, those onboard will be able to assemble a unique data set. They will record during a single calendar year what goes on in the ocean, in the air, and on the ice (where those two systems meet), creating a holistic profile of the processes that drive the birth and death of sea ice. From this information, scientists will "create a more robust model of the Arctic climate system," Rex writes.

If all of this is starting to sound a bit wonky, that's because *The Greatest Polar Expedition of All Time* is written by an atmospheric scientist rather than a nature essayist like Barry Lopez or a climate novelist like Ashley Shelby, whose 2017 book *South Pole Station* explores the way community is forged (and tested) by isolation and ice. There are no characters (beyond the author) and no conversations between those people he resides alongside. The book reads more like a ship log than it does a piece of literary reportage. If you've ever wondered what it is like to gather the information on which the IPCC reports are built, this is your front-row seat. The series of dated entries is dense with the particular drama of conducting state-of-the-art science in a place where satellites don't reach and there's nowhere to refuel (be it with candy or combustibles) when the supplies run low.

As someone who has lived on a research icebreaker (and is currently at work on a book about the experience), I took great pleasure in reading the details of day-to-day activities. On the *Polarstern,* even the most mundane tasks require planning, patience and ingenuity to execute. How does one way-find on a giant slab of ice that is drifting steadily through complete darkness? Invent a coordinate system where the ship's bow—the sin-

Illustration by London Ladd

gle most important reference point in this Seussian landscape—serves as the axis around which everything else is oriented. Want to leave the boat? Bring an armed polar-bear guard, an emergency survival kit and at least two backup headlamps. Searching for souvenirs? Make them yourself, by suspending oversized ice crystals in hardened acrylic lifted from the machine room.

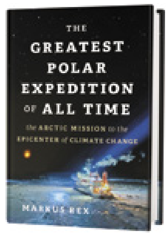
The expedition has five phases, with crew and scientists cycling on and off the boat, making its leader into the one reliable human through line. Rex's voice is endearing and antiquated in turns. There is no bluster, no boasting, no chest puffing here, just a genuinely enthusiastic scientist overseeing a season of fieldwork that has taken a lifetime to prepare. Yet in the context of writing a climate book for a wide audience (versus an academic paper slated for peer review), his passion for data collection blinkers him to how polar narratives, including his own, uphold many of the historic power imbalances that have both created the climate crisis and impeded our ability to act.

Omission plagues the polar canon, and this book is no exception. Women rarely appear, let alone speak; Indigenous peoples serve as set pieces as opposed to residents with invaluable knowledge that interlopers lack; and those whose maintenance work makes these complex logistical endeavors possible—in the form of cooking, cleaning and caring for the ship and its expedition members—lurk in the subtext, offstage.

In the century since the "Heroic Age of Polar Exploration," Earth's operating system has changed in myriad and troubling ways, as a direct result of the imperialist logic that drove those men poleward in search of fame and fortune. Yet the stories carried back from the places where these changes are most profoundly felt hasn't evolved at the same stunning clip. The tales we often celebrate showcase bearded gentlemen with lofty educations (in this case, a doctorate from the Freie Universität Berlin) boldly going where no one has gone before to achieve the seemingly unthinkable.

Blessedly, there are exceptions: Bathsheba Demuth's *Floating Coast,* which recasts the Arctic as an inhabited region of ecological plenitude; or Joan Naviyuk Kane's *Hyperboreal,* a lyrical investigation of loss and continuity on King Island, the author's ancestral home, from which her family was forcibly removed by the Bureau of Indian Affairs; or Mat Johnson's satirical novel *Pym,* a wildly subversive investigation of the racial ideologies that shape polar storytelling.

The most surprising moment in *The Greatest Polar Expedition of All Time* comes about two thirds of the way through, when the pandemic threatens to end the mission early. MOSAiC is an inherently international collaboration, with 20 nations participating, but as borders close and the icebreakers that were supposed to support the ship are sent



The Greatest Polar Expedition of All Time: The Arctic Mission to the Epicenter of Climate Change
by Markus Rex, translated by Sarah Pybus. Greystone Books, 2022 ($28.95)

home, the *Polarstern* just keeps drifting. All the meticulously laid plans—for refueling, personnel changes, refilling of the refrigerator stores—must be reimagined and fast.

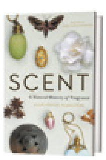
The only vessels that are eventually permitted to assist hail from the same country as the ship itself, suggesting in times of crisis (a marker with which we are certain to become more familiar in the future) global collaboration will become increasingly difficult to summon rather than easier. At some level this is something we already know to be true, having all lived through the early pandemic ourselves. But it is still unsettling to hear that of the more than 80 different institutions involved in MOSAiC, the German Federal Ministry of Education and Research is the only one able to provide the aid necessary to save this unprecedented mission.

Once the obstacles posed by the pandemic have been overcome, life on the *Polarstern* returns to "normal" rather quickly. Turbulence sensors are deployed, ice cores extracted, seismic measurements collected. Then the ice Rex and his team have lived alongside for nearly a year melts, and everyone goes home. Almost as if nothing has changed at all.

Elizabeth Rush is author of *Rising: Dispatches from the New American Shore* (Milkweed, 2018), which was a finalist for the Pulitzer Prize in General Nonfiction. She teaches creative nonfiction at Brown University.

IN BRIEF

Scent: A Natural History of Fragrance
by Elise Vernon Pearlstine, illustrated by Lara Call Gastinger. Yale University Press, 2022 ($28)

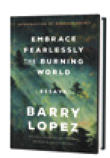


Reading *Scent* feels like going on a meandering nature walk through the history and science of fragrance, guided by a wildlife biologist turned natural perfumer. Within a single sentence, author Elise Vernon Pearlstine writes that incense "rises to the heavens to carry messages to the gods" and "pretty much always involves sesquiterpenes." Conjuring sights and sounds from text is difficult enough, but *Scent* delivers on its title in a way that Smell-O-Vision merely wishes it could do. Despite the occasional pitfall (describing multiple fragrant subjects as "mysterious" and "exotic"), the book is an evocative journey that awakens one's curiosity to an oft-forgotten sense. *—Dana Dunham*

The Red Arrow: A Novel
by William Brewer. Knopf, 2022 ($27)

The Red Arrow is somehow both a harrowing depiction of depression and a laugh-out-loud mystery about physics, psychedelics and the publishing industry. It opens on a *Frecciarossa* ("red arrow") train in Italy, where an unnamed American writer is searching for a missing physicist whose memoir he is ghostwriting to get out of debt. After years of fighting suicidal depression that he calls "the Mist," an experimental treatment with psilocybin mushrooms has set his life on an entirely new course—as long as he can find who he is looking for. At turns delightful and demanding, William Brewer's debut novel is a serpentine ride that culminates in a moving encounter between art and science. *—Adam Morgan*

Embrace Fearlessly the Burning World
by Barry Lopez. Random House, 2022 ($28)



This posthumously published collection of essays by nature writer Barry Lopez reveals an exceptional life and mind. Organized thematically, the essays center on Lopez's abiding love for the environment and his extraordinarily fine-tuned sense of place. He writes deeply nuanced reflections on locations as disparate as Antarctica and California's San Fernando Valley, interlaced with gentle meditations on art, travel, friendship, family and searing personal trauma. While certainly a testament to his legacy and an ephemeral reprieve from his death in 2020, this book is more than a memorial: it offers a clear-eyed praxis of hope in what Lopez calls this "Era of Emergencies." *—Dana Dunham*

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).

Science Takes On Bullies

Intellectual achievement does not excuse abusive behavior

By Naomi Oreskes

Early this year one of the world's most prominent scientists, Eric Lander, had to resign his position as President Joe Biden's science adviser and director of the White House Office of Science and Technology Policy. He was forced to quit because of evidence that he had bullied staff members and created a hostile work environment. Lander, a leader in the successful effort to sequence the human genome, had headed the prestigious Broad Institute of Harvard and M.I.T. before being tapped for the White House job. He now joins the ranks of other top scientists who have been sanctioned over behavior ranging from disrespect and bullying to illegal sexual harassment.

The most publicized cases have involved Title IX violations. (This is the federal civil rights statute that bars sexual harassment in educational programs that receive federal funds.) In 2015 astronomer Geoffrey Marcy resigned from the University of California, Berkeley, after a Title IX investigation found him guilty of sexual harassment, including kissing and groping students. In 2018 evolutionary biologist Francisco Ayala, a one-time president and chair of the board of the American Association for the Advancement of Science, resigned from U.C. Irvine after an investigation found that he had violated the university's policies on sexual harassment and sex discrimination, even after repeated warnings. In 2019 geologist David Marchant—who had a glacier named for him—was fired from Boston University after an investigation concluded that he had repeatedly made sexual comments and used derogatory sex-based slurs against a former graduate student. (The student also alleged Marchant pushed her down a rocky slope, although the investigation did not confirm this.) In a historic first, in 2021 the National Academy of Sciences expelled both Marcy and Ayala from its ranks. Marchant's glacier was renamed.

But not all cases fall under Title IX. As Lander's case shows, there are many forms of bad behavior in science that don't rise to the level of illegality, and perhaps for that reason colleagues often look the other way.

Why? The reasons are complex and likely include some outright sexism and a whole lot of implicit bias. But there's another problem in scientific culture that is rarely addressed: the acceptance of personal misconduct in light of high professional accomplishment.

Many academics seem to believe that brilliant people should be excused a degree of bad behavior. This can veer into an intellectual superiority complex. Arthur T. Hadley, president of Yale University from 1899 to 1921, offered this view in an influential 1925 text that argued intelligence should be "a determining factor" in deciding on allowable personal conduct. The greater your brainpower, the greater your right to do as you please.

Hadley is mostly forgotten, but his attitude persists. It helps to explain why academics often rally around bullies with arguments about how accomplished they are as geologists, biologists, anthropologists or even literary theorists. This is a logical error: it conflates intellectual greatness with human decency, which are, clearly, two different things. It also may help explain a pattern common in these cases: that some people close to the culprit insist they never witnessed anything like the alleged behavior. In the Marchant case, a fellow geologist who had worked with him for 11 years insisted the accusations were "inconsistent" with his experiences. But Marchant may have behaved well around those he respected, while acting badly toward people of lesser professional stature.

Call it the Raskolnikov effect after the law student in Fyodor Dostoyevsky's *Crime and Punishment,* who justified theft and murder because he believed the crimes would let him overcome his poverty and fulfill his exceptional intellectual potential. Bullying is not murder, but the mindset that motivated Raskolnikov often undergirds other forms of antisocial behavior, and surveys show this kind of personal abuse in science is widespread.

It is an important step forward when the research community holds its most prominent members accountable for their actions. It's not unfair, inappropriate or an overreaction. It's about time.

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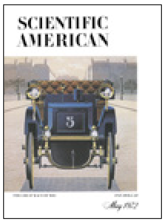
MAY

1972 Don't Stare at Me

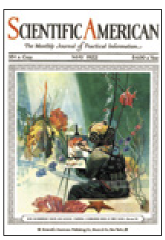
"To what extent is staring an aggressive stimulus in human interactions? A group of psychologists at Stanford University had confederates stand at street corners and stare at people who were waiting for the traffic light to change to green. People who realized they were being stared at crossed the intersection faster than people who were not being stared at. The discovery opens up some interesting lines of research. Is a stare always perceived as a threat, even in the absence of other aggressive cues? Perhaps a stare is interpreted as an invasion of personal space rather than hostile intent."



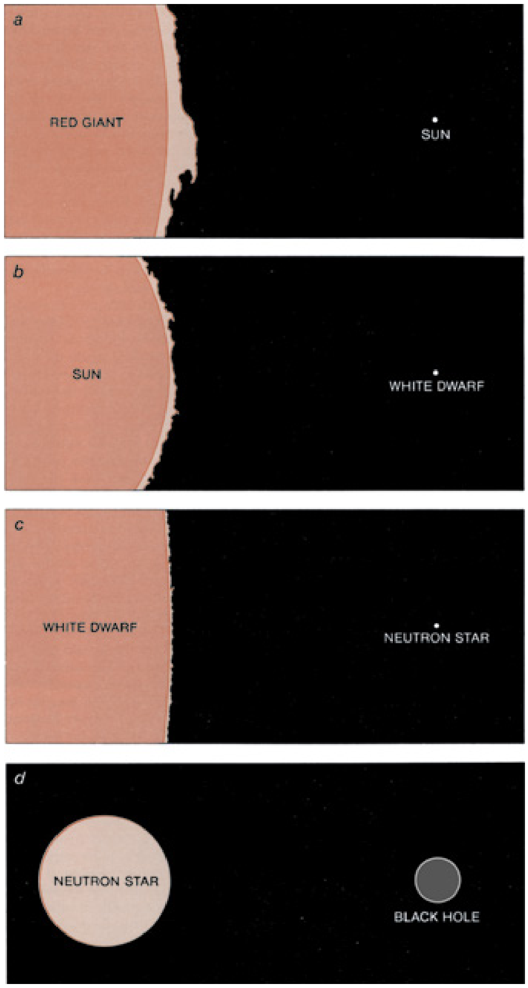
1972

1922 Public Radio

"We are making substantial progress toward telephony from ship to shore. Recently an official of the Bell System was called at his residence in New Canaan, Conn., by Captain Rind, who was on his ship the 'America,' about 370 miles distant. Over 100,000 persons heard the conversation, because the radio link that connects the wire telephone system with the ship radio set makes use of radio waves that may be intercepted with amateur radio receiving sets. A telephone message, once given to the radio transmitter for propagation through the air, is virtually public property. As upwards of one-half million radio amateurs throughout the country know, it is the simplest matter to listen in. However, there are ways in which secrecy may ultimately be obtained for the radio link of a telephone system."



1922



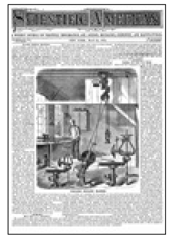
1972: The sun is compared with potential future stages: red giant, then white dwarf, then neutron star. "The red giant (*a*) is 250 times larger than the sun. The sun (*b*) has 100 times the diameter of a white dwarf (c), whose diameter is about 700 times greater than the neutron star. That star has only to collapse to a third of its diameter to form a black hole (*d*), no more than four miles across."

Denial, Pre-*Hindenburg*

"There can be no question that the tragic loss of the 'Roma,' following all too closely upon the disaster to 'ZR-2,' has raised doubt as to whether lighter-than-air ships are practicable and safe. In the presence of such disasters it is easy to draw conclusions that are not justified by the facts. Bearing this in mind, we venture to state that there is nothing so far disclosed with regard to the wreck of these two ships which justifies the belief that transportation by this means is a dream which can never be realized on a large and profitable scale."
The spectacular fireball that consumed the LZ 129 Hindenburg *on May 6, 1937, effectively ended the age of airship travel.*

1872 Vesuvius Erupts Again

"The volcano of Mount Vesuvius, near Naples, in Italy, has lately broken out with violent eruptions of lava, completely destroying some of the mountain villages. The lava streams advanced at the rate of three fifths of a mile per hour. Lightning darted incessantly from the summit, and the quakings of the mountain were violent and frequent. Burning cinders, stones, and scoriae fell fast and thick in the surrounding towns. This is the most destructive eruption that has taken place since 1631."
Vesuvius has erupted many times since it consumed Pompei in C.E. *79. Its most recent significant eruption was in 1944.*



1872

Here There Be Dragons

"Among the remains discovered last year in Kansas by Professor [Othniel Charles] Marsh and party were bones of the flying dragon. Marsh judges that the dragons must have measured, from tip to tip of their extended wings, some twenty feet."
Later work concluded Marsh had found some of the first pterosaur fossils in North America.

Exploding Pills

"Some pills prescribed by a physician in England contained one half grain nitrate of silver, one sixth grain nux vomica [a tree extract], and one half grain muriate of morphine, together with conserve of roses and extract of gentian [an herb]. They exploded in a very short time, evolving a considerable amount of heat. A similar case occurred in the practice of Dr. Jackson, of Nottingham, who prescribed pills containing four grains of nitrate of silver, one grain muriate of morphia and extract gentian. The patient, who had the box about her person, was badly burned."

Scientific American, Vol. 226, No. 5; May 1972

Text and Graphic by Katie Peek

A Checkup on the World's Coral Reefs

The prognosis isn't *all* bad

The United Nations recently released a sweeping report on the health of the planet's coral. Healthy reef cover—where squishy polyps and colorful algae coat the white skeletons of hard coral—has dropped 14 percent in the past decade. Coastal development, ocean plastic pollution and overfishing all take their toll, allowing destructive algae to proliferate.

But warming oceans, which bleach coral, are the biggest threat to reefs worldwide. The all too familiar story has a few bright spots, however. Coral rebounded after major bleaching events in 1998 and 2005, showing recovery is possible. And the most biodiverse coral in the world—the so-called Coral Triangle in the western Pacific Ocean—is holding its ground.