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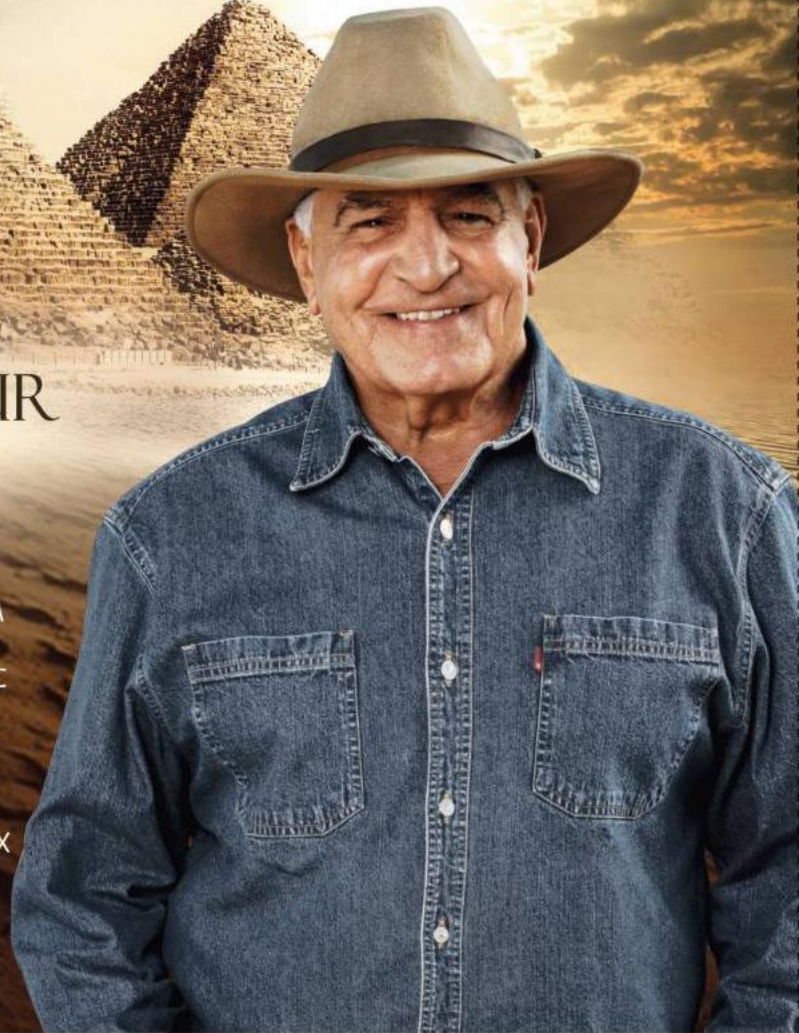
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Photograph by Gaby Barathieu.

SCIENTIFIC AMERICAN



Thomas Fuchs



DSPhotography/CP/Getty Images



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

Good Habitats

Humpback whales hunt using one of the most hilarious strategies in nature. Groups of whales swim in a circle around their prey ... and blow bubbles. As the bubbles rise, they form a column that acts as a virtual net and concentrates prey. The whales swim upward in a spiral, spewing bubbles all the way, then lunge into the center of the column to grab an enormous mouthful of krill. But how do these gigantic creatures find patches of tiny krill in the first place? *Scientific American's* evolution and ecology senior editor Kate Wong went to Antarctica with a group of scientists studying a chemical that may give whales a scent of supper. The research, helped along by citizen scientists taking cruises to Antarctica, could help predict endangered whales' behavior and save them from ship collisions. We hope you enjoy our cover story, starting on page 26, almost as much as Kate enjoyed her reporting adventure.

It's hard to wrap your head around imaginary numbers. Unlike "real" numbers, they don't refer to physical quantities. But maybe in some sense they do? Imaginary numbers produce a negative number when multiplied by themselves. Complex numbers (which are a combination of real and imaginary numbers) have been useful in quantum theory, but many physicists assumed they were just a mathematical convenience. Physicists Marc-Olivier Renou, Antonio Acín and Miguel Navascués recently created tests of quantum theory that show imaginary numbers are necessary for certain predictions (page 62). What does it all mean for the nature of reality? They're still working on that.

We've been talking a lot at *Scientific American* HQ about the risks and potential rewards of artificial-intelligence programs that can generate text. This is a Very Serious Issue with implications for copyright, plagiarism, misinformation, and more—but it can also be funny. Our editors conducted an [online Q&A](#) with the AI ChatGPT and asked it why it should be regulated. (It correctly

pointed out that its own "level of sophistication raises concerns about the potential for ChatGPT to be used for nefarious purposes, such as impersonating individuals or spreading misinformation.") On page 68, computer scientist Giacomo Miceli explains how and why he created an "infinite conversation" between two AI chatbots trained to impersonate filmmaker Werner Herzog and philosopher Slavoj Žižek, who are perfect targets of a goofy but illuminating fake. (Chickens are involved.)

Have you ever worked in an open office? We're hoping to hear from readers about their own office experiences in response to *Scientific American* contributing editor George Musser's story on page 36. (George worked alongside many of us years ago in our first open-plan office.) Many people hate them—the lack of privacy, the noise, the germs. But they don't have to be so dehumanizing, and designers are using insights from people who are deaf or autistic to build more welcoming and productive office habitats.

Leopards have made human habitats their own. On page 50, ecologist Vidya Athreya shares her fascinating career studying leopard behavior in India, with a goal of protecting both the big cats and the people they live among. It reminds me of research on coyotes in Chicago—both types of carnivores stay in the shadows during the day and roam at night, effectively time-sharing densely populated cities. The gorgeous photos also tell the story well.

Chien-Shiung Wu was the first scientist to document entangled photons, or what Einstein called "spooky action at a distance." It's not your fault if you haven't heard of her—she was passed over for a Nobel Prize in 1957 in one of the many discriminatory injustices in the award's history. Last year's physics prize honors research that built on her groundbreaking studies, and it's a great time to appreciate her rightful place in science. Turn to Michelle Frank's article on page 42. If you enjoy podcasts, we publish an ongoing series called "[Lost Women in Science](#)" that is full of brilliant characters, like Wu, whose work is just now being rediscovered. 📖

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December 2022

TELESCOPE OF THE UNIVERSE

Your special report on “A New Era for Astronomy” includes several photographs from the James Webb Space Telescope (JWST). In one article in the report, “Behind the Pictures,” by Clara Moskowitz and Jen Christiansen, science visuals developer Alyssa Pagan of the Space Telescope Science Institute comments on how scientists turn raw data from the telescope into images that give a truer representation than what our naked eye can see.

I was stunned by these photographs, first by their beauty and second by the six-pointed stars around bright objects. I am guessing the latter are artifacts resulting from the construction of the telescope. I am also guessing the photo-processing software used to make the images includes an option for removing them. Are perhaps the images given to astronomers made with such an option on? What is the truth about those pretty six-pointers?

By the way, the six-pointers provide an easy way to tell a JWST photograph from a Hubble image: publicly available Hubble photographs have four-pointed stars.

THOMAS R. KRAMER *via e-mail*

The article on the components of JWST was excellent. The marvelous photographs made me feel very small, however—many magnitudes as small as a subatomic particle. It’s an old, big universe out there.

MIKE MAFFETT *Lake Burton, Ga.*

“It is good to see that autism therapists are coming to realize how harmful forcing conformity can be.”

JAMES W. SCOTT VERNON, N.J.

PAGAN REPLIES: Kramer’s intuition is right in that these spikes are caused by the construction of the telescope. Technically, there are eight diffraction spikes in total: the prominent six spikes he mentions, which are the result of the light diffracting off the edge of each side of the primary hexagonal mirror, and two smaller horizontal spikes, which are caused by the light interacting with the two struts holding the secondary mirror. How this pattern arises is described further in an infographic entitled “Webb’s Diffraction Spikes” that you can find at webbtelescope.org.

As of late, the calibration pipeline has no feature for removing the spikes. This kind of distribution of light from a single-point source is called a point spread function (PSF) and is unique to each optical system. While not infeasible, it is difficult to model and subtract such a complex PSF across an entire image. When the pattern obscures crucial information in a specific target that takes up most of the field, however, the scientists or image processors will go in and manually remove the PSF. Otherwise, we allow JWST to differentiate itself with its eight-spike signature.

NEURODIVERSITY

I found it interesting to read “Rethinking Autism Therapy” [The Science of Health], Claudia Wallis’s piece on how autism treatment is moving away from “fixing” the condition. I applaud the approach of allowing people to be who they are and commend the idea that society needs to work harder at accepting neurodiversity. In emphasizing past and current views about attempts to change behaviors, however, the piece may imply that applied behavioral analysis (ABA) is the only therapeutic model available. It seems to ignore therapies such as relationship development intervention (RDI), which allows for more flexibility on the part of the autistic person and those around them while helping them understand more about how so-

cial and other situations work, rendering those situations less confusing.

It would be appropriate to have a more balanced look at which autism therapies actually work to the advantage of the person in therapy, not just the perspectives of those who are looking in from the outside.

MIRIAM DUMAN GOLDBERG *via e-mail*

It is good to see that autism therapists are coming to realize how harmful forcing conformity can be. As a person on the spectrum myself, I hope that this can be communicated to the general population as well. Attempts to force changes in the way of thinking can create depression and quash creativity.

JAMES W. SCOTT Vernon, N.J.

TRAUMA AND EXPERIENCE

In “An Invisible Epidemic,” Elizabeth Svoboda discusses a type of trauma caused by a person’s core principles being violated, such as during wartime. This “moral injury” sounds like a way of life for many people. Gay and transgender people have to constantly adjust responses to external cues, circumstances and attacks. Over a long period of time, this can weigh heavily.

If the psychologists mentioned in the article would interview some older gay and trans people, they may find the coping mechanisms and support strategies these individuals have used to be helpful, which could move their own research on treatments forward.

STEVEN CAIN *Irving, Tex.*

COSMIC QUICK START

Jonathan O’Callaghan’s article “Breaking Cosmology” successfully describes JWST’s flurry of images of surprisingly early galaxies and possible explanations for them. I also commend the author’s brief comments on how the rush to publish these findings suggests a more efficient and faster peer-review process.

JAMES CARLISLE *Atascadero, Calif.*

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According to O'Callaghan, JWST data show early galaxies that seem too large and well developed for their age. I recall other *Scientific American* articles describing supermassive black holes that also seemed too large for their early times. Which came first? Could precocious supermassive black holes have contributed to the precocious development of galaxies?

K. CYRUS ROBINSON *armONx*,
Tampa Bay, Fla.

The article describes 120 million years as "a cosmic blink of an eye." This would be 0.87 percent of the universe's age of 13.8 billion years. An eyeblink of 0.1 second is 0.000000045 percent of three score and 10 years of life. Perhaps "a long winter's nap" might be a closer metaphor.

BILL CIPRA *via e-mail*

O'CALLAGHAN REPLIES: *Robinson asks a good question. The simple answer is that we don't know. We see supermassive black holes at the centers of nearly all large galaxies, but how such black holes formed so early in the universe is an open question. It's unclear whether they formed within already grown galaxies or were instead the seeds of such growth, perhaps created by the collapse of supermassive stars in the early cosmos.*

MIND OVER MATTER

"Constructing the World from Inside Out," by György Buzsáki [June 2022], explores how perception of our physical surroundings occurs in the brain. An even more puzzling question is how the brain constructs worlds that cannot be perceived by the senses, as Plato demonstrated in his dialogue *Meno*. This was also mysterious to Albert Einstein, who said in a 1921 lecture, "How can it be that mathematics, being after all a product of human thought which is independent of experience, is so admirably appropriate to the objects of reality?"

TONY JOHNSON *San Rafael, Calif.*

ERRATUM

"Overdose of Inequality," by Melba Newsome and Gioncarlo Valentine, included an image caption that erroneously referred to physician Edwin Chapman as Edward Chapman. His name was given correctly in the main text.

Use Nature as Infrastructure

In the climate crisis, wetlands have more economic value than new development

By the Editors

Coastal cities worldwide are squeezed by two opposing forces: urban sprawl and the rising sea. This struggle is intensely visible in the flatlands of South Florida, where burgeoning neighborhoods routinely flood and saltwater inundation damages the estuaries that protect communities from the worst of our climate crisis.

Massive resources are being put into environmental restoration projects there, and development is subject to many layers of approvals. Yet in 2022 the Miami-Dade County Commissioners voted to expand a legal boundary that contains sprawl to allow a 400-acre warehouse project. They are failing to see the value of this land in the greater ecosystem: pave over it, and you'll cut off waterways that sustain a critical buffer against flooding and erosion.

Wetlands, coastal plains, sand dunes, forests, and many other permeable surfaces do cheaply (or even for free) what engineered levees, seawalls and pumps do at a cost of billions of dollars. They protect the land around them from storm surge, flooding rains, erosion and pollution. They are vital infrastructure that makes us more resilient against climate change, and the cost of destroying them or weakening their ability to function must be factored into the decisions we make to build and grow.

To do so, the economic incentives to develop any natural landscape should be weighed against the protective economic value that land already provides. Economists call this an "avoided damage" valuation. Local planning boards might consider the value of a sand dune, oyster reef or swamp in flood protection versus the expense of replacing it with a seawall and water pump system. How do these "ecosystem services" fare against the cost of, say,

30 years of emergency operations, utility failures and repeated rebuilding? Maintaining and restoring natural infrastructure to support healthy functioning saves money, time and lives.

The concept of "natural capital," or the idea that ecosystem services should be valued in a similar manner as any form of wealth, dates back to the 1970s. Markets have always valued timber as a commodity, for example, but not the services that came along with producing it, such as soil maintenance, carbon storage, erosion control and nutrient cycling. We didn't need a market for resources that industrialists saw as abundant and endlessly renewable. This exploitative assumption turned out to be very wrong. Failing to measure the benefits of ecosystem services in policy and management decisions is a major reason many of those ecosystems disappeared. In one of many recent corrections to earlier misunderstandings of the value of nature, a 2021 World Bank report said that natural capital should redefine wealth.

Climate change makes the undervaluation of ecosystem services more dangerous. Wetlands that mitigate flooding in a community during rare deluges will have far more economic value in 2050 when damaging storms arrive more frequently. The value of a preserved forest is unfathomably large when it prevents new pathogens from emerging and spinning out into a pandemic. Clearly, monetary valuation of nature is tricky to estimate and has practical limits. It's also highly site-specific, with the protective value depending on the surrounding density of people, industries and infrastructure. It would be difficult to create a template that would help all types of municipalities crunch the math on natural assets.

It also seems crass to place a dollar amount on ecosystems that we'd rather view as priceless, existing for their own sake and valuable to humans in ways that transcend capitalism. This preciousness is ethically sound. But developers have long conflated pricelessness with worthlessness, allowing them to profit without paying for the consequences of destroying the environment. It's impossible to avoid difficult trade-offs between development and conservation—we cannot ignore the affordable housing crisis in the U.S., for example. The case for preserving nature as infrastructure, however, aligns with what many urban planners

are calling for as solutions: moving away from single-family zoning restrictions to allow for multifamily and mixed-use construction and communal spaces that reduce car dependency. Basically, less sprawl.

Economic value is never the only reason nature is worth preserving; it is simply a powerful, underused tool to help us make decisions about how to live more sustainably in a climate-changed world. If policy makers considered natural infrastructure in the language of economics, they might recognize just how deeply we rely on it. ■

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Michael W. Howard is a professor emeritus of philosophy at the University of Maine, as well as former president of the U.S. Basic Income Guarantee Network, past co-editor of *Basic Income Studies*, and co-editor, with Karl Widerquist, of two books on Alaska's Permanent Fund Dividend.

Universal Basic Income Evidence

A monthly payment could lift people out of poverty without increasing unemployment

By Michael W. Howard

The temporary expansion of the Child Tax Credit during the COVID pandemic was a major win for the U.S., lifting 3.7 million children out of poverty in December 2021 without significantly reducing parents' work participation. The expansion increased the amount of the payment and made it periodic rather than a single lump sum. It also ended the work requirement for parents. This positively affected one third of all children in the U.S. and even higher percentages of Black and Hispanic children, many of whose families were formerly excluded because the parents earned too little to qualify for the tax credit.

Despite its success, the credit's expanded benefit expired in January 2022, plunging those children back into poverty. Still, the legislation remains an important political milestone: Congress came close to permanently abandoning parental work requirements as a condition for cash assistance for families.

The Child Tax Credit expansion was one step toward a universal basic income, or UBI. This kind of policy could eliminate poverty, benefit tens of millions of people and save hundreds of billions of dollars by reducing the social costs of poverty.

A UBI is defined as "a periodic cash payment unconditionally delivered to all on an individual basis, without means test or work requirement." The Child Tax Credit can't be considered UBI because it is only for families with children whose means fall within a set range. A more ambitious bill, introduced by Representatives Rashida Tlaib of Michigan and Mondaire Jones of New York,

would eliminate the means test, thereby creating a universal child allowance.

Universal benefits have several advantages over means-tested benefits. They remove the stigma associated with targeted benefits, increasing uptake. Universal benefits tend to be more popular and thus are more politically secure and better funded. And dispensing with means testing makes them easier to administer. The universal child allowance would enroll all children at birth so no child would be excluded.

As an example of how such a system can work, Alaska has enacted a Permanent Fund Dividend, an annual cash payment that goes to nearly every resident without a means test or work requirement. Decades of evidence show that it contributes to poverty reduction and has no negative effect on people's willingness to work.

In the U.S., a universal child allowance and Social Security for seniors would mean that the two most vulnerable age groups in our population would have reliable income. Extending a basic income to the country's remaining adults faces more serious hurdles, such as the widely held belief that able-bodied adults should work for their income. But studies from the U.S. and Canada, among other research, support the idea that few people who receive a guaranteed income actually leave the workforce. Those who stop working for wages do so for good reasons, such as to finish high school or to care for young children. A modest guaranteed minimum income can help people pay for child care or transportation, making work outside the home possible for some who otherwise could not take it on.

We should also challenge the assumption that every able person receiving cash payments ought to be seeking a job. Traditional jobs are not the only form of work. Taking care of children and elders is work—performed mostly by women without compensation. UBI is a way of supporting and recognizing that work without intrusive state monitoring and reinforcement of gendered divisions of labor.

Moreover, income differences are only partially determined by individuals' efforts; much comes down to luck, such as the family one is born into, unfortunate accidents or unrecognized disabilities. A guaranteed minimum is one way to even out the luck, benefiting the unfortunate with some help from the fortunate.

To the extent that the mere fact of "churning"—money going out to everyone only to be taken back in taxes from some—is an obstacle to political support, a means-tested guaranteed income may be the more politically feasible policy, but it lacks some of the advantages of universal programs. In the meantime, if a truly universal child allowance is eventually adopted, it could build support for UBI down the road. ■

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ADVANCES



Rock hyrax excrement over tens of thousands of years holds crucial climate clues.

- “Organ-on-a-chip” models crucial vaginal microbes
- New genes get a tiny synthetic cell moving
- Strange material flouts rule of thermal physics
- Magnetic fields shape galactic structure

PALEOCLIMATOLOGY

Urine Luck

Stone Age critter pee could help solve a puzzle of ancient human development

High on a sheer cliff in South Africa’s Swartberg mountain range last September, University of Utah paleoclimatologist Tyler Faith finally reached something he hoped might solve one of anthropology’s stickiest mysteries. His target looked like goo that had oozed from the sandstone cliff and hardened into a foot-thick slab of black amber. Gas mask on, Faith got to work hewing away a 70-pound chunk; dust flung from his chainsaw quickly filled the air with a yellow-gold haze.

“It just gets in your pores,” Faith says. “The second you jump in the shower and that stuff finally rehydrates, it’s like: Imagine the most stinky alleyway where people have been peeing. It’s awesome. But yeah. All my gear now smells like pee.”

The substance is fossilized urine from untold generations of marmotlike critters called rock hyraxes—and it acts as an excellent record of the ancient climate. Sticky and viscous like molasses, hyrax urine hardens quickly in air. It traps pollen grains and charcoal, telling scientists when particular plants grew and wildfires raged. It also preserves chemical isotopes indicating precipitation and temperature. And the neat layers of the urine mounds or “middens,” which form where the animals habitually relieve themselves, can be precisely radiocarbon-dated.

Faith and his colleagues are using these clues to investigate controversial links



DS Photography/CP/Getty Images

between ancient climate change and a dramatic technological leap that occurred between 66,000 and 25,000 years ago, from the Middle to the Later Stone Age: that's when our early ancestors developed new [tools and cultural strategies](#) that modern hunter-gatherers still use today. The researchers are using hyrax middens to build a high-resolution regional climate history for South Africa, where a team of students and scientists from across the continent is also re-excavating Boomplaas Cave—one of very few places with a rich archaeological record of humans' transition into the Later Stone Age.

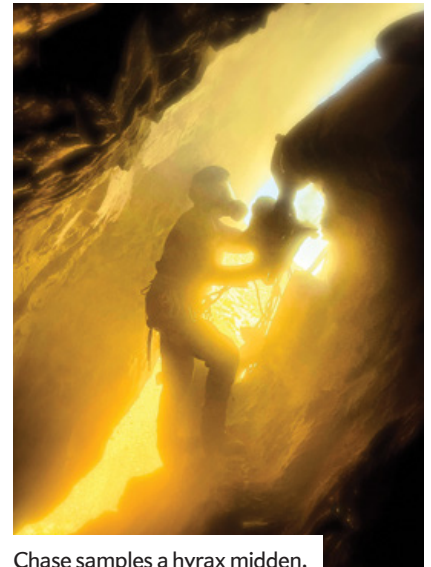
"It's really a period where the lights get turned on in terms of complex social and technological behavior," says the team's excavation leader Justin Parteger, an archaeologist at New York University and the University of Johannesburg. "The behavioral innovations across this transition were highly successful. And they led to our species really starting to dominate the ecosystems that they lived in."

Later Stone Age people seem to have started making a priority of "economizing something," says University of Michigan anthropologist Brian Stewart, who is not

involved in the research. Whether limited by raw materials, time or perhaps their tool kit's weight, people of this time began crafting smaller, more modular stone tools whose "bladelets" could be swapped out like today's replaceable drill bits. Symbolism and social organization advanced, too: Parteger notes that Later Stone Age sites are full of beads, which could be used to signal belonging and identity, as well as ocher, a clay pigment used to paint bodies and add identifying symbols to objects.

The Later Stone Age began in the run-up to the peak of the last Ice Age, and many researchers think the period's climate could have contributed to humans' technological and behavioral changes. Some propose that an increasingly volatile climate may have forced our ancestors to get more creative at effectively exploiting resources. But this is tricky to rigorously prove, particularly because in much of Africa the transition began just beyond the limit of radiocarbon dating—which doesn't work well for samples more than 50,000 years old. Without accurately dated archaeological material, it's impossible to draw clear lines between climate events and technology.

Boomplaas Cave offers a way around



Chase samples a hyrax midden.

this problem. The transition out of the Middle Stone Age began later there, so the cave's artifacts are within reach of accurate radiocarbon dating. And Boomplaas is one of few archaeological sites on Earth with a continuous record that spans the transition. But researchers here face another challenge: South Africa's sparse climate history.

"We don't have traditional archives like

Tyler Faith

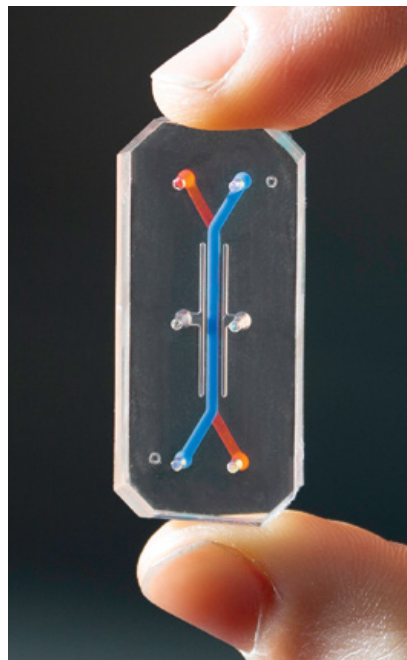
BIOTECH

Personal Space

A new chip re-creates the human vagina's unique microbiome

Scientists have developed what they say is the world's first "vagina-on-a-chip," which uses living cells and bacteria to [mimic the microbial environment of the human vagina](#). It could help test drugs against [bacterial vaginosis \(BV\)](#), a common microbial imbalance that makes millions of people more susceptible to sexually transmitted diseases and increases risk of preterm delivery during pregnancy.

Vaginal health is difficult to study in a laboratory setting, partly because study animals have "totally different microbiomes" than humans do, says Don Ingber, a bioengineer at Harvard University's Wyss Institute for Biologically Inspired Engineering. To address this, he and his



colleagues created their unique chip, described in the [journal *Microbiome*](#): an inch-long, rectangular polymer case containing

live human vaginal tissue from a donor and a flow of estrogen-carrying material to simulate vaginal mucus.

[Organs-on-a-chip](#) like this one mimic bodily functions, making it easier to study diseases and test drugs. Previous examples include models of the lungs and the intestines. In this case, the tissue acts like that of a real vagina in some key ways; it even responds to changes in estrogen by adjusting the expression of certain genes. And it can host a humanlike microbiome dominated by "good" or "bad" bacteria.

For example, a lot of the time "*Lactobacilli* bacteria keep your vagina nice and acidic," says Ruth Mackay, who works on organs-on-a-chip for women's health at Brunel University London and was not involved with the new study. But if other bacteria such as *Gardnerella* take over, she says, it can "disrupt that *Lactobacilli*," which can lead to BV.

Ingber and his colleagues have demonstrated that *Lactobacilli* growing on the chip's tissue help to maintain a low pH by producing lactic acid. Conversely, if the researchers introduce *Gardnerella*, the chip

Wyss Institute, Harvard University

ice cores or [cave deposits] and lake records,” says the research team’s pollen expert, paleoecologist Lynne Quick of Nelson Mandela University. “So before the hyrax midden stuff, we had very limited and discontinuous records.”

Most attempts to link climate change to the Later Stone Age transition have focused on measurements from polar ice cores and deep-sea sediments. But these materials primarily reveal general, global climate trends. As with anthropogenic climate change today, ancient climate change affected different areas in different ways. Faith says South Africa’s paleoclimate is still so little known that it’s unclear whether the region was dry and harsh or wet and lush at the peak of the last Ice Age.

Team member Brian Chase, a paleoclimatologist at the University of Montpellier in France, saw a possible solution to this puzzle in hyrax middens, where these small mammals—which look like rodents but are more closely related to elephants—have dutifully returned to do their business for millennia. Chase has devoted his career to unlocking these overlooked data troves and has collected hundreds of samples from southern Africa. “Personally, I think

they’re the best paleoenvironmental archives on the planet,” Chase says. “It is a uniquely rich resource.”

These middens are “beautiful” archives, Stewart says, because they can be radiocarbon-dated along with the nearby Later Stone Age transition artifacts. “These are continuous records, and that’s an amazing thing to have—just like the ice cores, but they’re right next to your site.”

“This is the way we’re going to actually move forward,” he adds, “instead of making these kind of wavy pronouncements about what the climate is doing at a global level.”

Faith, Chase and Quick sampled middens near Boomplaas Cave last September and received the first radiocarbon dates from the samples earlier this year. Combining the continuing Boomplaas excavations with their unconventional climate record, the researchers say, offers a real shot at finally unraveling the contentious links between climate and technological change in the Later Stone Age—and beyond.

“There’s this whole other sphere of questions that we’re going to be able to jump into by having those giant blocks of pee to play around with,” Faith says. “We hope it’ll be useful to a lot of people.” —*Elise Cutts*

develops a higher pH, cell damage and increased inflammation: classic signs of BV. In other words, the chip can show how a healthy—or unhealthy—microbiome affects the vagina.

The next step is personalization. Ingber says his team has already begun to study volunteer individuals’ varying microbiomes by loading their personal bacterial communities onto chips using vaginal swabs.

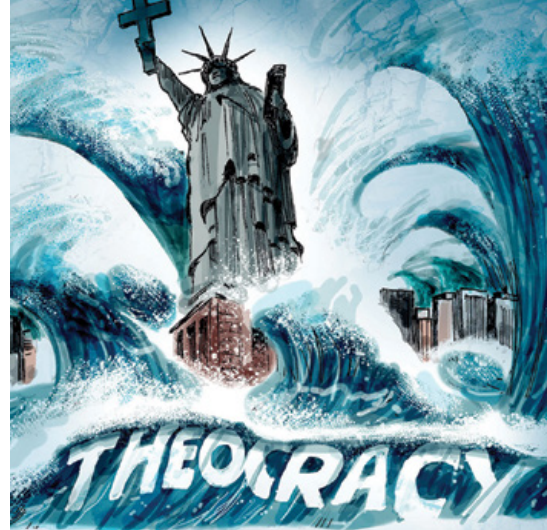
The chip is a significant leap forward, says sexual health physician Achyuta Nori of St. George’s, University of London, who was not involved with the study. “It could change how we practice medicine,” he says. Nori is particularly excited by the prospect of testing how typical antibiotic treatments for BV affect the different bacterial strains. Currently “the quality of evidence for most women’s health [issues] is very, very poor,” he says. “This is an opportunity to bring women’s health into the modern times, using modern technology.”

Critics of organ-on-a-chip technology often raise the point that it models organs in isolation from the rest of the body. “It

does have its limitations,” Mackay says. For example, many researchers are interested in vaginal microbiome changes that occur during pregnancy because of the link between BV and labor complications. Although the chip’s tissue responds to estrogen, Mackay is not convinced it can fully mimic pregnancy without feedback loops involving other organs.

Ingber says that for simulating processes such as pregnancy, researchers “may not need all the other complexity that people assume is important.” Still, his team is already working on connecting the vagina chip to a cervix chip, a combination that could better represent the larger reproductive system.

Even if some applications require more development, Mackay is thrilled that the chip is a reality. Beyond being a promising technological advance, she says, the interest of someone like Ingber—whom she calls the “godfather” of organ chip technology—may help normalize research on vaginas. “There shouldn’t be any stigma around it,” she says. “But there is.” —*Ida Emilie Steinmark*



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Laser in action above Säntis

TECH

Striking Back

Scientists fire lasers at the sky to control lightning

Lightning strikes about 40 million times in the U.S. every year. This natural phenomenon is terrifyingly random, and we rely mainly on lightning rods—a nearly 300-year-old technology—to deal with it. But researchers are exploring a more 21st-century solution: laser beams.

Pioneered by Benjamin Franklin, the lightning rod works well to defend a building. But it has limited ability to protect larger swaths of land or sprawling facilities such as wind farms, airports and rocket launch pads. So, for a study in *Nature Photonics*, a team of scientists tested a high-powered laser to guide lightning strikes atop a mountain in Switzerland. This “laser lightning rod” technique could one day deflect strikes from important large-scale infrastructure, the research team says.

“What they’ve done is very impressive,” says Jerry Moloney, an optical scientist at the University of Arizona, who was an early pioneer of this laser application but

was not involved in the study. It’s “a very, very sophisticated setup.”

Lightning occurs when friction among water droplets and ice crystals creates a static electrical charge within clouds, usually during storms. This electricity builds and eventually discharges, propelling giant sparks either upward or downward along the path of least resistance between the cloud and the ground. Regular lightning rods are made of conductive metal; they provide a preferential point for the lightning to strike and then safely channel the charge around a building and into the ground. But metal is not the only way to lure lightning away from vulnerable targets.

In the new experiment, a high-powered laser turns a column of air into an electrical conductor. When the laser fires, it separates electrons from air molecules in the beam’s path, creating charged particles in a process called ionization. This transforms the air, which is typically insulating, into an attractive point for the lightning to hit—effectively creating a towering, temporary and controllable lightning rod in the sky above the area to be protected. Scientists have dreamed of building laser lightning rods for decades, but previous experiments

largely failed. Older lasers could pulse only around 10 times per second, too slow to keep an air column ionized, explains Aurélien Houard, a physicist at the École Polytechnique in France and lead author of the study. The laser used in the study can fire 1,000 times per second, with each pulse lasting one trillionth of a second.

“You can burn stone if you want with this laser,” Houard says. It consumes about 10 kilowatts per hour: roughly the electricity required to operate a commercial oven or seven domestic space heaters, adds the paper’s senior author Jean-Pierre Wolf, a physicist at the University of Geneva.

The researchers tested their laser’s lightning-drawing ability atop Säntis, a prominent peak in the Swiss Alps chosen because lightning often hits a telecommunication tower at its summit. There, during the summer of 2021, the team recorded preliminary results while observing 16 lightning strikes, four of which occurred while the laser was powered on. And in all four cases, sensors—either a high-speed camera or a high-frequency electromagnetic wave detector—captured the lightning following the beam’s path. The authors hope to fine-tune the technique with more data from future studies.

“The next step will be closer to the real-world applications,” Wolf says, “basically redoing this experiment, say, close to a launch pad or close to an airport.”

Lightning strikes at airports are an “ongoing issue,” and they not only delay flights but also can injure or kill employees and travelers, says Irene Miller, an aviation researcher at Southern Illinois University, who was not involved in the study. Most airports currently rely on early-warning systems to prevent planes from taxiing or landing when the risk of a strike is high.

It remains unclear how laser lightning rod technology might be adapted to this setting; even tiny lasers aimed at the sky are notoriously dangerous to pilots. During their recent mountaintop experiment, the researchers worked with aviation authorities to designate a no-fly zone around Säntis. Narrow, temporary no-fly zones and an auto-shutoff function when planes are in range could potentially address safety concerns, the study authors say.

For now, though, Benjamin Franklin’s innovation will have to do. —Allison Parshall

VIROLOGY

Pet Viruses

Dogs teach an old virus new tricks

Mutant strains of a common human flu virus have been found in dogs for the first time, prompting concerns that such viruses could start to spread easily among pets—and potentially evolve into dangerous new strains that jump back to humans.

Nanjing Agricultural University virologist Shuo Su and his colleagues identified two dogs in southern China with different mutant strains of the influenza C virus, which infects almost all humans—mostly as children—and usually causes mild illness.

The researchers genetically sequenced these strains and found that mutations affected their structure near the part that binds to a host's cells. These changes mean "it might be on the way to replicate better in dogs," says Freie Universität Berlin biochemist Michael Veit, a co-author on the new work. People sometimes pass flu viruses to a pet dog, where the contagion typically stops. But the newly found strains' particular mutations suggest that they more likely spread from dog to dog, Veit says.

Although most adults have already been exposed to influenza C, the researchers say we might have little immunity against a new strain that jumps back to humans after mutating in animals. For a letter published in the Journal of Infection, the scientists describe this finding and say

it shows that viruses should be tracked more thoroughly in dogs and other pets through regular testing and sequencing. Cornell University animal virologist Colin Parrish, who was not involved in the study, says he would "certainly advocate" for that.

"We have sort of ignored dogs and cats as potential reservoirs or intermediate hosts," he says. The U.S. has no formal monitoring programs for viruses in pets, but Parrish's research group routinely surveys dogs for new respiratory viruses.

Two flu viruses are known to spread among dogs around the world: one that jumped from horses and one from birds. In southern China, there are also reports of dogs spreading flu strains from pigs, suggesting the region could be an unusual hotspot for viruses in dogs.

It is too early to say whether dog-borne influenza C will become a problem. More studies are needed to confirm the virus is spreading among these animals and, if so, how easily. But the researchers say it and other viruses should be monitored carefully to catch any emerging disease strains. Increasing surveillance "could be done really, really simply," Parrish says.

A good place to start would be kennels and similar places where viruses can easily spread and evolve, says University of Nottingham virologist Janet Daly, who was also not involved in the new study. "If you are keeping or farming animals at high density," she says, "that's where you need to look."

—Ida Emilie Steinmark



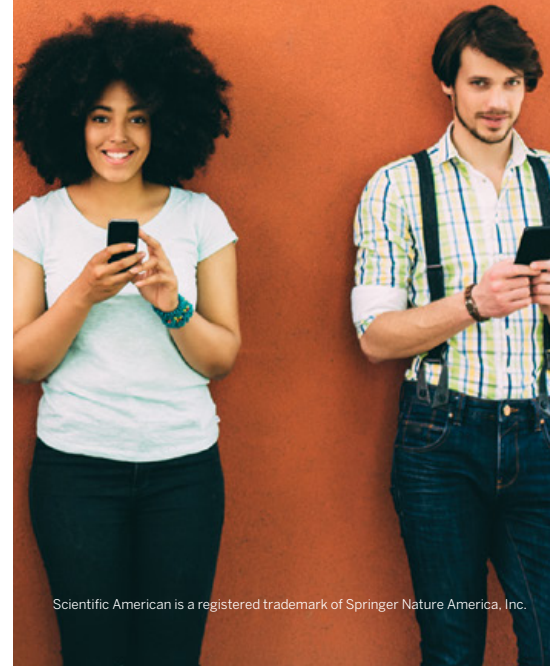
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SCIENTIFIC AMERICAN



NEWS AROUND THE WORLD

Quick Hits

By Allison Parshall

GUATEMALA

Scientists fired lasers from an airplane to map nearly 1,000 ancient Maya settlements underneath the rain-forest canopy. The technique revealed pyramids, reservoirs and canals, laying bare the stunning breadth and interconnectivity of the civilization around the millennia-old city of El Mirador.

INDIA

Geologists discovered 92 fossilized nests filled with 256 titanosaur eggs—one of the largest dinosaur hatcheries ever found, researchers say. Six species of these massive, long-necked herbivores laid eggs there, indicating more diversity than expected. The animals nested close together, like many modern-day birds do.

JAPAN

In an unlikely partnership, Japan's rare Amami rabbit has a mutually beneficial arrangement with a parasitic plant that sucks energy from others' roots. Scientists found that very few other animals will gobble up the plant's dry and unappealing fruits and disperse its seeds.

SIBERIA

The first humans arrived in the Americas from northeastern Asia, but Native American DNA found in ancient Siberians' genomes suggests it wasn't a one-way trip. Indigenous Americans most likely traveled via boat to Siberia multiple times, including as recently as 1,500 years ago.

SINGAPORE

Like dogs breeding with wolves, chickens sometimes mate with their undomesticated cousins. New research suggests chicken DNA is supplanting wild genomes of local red junglefowl. This endangers the latter's genetic diversity and potentially its ability to adapt to disease.

U.S.

The Food and Drug Administration will no longer require new drugs to be tested on animals. Developers can use alternative methods, such as simulating human tissues with high-tech chips, to prove a drug is safe to test in humans.

For more details, visit www.ScientificAmerican.com/apr2023/advances

MICROBIOLOGY

Shape-Shifters

The world's tiniest cell goes mobile

As a child, Makoto Miyata loved tinkering with radios and amplifiers. Now his interest in fiddling with things has only grown—but as a cellular biologist, he does it at a much finer scale. For a paper in *Science*, Miyata's team at Osaka Metropolitan University in Japan has tweaked the genes of the smallest synthetic life-form to make it move on its own, hinting at how minimal genetic additions could have helped primordial cells begin to move.

Researchers have long been working to understand how the earliest natural cells might have developed movement. Such studies have used the bacterial genus *Spiroplasma*: single-celled, helix-shaped parasitic

microbes that move by simply bending, flexing and changing their shape—not by using specialized appendages, as many other bacteria do. In *Spiroplasma*, scientists had already identified seven genes likely to aid this kind of cell movement. But confirming these genes' precise roles experimentally has proved challenging.

The team turned to a synthetic cell, called JCVI-syn3.0 (syn3.0 for short), which researchers at the J. Craig Venter Institute created in 2016. The cell survives and replicates with a record-breakingly small total of 473 genes—humans, by comparison, have more than 20,000. But syn3.0 can't move.

Miyata and his colleagues inserted combinations of the seven movement-associated *Spiroplasma* genes into syn3.0 cells. He says he vividly remembers the moment he peered through a microscope and saw the previously

PHYSICS

Feeling the Heat

Strange material breaks a classic rule of physics

A basic tenet of college physics is that as pressure increases, thermal conductivity—a material's ability to conduct heat—increases, too, because atoms that are squeezed together interact more.

More than a century of research has confirmed this rule. But engineers have now found an exception: when they applied intense pressure to boron arsenide, a recently discovered semiconductor material, thermal conductivity decreased. The finding, described in *Nature*, challenges established theory and potentially upends current models of how substances behave under extreme conditions.

"Now that we've made this first discovery, we think this can't be the only material with abnormal behavior," says study senior author Yongjie Hu, a chemist and mechanical engineer at the University of California, Los Angeles. If other substances show this property, "the established understanding of thermal conductivity might not be correct."

In prior studies, Hu and other researchers identified boron arsenide as having exceptionally high thermal conductivity. The scientists also calculated that conventional thermal

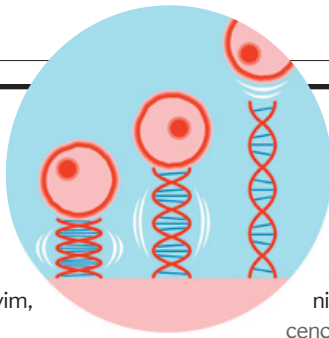
conductivity rules might not apply to it in certain circumstances.

To test those predictions, Hu and his colleagues placed a tiny piece of boron arsenide less than 100 microns thick in the gap between two diamonds. They applied pressure to the diamond sandwich to create a force on the boron arsenide hundreds of times greater than that at the bottom of the ocean. The researchers used ultrafast optics, spectroscopy and x-rays to document how boron arsenide's thermal conductivity begins to decrease as heat propagates across the sample and it is subjected to intense pressure. They observed that the decrease comes from similar types of heat waves overlapping and canceling one another out—a phenomenon predicted by quantum mechanics.

If Hu and his colleagues can show this behavior generalizes to other materials, he says, physicists may have to revise established models for environments such as outer space or planetary interiors, including Earth's. The latter could alter predictions about climate change because terrain temperatures are affected by what happens inside the planet.

The new study provides "the first and best experimental evidence that I know of to show that thermal conductivity can be tuned," says University of California, Berkeley, geophysicist Raymond Jeanloz, who was not involved in the research. The finding, he adds, "opens up the possibility" of advanced technologies that save energy and cool electronics by controlling thermal conductivity. —Rachel Nuwer

stationary synthetic cells “dancing.” Nearly half had taken on new shapes; some had even developed twisting helical forms to swim, just like *Spiroplasma*.



plasma-like movement. Strychalski notes that other researchers used a similar DNA-insertion technique to add jellyfish fluorescence genes into feline embryos, creating domestic cats that glowed.

Miyata had imagined creating a synthetic cell that could move, but he says it was still “quite surprising” when it actually happened. He wasn’t the only one surprised, according to National Institute of Standards and Technology cellular engineer Elizabeth A. Strychalski, who was not involved in the study but attended a presentation ahead of its release. “When they showed the video of these organisms swimming and how their [shapes] had changed, you could almost feel the collective gasp,” she says. Miyata’s team found that introducing combinations of just two genes was enough to produce *Spiro-*

But few had expected it could work in synthetic cells. This experiment “felt very bold,” she says, “and [its success] is also tremendously motivating and uplifting for the field.”

Although it’s hard to imagine what conditions triggered cells’ first movements billions of years ago, this research shows how small changes could help them take that massive leap. The study also has implications for the future, Strychalski says: “Mobile synthetic cells might someday be engineered to seek out contaminants, pathogens or even cancer cells in the human body.” —Saugat Bolakhe

MEDICINE

Lung Delivery

A drone speeds transport of a fragile donated organ



As organ transplant science advances, its biggest hurdles are increasingly logistical ones—such as securing a flight and navigating through traffic fast enough to deliver an organ before it deteriorates.

Enter the drone, for which researchers recently documented a milestone test in *Science Robotics*. After hundreds of practice flights, their drone carried a human donor lung on a five-minute journey from the roof of Toronto Western Hospital to Toronto General Hospital for a successful transplant. The trip can take 25 minutes by road.

This study suggests that drone delivery “may have a unique opportunity for organs like hearts and lungs that can tolerate less time on ice,” says Joseph Scalea, a transplant surgeon now at Medical University of South Carolina, who was not involved in the study. In 2019 his team at the University of Maryland made a groundbreaking drone delivery of a kidney—an organ that can survive 24 hours if packed in ice. Lungs and hearts last for less than half that long.

For the new study, Toronto General (which performed the first successful lung transplant in 1983) and Unither Bioelectronics replaced a commercial drone’s landing

gear with a lightweight carbon-fiber container for the large and fragile organ. The team enhanced the drone’s connectivity so radio frequencies wouldn’t interfere with its GPS and installed a parachute set to open automatically in case of midair malfunction.

Since the successful test flight, the researchers have been working with aviation authorities to create a drone corridor through commercial airspace—but there are regulatory hurdles. For example, civilians are typically not allowed to fly drones beyond their visual line of sight in densely populated areas.

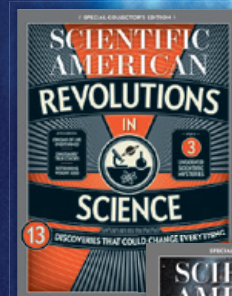
Shaf Keshavjee, director of Toronto General’s lung transplant program, envisions drones someday carrying lungs long distances for specialized repair to make them transplant-ready. For now, though, he’s focusing on the journey from airport to hospital—which takes 40 minutes in traffic and just eight by drone—and he anticipates the first such flights as early as this summer. He calls this work “The Last-Mile Model.”

“When the Wright Brothers left Kitty Hawk, they flew only 120 feet the first time,” Keshavjee says. “But now look at where air travel is.” —Caren Chesler

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MYCOLOGY

Science
in Images

By Susan Cosier

Oyster mushrooms feature in cuisines around the world, but they should be off the menu for hungry worms—which these delicious fungi kill and devour with abandon. Now researchers finally know how they do it.

A study published in *Science Advances* details how oyster mush-

rooms use a particular toxin to paralyze and knock off fungus-eating roundworms called nematodes. The fungi, which grow on nutrient-poor rotting wood, then consume the nitrogen-rich worms.

“Nematodes happen to be the most abundant animals these fungi encounter, so I think it’s very interesting evolutionarily, this cross-kingdom prey interaction,” says study senior author Yen-Ping Hsueh, a molecular biologist at Academia Sinica in Taiwan.

The study team of geneticists, molecular biologists, biochemists and fungal biologists had previously found that oyster mushrooms exude an unidentified toxin that somehow paralyzes the worms within minutes and causes calcium to flow into their cells, killing them. This mechanism differs from those used by other carnivorous fungi and could be unique to oyster mushrooms.

For their new work, the researchers grew and analyzed samples of the fungi’s tissue, finding no noticeable toxin even when they broke it up. They reasoned that whatever was killing the

Guy Edwardes/Minden Pictures



worms must be a volatile compound that evaporates when disturbed. When they damaged the oyster mushroom tissue again and then analyzed the nearby air with gas chromatography-mass spectrometry, they finally found 3-octanone—a nerve gas that turned out to be encapsulated in microscopic, lollipop-shaped structures on the mushroom surface. When nematodes touch the mushrooms, these structures release their gas, disrupting the worms' cell membranes to cause paralysis and death. The worm is then digested via the mycelium, a mushroom's threadlike feeding network.

Before this work, “we didn't really appreciate how many fungi in the wild are defending themselves against nematodes or even using nematodes as food,” says Nick Talbot, a geneticist at Sainsbury Laboratory in Norwich, England, who studies how fungi can harm plants but was not involved in the new research. The study demonstrates “a very novel approach,” he adds. “These organisms are really difficult to work on, and Dr. Hsueh is showing that you can do some really amazing work with them.”

MICROBIOLOGY

Pressing On

Microbe withstands the solar system's many pressures

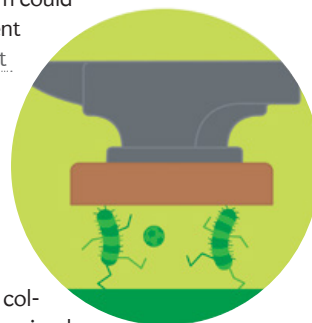
When it comes to thriving under pressure, microbes have us solidly beat. New research reveals that *Carnobacterium*, a genus often associated with spoiled meat, can successfully divide and replicate across an enormous range of external pressures—from the equivalent of a very thin atmosphere to crushing ocean depths. This adaptability is unknown for any other life-forms on Earth, researchers report in *Astrobiology*. Such hardiness suggests a single organism could survive in radically different environments throughout the solar system.

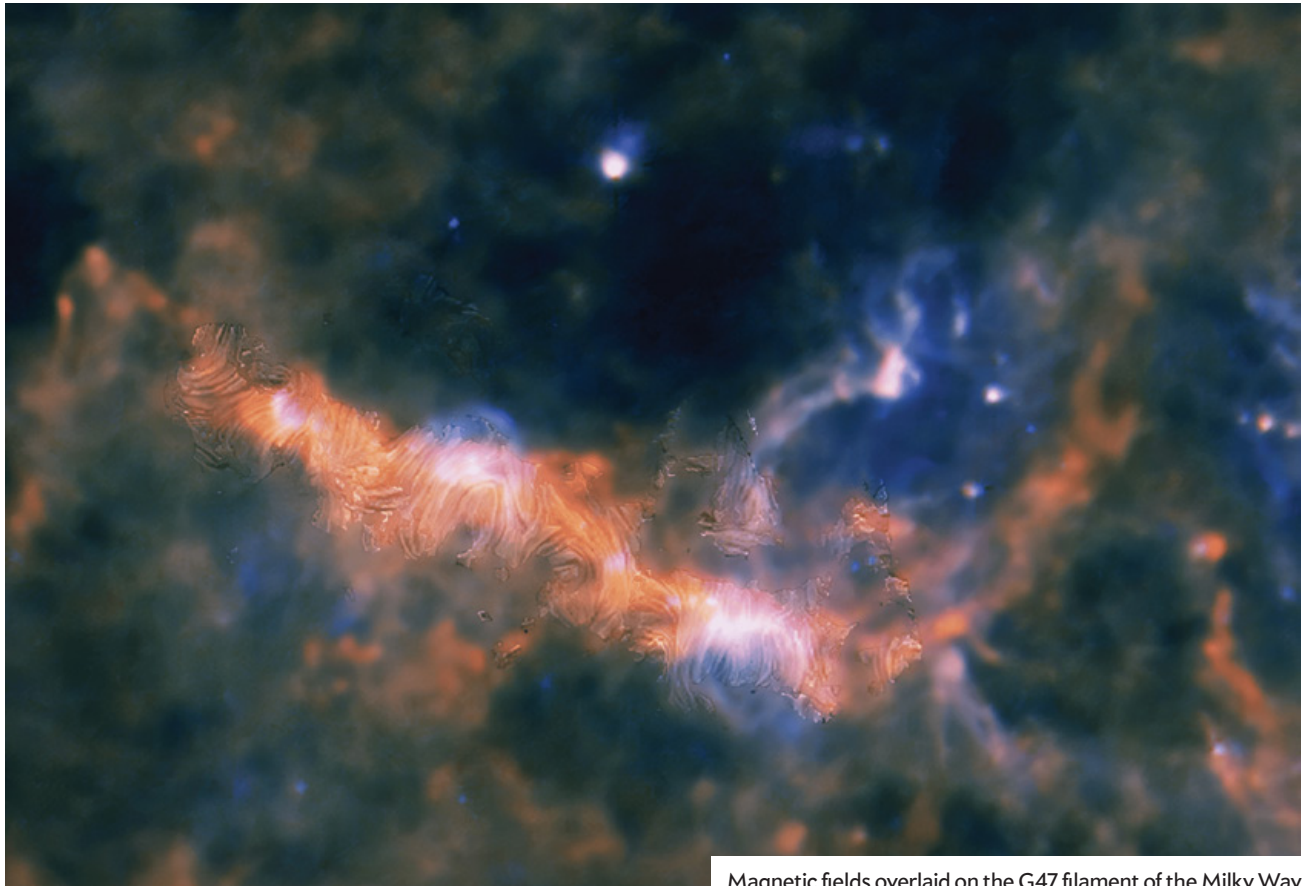
Tipped off by previous findings of various *Carnobacterium* strains flourishing at high and low pressures, University of Florida microbiologist Wayne Nicholson and his colleagues systematically examined 14 strains' responses to a wide span of pressure conditions. The team focused on strains isolated not only from meat (including seafood, chicken and bologna) but also from Siberian permafrost, an Antarctic lake and deep within the North Pacific's Aleutian Trench.

In the laboratory, Nicholson and his team exposed each strain to pressures ranging from 0.01 to 100 times Earth's atmospheric pressure at sea level—corresponding to the pressures on the surface of Mars and inside the liquid water ocean of Jupiter's moon Europa, respectively. The researchers found that 11 strains grew measurably at every pressure tested. Very few past studies focused on how well microbes tolerate a range of pressures, Nicholson says, but these results are nonetheless surprising given that most other organisms seem to be far more pressure-sensitive. “Humans have trouble breathing on Mount Everest,” he notes, “and that's about 30 percent of sea-level atmospheric pressure.”

Other bacteria have been shown to do well at comparably high pressures, says Felipe Gómez Gómez, an astrobiologist at the National Institute of Aerospace Technology in Madrid, who was not involved in the study. But these results are novel because they show that the same *Carnobacterium* strains can endure so much pressure variation, he says: “What's really challenging is the whole range.” These microbes' ability means they could, for instance, theoretically survive at various depths in an alien ocean, Gómez Gómez adds. “This work has important astrobiological implications.”

—Katherine Kornei





Magnetic fields overlaid on the G47 filament of the Milky Way

ASTRONOMY

Star Magnet

Intricate magnetic fields regulate star growth in our galaxy's "bones"

The Milky Way's rotating disk of gas and dust gives rise to graceful spiral arms, which make up the galaxy's most active star formation sites. Now researchers using an airplane-borne telescope high in Earth's atmosphere have found a mechanism for how **magnetic fields** shape star birth in the dense filaments, or "bones," that wind their way through these arms.

The new work describes how galaxy-scale magnetic fields, based on their orientation and strength, can both funnel material from one area to another and prevent the dust and gas that make up the densest regions from collapsing under gravity. These processes dampen star formation; without them, we'd have a much brighter night sky than we see today.

Ground-based telescope observations in 2015 confirmed the physical properties of the gas and dust bones that lined [the Milky Way's arms](#). But researchers did not know the precise role of magnetic fields in star-forming activity at smaller scales. "We knew the bones existed, but back then there was no way to map the details of their magnetic structure," says Simon Coudé, a postdoctoral researcher at Worcester State University and the Center for Astrophysics | Harvard & Smithsonian. Coudé presented the new find-

ings at the American Astronomical Society's 2023 winter meeting.

For this work, the researchers are determining the fine-scale direction of these magnetic fields by measuring how dust particles align. Specifically, they're quantifying how magnetic properties help keep gas and dust in the massive bones from collapsing to form stars. With data from instruments flown onboard the Boeing-747-borne telescope [SOFIA in its final years of activity](#), "we could view the field structure in star-forming clouds across large swathes of the galaxy," Coudé says.

One bone map from this project showed that magnetic fields tended to be perpendicular to the bone's length in dense areas of active star birth and more parallel elsewhere. This could mean that the parallel fields from less dense regions feed material into denser ones, where fields are strong enough to limit gravitational collapse despite the additional star-forming material, the researchers say. They also found magnetic fields along other galactic bones strong enough to dampen star formation in all but the most active areas.

"We've known that entire galaxies are permeated by magnetic fields. Now we see these fields' structures in the densest regions, where they're sensitive to star formation," says Enrique Lopez-Rodriguez, an extragalactic astronomer at the Kavli Institute for Particle Astrophysics & Cosmology at Stanford University, who was not involved in the study. Ultimately, he adds, this will lead to understanding how the balance between gravity and large-scale magnetic fields dictates star formation at the smallest scales, in other galaxies as well as our own. —Rachel Berkowitz

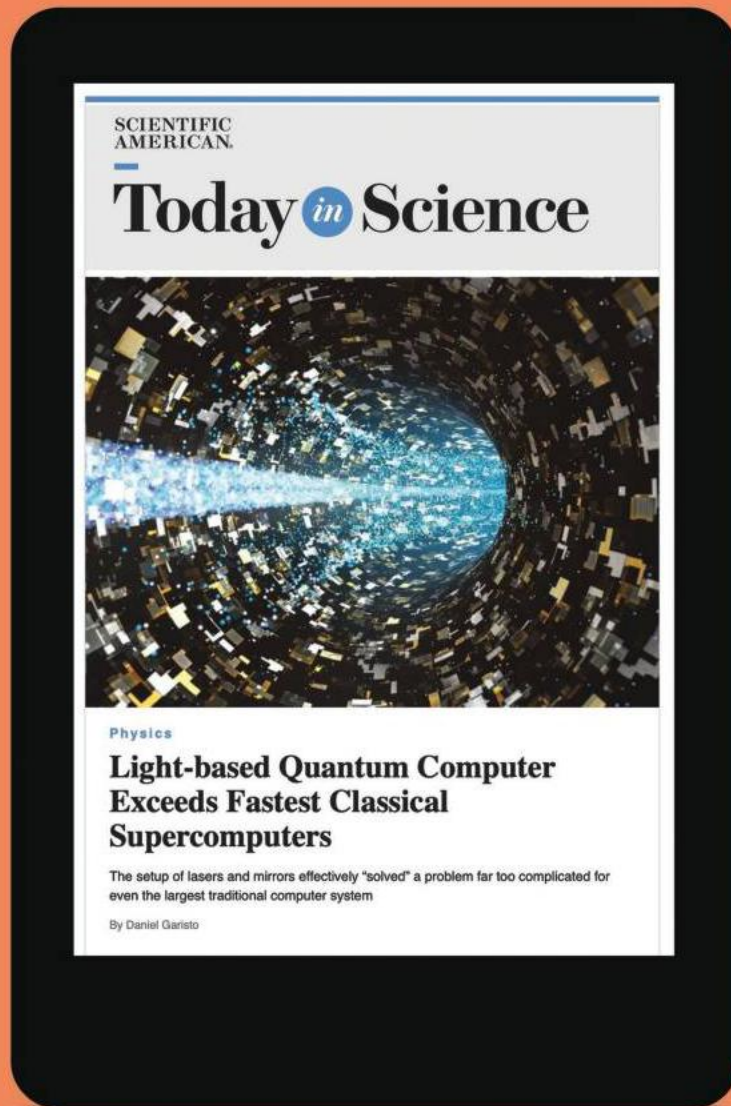
ESA/Herschel/PACS/SPIRE/Ko Wang et al., 2015; Polarization map: Stephens et al., 2022

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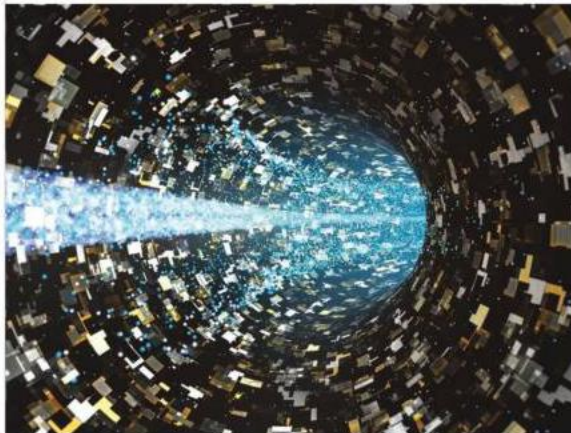
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Today *in* Science



Physics

Light-based Quantum Computer Exceeds Fastest Classical Supercomputers

The setup of lasers and mirrors effectively "solved" a problem far too complicated for even the largest traditional computer system

By Daniel Garieto

Howard V. Hendrix has written about population and climate issues in novels, essays and poetry. His recent contributions to *Analog* and the *San Francisco Chronicle* are informed by the loss of his home in California's Creek Fire of 2020.



Extravehicular Activity

Let us stand outside our spacecraft long enough at height high enough to see Earth breathing its seasons, to feel its pulses across years, the rise and fall of global indices—

vegetation, water vapor, total rainfall, snow cover, land surface temperature, net radiation, sea surface temperature—

inhale, influx, diastole, exhale, efflux, systole.

Is this macro of our microcosm running a temperature?
Pulse growing more erratic?
Breathing more shallow?

How are we feeling?
How long can we stand outside our spacecraft?





Lydia Denworth is an award-winning science journalist and contributing editor for *Scientific American*. She is author of *Friendship: The Evolution, Biology, and Extraordinary Power of Life's Fundamental Bond* (W. W. Norton, 2020) and several other books of popular science.

Checking Up on Telehealth

For cancer care and other specialties, virtual visits are working surprisingly well

By Lydia Denworth

Like many people, I was introduced to telehealth during the pandemic. I met with my psychiatrist virtually, settling onto my couch instead of hers for our sessions. But those appointments required only a conversation. It made sense that psychotherapy easily made a switch to the online world.

What's more surprising is how often telehealth now is being used in other medical areas, such as in cancer care. Although chemotherapy and immunotherapy are typically done in person, follow-up visits and medication and symptom management can be done virtually, says Leah Rosengaus, director of digital health at Stanford Health Care in California, where 44 percent of oncology visits are virtual. For patients with cancer receiving routine treatment, that equals a lot less hassle. And for a patient with a poor prognosis, it might be even more meaningful. "The biggest gift [we can] give them is time," Rosengaus says.

Telehealth programs made up less than 1 percent of all health care in the U.S. until March 2020, when, of course, everything changed. The pandemic restricted personal contact, and telehealth surged. (At Stanford, it went from less than 2 percent to more than 70 percent of visits in just a few weeks.) State and federal regulators relaxed rules that required doctors to see patients personally before offering care, and insurers began to cover virtual visits. Now the use of technology such as video chats, secure messaging, and

even old-school phone calls to allow clinicians and patients to communicate appears to be here to stay. It has settled at 10 to 30 percent of patient appointments in many large hospital systems.

In general, the quality of telehealth care seems high. Nearly 87 percent of the time, Mayo Clinic researchers reported in *JAMA Network Open* last fall, an initial virtual diagnosis agreed with a later diagnosis made in person. Oncology and psychiatry proved especially accurate; ear, nose and throat and dermatology appointments—which rely more on physical examinations—were somewhat less so. A 2022 study of more than 500,000 patients found equal or better outcomes for telehealth across 13 of 16 primary care measures, such as management of diabetes and following through on flu shot appointments, when compared with in-person visits.

The quality-of-care results seem highest in the specialties that use telehealth most. Endocrinologists, for instance, like it because their patients get lab work done separately and then discuss results with doctors virtually; surgeons are using it to confer with patients before and after procedures.

Patient satisfaction with these visits is good, according to reports from large health-care systems. People say they like the convenience of virtual care—there is no travel, no parking, no child or pet care to arrange. Sanford Health, which serves a widespread rural population from its base in Sioux Falls, S.D., estimates its patients who used virtual care were spared two and a half million miles of driving in 2022.

In some cases, technology is providing clinicians with better insights into those they care for. Jeremy Cauwels, chief physician at Sanford, says an endocrinologist in his organization now carves out several hours a week for video visits with diabetes patients after discovering how much information about diet and habits he could glean from observing them at home.

People vary in how much of their home life they are willing to show, of course. Whereas some patients would never turn a camera on in the living room, others cheerfully display the insides of their medicine cabinets or refrigerators. "We're getting a window into the patient's lived environment that we never had before," Rosengaus says. "That harkens back to the days of doctors and house calls."

Virtual visits do not work for everything and everyone. In the large 2022 telehealth study, in-office patients were more likely to receive and adhere to some medications, such as statins for cardiovascular disease. Starting "a lifelong medication" is a big decision that may be best suited to an in-person discussion, the authors suggest. Another study found that patients who followed up an emergency hospital visit via telehealth rather than in person were more likely to be readmitted to the hospital.

Clearly, medical providers must fine-tune the best use of this technology. The rest of us will keep finding our comfort level (I draw the line at showing my medicine cabinet). The goal, proponents say, is not simply to increase telehealth use but to optimize it and create a good form of hybrid care they call "clicks and mortar." ■





Taking Down the Hive Criminal Ransomware Group

A cybersecurity expert explains the FBI's operation

By Sophie Bushwick

In ransomware attacks, hackers encrypt a computer system and then extort victims to pay up or risk losing access to their data. Victims have included large companies such as the meat supplier JBS, major infrastructure such as the Colonial Pipeline and entire countries such as Costa Rica. The Department of Justice recently announced some rare good news about this criminal industry: The FBI infiltrated a major ransomware group called Hive and obtained its decryption keys. These keys let the ransomware victims recover their data without paying the demanded fee. The FBI's work helped affected parties avoid paying \$130 million. Afterward American law enforcement worked with international partners to seize Hive's servers and take down its website.

According to the DOJ, Hive has been a major player in the ransomware space since June 2021, attacking more than 1,500 victims in more than 80 countries and extorting more than \$100 mil-

lion from them. "I'd say that's up there with the largest ransomware groups we've got data on, in terms of how many organizations have been impacted and how much money is being paid out," says Josephine Wolff, an associate professor of cybersecurity policy at Tufts University. *SCIENTIFIC AMERICAN* spoke with Wolff about how the FBI took down Hive and how much of an impact this law-enforcement operation will have on other ransomware criminals.

[An edited transcript of the interview follows.]

What action did the FBI take against Hive?

There are two parts of this, both of which are really interesting. The first thing that law enforcement did was to actually infiltrate their internal communications for a period of several months—we think going back to last summer, based on what the Justice Department has said. And because law enforcement was inside their comput-



ers and able to see who they had infected and, more important, what the decryption keys were to undo that ransomware, the Justice Department has said it was able to help lots of victims who had been targeted and actually unencrypt their systems by essentially stealing those decryption keys from the Hive servers without Hive's knowledge of what was going on. So for months you had an undercover presence in those servers of law enforcement, taking decryption keys and giving them to victims so they can recover their computers.

The second part of that, which is what just happened, is the takedown. And that's where the Justice Department actually goes in and seizes servers and removes Hive's website. For that part, it's harder to know what the long-term impacts will be because servers and websites are replaceable. So it's a good disruption, but it's not necessarily equivalent to saying, "These people will never be able to distribute ransomware again." And my guess would be that the reason the takedown happened is because the law-enforcement presence in Hive's system had been detected. Because otherwise I think you would try to maintain that presence as long as you reasonably could.

Is the FBI likely to continue putting together operations like this that involve embedding agents in the systems of criminal organizations for months?

Honestly, I hope so. It's a tricky thing to do because many cybercriminal organizations, for obvious reasons, are fairly cautious about who has access to their servers. My guess is that this is a little bit of an anomaly, finding one that was poorly protected enough. Perhaps that is also tied to the fact that Hive is a "ransomware as a service" organization: you see them renting out their malware to a bunch of other bad actors. Therefore, it is being used quite widely by a whole bunch of different entities in this space, and they have a lot of dealings with people who are not internal, known members of their own organization but are customers buying their services. Perhaps that made it easier to introduce new people to the organization and the systems. Certainly this is something law enforcement will keep trying to do. I hope it'll be successful.

Will Hive's downfall deter other ransomware groups?

That depends a little bit on some of the next steps. I think this is not a story that's necessarily going to make cybercriminals run in fear. My guess is that some of the larger organizations are going to be sweeping their own systems and looking for any signs of a similar presence that they should pay attention to. I don't know that it's going to make anybody tone down their ransomware operations, partly because I think there's less attention to that and less fear of that for cybercriminals who operate overseas. But it's certainly going to give people some nervousness about the possibility of their own systems being infiltrated in this manner.

What else have these groups been up to lately? What's the current state of the ransomware world?

We continue to see these fairly significant, really impactful ransomware attacks on health-care institutions, at local and national government levels, at private institutions. My sense, certainly from insurers, has been that the rate of ransomware has slowed a bit in the past six months to a year—that it's not as frequent or as common as it was perhaps in 2020, 2021, at the moment when it was doing the most damage and causing the greatest number of claims. But that's not to say it's gone away.

Why is that slowdown happening?

There are different ideas about that. Many of the insurers would say, "We've gotten better at requiring policyholders to take certain measures to protect themselves"—the most straightforward of which is creating backups, requiring that everyone be able to reboot their systems if everything gets encrypted. And they think that has helped reduce, at least, the number of claims and the amount of damages caused by ransomware attacks. To some extent, the war in Ukraine throws the ransomware industry into some amount of disarray. There's a set of ransomware groups and cybercrime organizations that have people in Ukraine, often leaders based in Russia, who are starting to leak information about each other and undermine each other's efforts from within.

The other piece of it is pretty aggressive

policing in the U.S. but also in Europe: trying to catch people, do takedowns and make ransomware a less lucrative crime. Some of that also centers on regulation of the cryptocurrency industry: trying to sanction certain cryptocurrency exchanges that criminals are using to process these payments. Cryptocurrency intermediaries facilitate currency payments at scale and across national borders, which is so essential for this to be a profitable business. Another thing that the U.S. government definitely is pursuing is the international partnership piece. Most of these criminals are based not in the U.S. or other countries where most of the victims are located. Taking them down requires very active collaboration with law enforcement overseas.

Are cybercriminals changing up their tactics to counter the more robust response from law enforcement?

One piece we haven't touched on a lot is the question of what happens when ransomware operators don't just encrypt a victim's system but also steal copies of all their data and then threaten, "If you don't pay a ransom, I'm going to leak all of your data online." And that has been growing in frequency for the past couple of years. It's particularly problematic when you think about solutions we've seen, where the hope is "if we provide the decryption key, then people won't pay the ransom." If there's a stolen copy that's being held over a victim's head, that's a less effective mitigation.

What else can we learn from Hive's takedown?

In the Department of Justice announcement, they said that when they were inside the Hive servers, they could see who was being targeted. But they were only getting reports from about 20 percent of those victims. This gives us one data point for what percent of ransomware attacks are actually being directly reported to the FBI versus the ones for which the FBI had to proactively reach out and say, "It looks like this ransomware group may have impacted you. We think we can help." Twenty percent is a pretty low number in terms of trying to understand the scale of this problem beyond what people voluntarily report. ■



BIOLOGY

BIG LITTLE MYSTERY

Researchers are racing to figure out how giant filter-feeding whales find their tiny prey. The answer could be key to saving endangered species

By Kate Wong



**HUMPBACK
WHALES** and
other baleen
whales are the
largest creatures
on Earth, yet they
eat some of the
smallest prey in
the oceans.

Kate Wong is a senior editor for evolution and ecology at *Scientific American*.



W

HEN IT'S TIME TO EAT, HUMPBACK WHALES HEAD TOWARD THE ENDS of the earth. Their mission: feast until they are fat and happy. They must build up their energy reserves, packing on nearly a ton of blubber a week to sustain them on the voyage from their polar and subpolar feeding grounds to the balmy waters where they breed. The journey may require traveling thousands of miles over several months—and they must be ready to reproduce when they arrive. Perhaps because nature loves a paradox, these colossal predators, which can measure 60 feet long and weigh 40 tons, accumulate these fat stores by eating some of the smallest prey in the sea—including krill, shrimplike crustaceans that live in all the world's oceans but are concentrated in the cold waters found at high latitudes.

We know a lot about how humpbacks eat. They filter seawater through plates of keratin, called baleen, that line their upper jaws and resemble the frayed bristles of a worn toothbrush. They devour several thousand pounds of their tiny prey every day. To obtain that quantity of food, they must seek out dense aggregations of the crustaceans. Once they find a swarm, they may deploy a clever cooperative hunting tactic, swimming in circles while blowing columns of bubbles to create a kind of net to corral the krill. Then they feed, lunging at the tightly gathered prey with jaws agape, engulfing thousands of gallons of krill-filled water in their pleated throat pouches before straining the catch through their baleen.

Yet for all scientists have learned about these charismatic leviathans, no one knows how baleen whales (a group that includes humpback, blue, fin and sei whales, among others) find their food in the first place. Their cousins the toothed whales—sperm whales, belugas, dolphins, and the like—use ultrasonic sonar signals to detect prey, but baleen whales don't have that ability. Somehow they still manage to find their minuscule quarry in the infinite sameness of the sea.

It's a mystery that scientists are eager to solve. In part that's because it is a huge gap in our basic knowledge of high-profile species. More urgently, the question of how baleen whales seek out their food has important conservation implications, particularly for a baleen species called the North Atlantic right whale.

The North Atlantic right whale, a dark, stocky cetacean that eats rice-size zooplankton called copepods, has the unfortunate distinction of being one of the most endangered mammals on the planet. Commercial whaling nearly extinguished this species in the early 1900s. By 1935 the League of Nations banned the hunting of all right whales. But unlike other species whose numbers plummeted because of whaling, the North Atlantic right whale has been unable to make a comeback. The animal's feeding grounds off the coast of New England and the Canadian Maritimes overlap with areas of intense human activity. Collisions with ships and entanglement in fishing gear, along with climate change-induced disturbance of their habitat and prey, have taken a terrible toll.

The most recent estimates indicate that fewer than 350 North Atlantic right whales remain, only 70 of which are females of reproductive age. According to some projections, the species could go extinct in the next couple of decades. Understanding how baleen whales track down their prey could help scientists predict where the whales will go to feed—and better manage human activities in those areas that might harm the whales.

All of this matters for more than just a single species of whale. North Atlantic right whales and other baleen whales are ecosystem engineers, feeding in deep water and then releasing nutrients near the surface through their feces, which support the growth of microscopic

Scott Wilson (preceding pages)



Kate Wong; Activities completed/image taken under Antarctic Conservation Act permit ACA2019-018 and Environmental Protection and Biodiversity Conservation Permit 2018-0020

plantlike organisms called phytoplankton. The phytoplankton, in turn, nourish krill, copepods and other tiny drifting creatures known as zooplankton that are eaten by larger animals. The whales' tissues also trap enormous amounts of carbon dioxide that could otherwise contribute to global warming—an estimated 33 tons for the average large-bodied whale. And when whales die, their carcasses sink to the seafloor, where they sustain entire communities of deepwater organisms—from sleeper sharks to sulfur-loving bacteria—that are specially adapted to using these so-called whale falls for food and shelter. The health of baleen whale populations supports the health of a host of other species.

The most direct way to learn how a baleen whale finds its food is to tag it with a device that can record its underwater behavior and watch the animal forage. That's not possible with North Atlantic right whales, which are so stressed from human activity that any direct human contact could just make things worse. Fortunately, the right whale has cousins, such as the humpback, that are in much less peril. And one of the best places to watch them eat is on their feeding grounds at the bottom of the world.

IN 2020, TWO WEEKS BEFORE the World Health Organization declared the COVID-19 outbreak a pandemic, I boarded a ship to Antarctica to follow one research group's efforts to learn how baleen whales find food. I went as a guest of the cruise operator, Polar Latitudes, to observe a study being carried out by the seven scientists they were hosting on their tourist boat and to lecture on whale evolution.

By joining a tourist expedition, the international team of researchers based in the U.S., Sweden and Japan saved on the exorbitant costs of getting to the white continent. In return for three shared staterooms, meals, and the use of two sturdy inflatable rubber boats called Zodiacs, the scientists gave the other passengers regular updates on their research, which was billed as a whale-focused expedition for citizen scientists.

The team was testing a hypothesis about baleen whale foraging that grew out of research on seabirds. Starting in the mid-1990s, Gabrielle Nevitt of the University of California, Davis, showed that dimethyl sulfide (DMS), a chemical that is released when phytoplankton are eaten by zooplankton, attracts tube-nosed seabirds—a group of carnivorous birds that includes albatrosses,

RESEARCHERS are studying humpback whales in Antarctica to learn how they find krill.

petrels and shearwaters—which then eat the grazing zooplankton. It’s a mutualistic arrangement: by luring the seabirds with the scent of DMS, the phytoplankton gain protection from the zooplankton. Even at the bottom of the food chain, the enemy of your enemy is your friend.

Cruise team leaders Daniel Zitterbart of the Woods Hole Oceanographic Institution, a physicist who uses remote sensing methods to study the behavior and ecology of whales and penguins, and whale behavior specialist Kylie Owen of the Swedish Museum of Natural History wondered whether whales might be similarly attracted to DMS. If so, then following the chemical toward higher concentrations should, in theory, lead whales to denser concentrations of the krill and other phytoplankton eaters than foraging randomly would. To find out, Zitterbart and Owen joined forces with whale biologist Annette Bombosch of Woods Hole; zooplankton researcher Joseph Warren of Stony Brook University; Kei Toda of Kumamoto University in Japan, who developed technology for measuring DMS, and his then graduate student Kentaro Saeki; and oceanographer Alessandro Bocconcelli of Woods Hole, who has helped pioneer the use of sophisticated digital tags to study whales.

The team planned to tag humpbacks with custom-built instruments containing pressure sensors, accelerometers, magnetic compasses and hydrophones that record their underwater behavior, along with a radio transmitter to enable tracking. Their permits allowed them to tag only a total of five whales, and they had to do it in just five days—the rest of the 12-day cruise would be spent in transit. They had little room for error.

WE LEFT FROM THE ARGENTINE PORT of Ushuaia, the southernmost city in South America, on February 28 and spent the next two days of the leap year crossing the Drake Passage, the notoriously turbulent 620-mile-wide waterway between South America and Antarctica, escorted by albatrosses and petrels. On March 1, we passed over a boundary zone known as the Antarctic Convergence and entered the calm, cold waters of the Southern Ocean. For the first time since entering the Drake, we glimpsed land off the starboard side of the ship—Smith Island, part of the South Shetland Islands of the British Antarctic Territory.

With the stomach-churning swells of the Drake behind us and the soporific effects of the motion sickness medication wearing off, I could now fully register my extraordinary surroundings. Icebergs, bergy bits and growlers—some of the many forms of ice here—joined sea and sky to display every shade of blue. Fuzzy Gentoo penguin chicks chased after their exhausted parents to demand food. Platinum blond crabeater seals lounged on divans of drifting ice, basking in the sun. I let the otherworldly beauty of the place wash over me.

On the morning of March 4, I awoke to daybreak in Paradise Bay, a scenic harbor where whaling ships once anchored. From my seat on the pontoon of a Zodiac, I watched the rising sun pierce through an opening in the cloud cover to bathe a distant glacier in golden light.

We were in whale country now, encountering groups of the mammals as they floated on the surface like logs, exhaling tall plumes of moist air. The wet *whoosh* of whale breath joined the thunder cracks of calving glaciers and the rumbles of avalanches.

The day before, the scientists had successfully tagged their first humpback. The passengers cheered when the scientists announced the update at breakfast. Unfortunately, the whale proceeded to sleep the entire time it was under observation. But later the same day they tagged a second whale, and this one was a model subject, making several dives up to 850 feet. Data from the sensors indicate that the whale was lunge feeding—exactly what they wanted to see.

This morning the team was attempting to tag a third individual—and hoping it behaved like number two. Zitterbart, a tall, animated man who thinks and talks with formidable speed, got up at 5:30 and headed to the ship’s bridge to find out whether any whales were around and what the weather was like. The day looked promising. Whales had been spotted in the area, and the water was still—the better for retrieving tags, which are programmed to stay on a whale for just a few hours before detaching and floating to the surface.

By 6:45 the research boats were lowered into the water, and the scientists were preparing to tag a whale that had been sighted nearby. A 20-foot-long carbon-fiber pole extended beyond the bow and stern of the tag boat. They use the pole to slap the tag, which has four suction cups on its underside, onto unsuspecting humpbacks once they get to within 10 feet of the animal. Bombosch and Bocconcelli navigated across a glassy expanse of open water toward a group of whales, slowing on the approach. That bunch looked lazy, though. They didn’t want to tag another slumbering whale, so Owen and Bombosch decided to target another group that looked more active.

From my vantage point in a separate Zodiac, two humpbacks came into view. Only their small dorsal fins and the uppermost part of their sleek black backs were visible. They didn’t look all that big. But like icebergs, most of their mass is below the waterline. At a distance, you only get a sense of how huge humpbacks are when they wave their great flippers in the air, raise their tail flukes ahead of a deep dive, or propel their entire bodies clear out of the water in a glorious breach.

Zitterbart gripped the unwieldy tagging pole and stood tensed, one foot on the bow box and one in the boat. Attaching the tag is a fraught operation. To ensure a strong signal from the transmitter, he had to place the tag as high on the animal’s back as possible but not too close to the sensitive skin surrounding the blowhole. As the tag boat neared the whales, Zitterbart raised the pole and then, at exactly the right moment, cast it down with just enough force to plunk the tag securely onto one of the animals. The whale startled, then sank out of sight—a typical reaction—and the researchers moved quickly to stow the pole, mark the GPS location of the tagged whale and prepare to monitor the animal. They were now three for three with attaching the tags.



Once the tagged whale resurfaced, they would spend the next few hours tracking it by eye and with the aid of a VHF receiver tuned to the tag's transmitter, keeping a distance of more than 300 feet from the animal so as not to interfere with its routine. They needed to recover the tags—which store the behavior data and cost \$10,000 apiece—when they automatically detached from the whales at the preprogrammed time after deployment. Now the team just had to hope they chose a cooperative subject. “Ideally we’d tag an active whale that’s not feeding yet, and it would swim away to feed,” Owen explained. After that, the researchers in the prey boat would sample the water to see if krill and DMS concentrations were increasing along the whale’s path. If they tagged a whale while it was already feeding, they would have no trail to follow. But the humpbacks are wild animals, with agendas of their own. “The stars really need to align for things to go the way we want them, too,” Owen said.

TO VISIT ANTARCTICA is to encounter forces that have shaped the fortunes of baleen whales across eons. Descended from four-legged land animals, whales underwent one of the most dramatic transformations of any vertebrate group when they transitioned to life in the water. Like all organisms, whales evolved under the influence of environmental change. They got their start some 50 million years ago in the greenhouse conditions of the Eocene epoch. Back then, the southern supercontinent of Gondwana was in the process of disbanding, and the ancient Tethys Sea reached from the Pacific Ocean to the Mediterranean. In the warm, shallow waters of Tethys,



BALEEN WHALES gulp enormous amounts of prey-filled water and then strain it through plates of keratin called baleen (top). Antarctic krill (bottom) is a favorite food of humpbacks.

early whales underwent the first phase of their transformation: becoming seaworthy. Forelimbs morphed into flippers, noses became blowholes, ears remodeled to hear while submerged. Some 10 million years after their furry, four-legged ancestors walked along the water’s edge, whales had adapted so thoroughly to aquatic life that they could no longer venture ashore.

The second phase of whale evolution unfolded as the planet transformed into a so-called icehouse world. As the Eocene gave way to the Oligocene, tectonic forces dealt a final blow to Gondwana, cleaving apart Australia, South America and Antarctica. When the separation of these landmasses was complete, the Antarctic circumpolar current swept around Antarctica, isolating it from warmer waters and pulling up nutrients from the deep that supported an abundance of phytoplankton and zooplankton. So vast and powerful was this new current, in fact, that it altered ocean circulation, temperature and productivity across the globe. From this crucible of tec-



NORTH ATLANTIC right whales are critically endangered. Researchers hope to use dimethyl sulfide to predict where these whales will go to eat—information that could guide conservation management of the animals.

tonic, climatic and oceanic change, the forerunners of modern baleen whales emerged. By 35 million years ago early representatives of this lineage were patrolling the seas. Over millions of years their descendants would eventually acquire the baleen and gigantic body sizes for which this branch of the whale family is known.

Although baleen whales were molded by dramatic environmental and ecological change on evolutionary timescales, that long history did not inoculate their modern descendants against the dangers of profound change on shorter timescales. In the 20th century alone, industrial whalers armed with exploding harpoons and factory ships that could process carcasses offshore slaughtered more than two million baleen whales, pushing many populations to near extinction and degrading their ecosystems. Some species have been recovering since the demise of that industry—only to now face a new round of existential threats. Warming seas and commercial fishing are changing the availability of the zooplankton the whales depend on for food.

Four days after observing the tagging operation, I joined Warren, Zitterbart, Saeki and Julien Bonnel of Woods Hole on the prey boat. The cruise ship had to make a detour to Frei Station, a Chilean base with an airstrip on King George Island in the South Shetlands, to evacuate an injured passenger to the nearest hospital, in Chile. The researchers decided to use the unexpected stop to map the krill and DMS concentrations in a shallow embayment on the island's north side.

We wore jackets, hats and gloves against the morning cold, but just a few weeks earlier Antarctica had logged an all-time high temperature of 64.94 degrees Fahrenheit. The Antarctic Peninsula, where we had been exploring, is one of the fastest-warming regions

on the planet. As a result, it's losing large amounts of ice, which is bad for krill, Warren said. Juvenile krill depend on winter sea ice for shelter and are thought to eat algae that grow on the underside of the ice.

Rising temperatures are not the only source of pressure on krill. Demand for the small crustaceans has surged over the past two decades, mostly from the nutritional supplements industry, which promotes krill oil as a rich source of omega-3 fatty acids for humans, and the aquaculture industry, which uses krill in feed for farmed fish. Whether the krill fishery is being managed sustainably is a contentious question. But a 2020 study of krill predators found that even with conservative catch limits for Antarctic krill in the waters around the Antarctic Peninsula—less than 1 percent of the stock in the southwestern Atlantic sector of the Southern Ocean—penguins in this region are declining, perhaps because the fishing vessels are focusing their efforts in areas that the penguins also favor. As the distribution and biomass of krill and other prey species change, predators—including whales—have to adapt their foraging routines accordingly.

As the Zodiac chugged away from the cruise ship, the researchers set up their equipment. They use an echo sounder to send sound waves down into the water, where they bounce off krill and any other animals they encounter, generating a picture on Warren's laptop of the creatures drifting in the water column. The lower the frequency of the ping, the deeper the transducer can "see." Higher-frequency pings, in contrast, can see smaller targets. The team uses two frequencies, one low and one high, to search for aggregations of the tiny krill, which typically hang out in the upper 650 feet of the water column. Warren's lab mascot, a small squeaky-

Foto-4440/Getty Images

toy pig named Sir Pings-a-Lot II, was overseeing the proceedings. “This is as exciting as it’s going to get,” Warren joked as he dropped the echo sounder overboard.

Krill are not as thrilling to track as their predators, but in recent years the science that happens in the prey boat has produced the greatest gains. As the boat traveled along its transect lines, Saeki reached over the side to scoop seawater from the surface every two minutes for analysis. Two plastic cases about the size of a handbag and carry-on suitcase contained the equipment for measuring any DMS in the water samples. A bubbler pushes air into the sample to get the DMS into the gas phase; a dryer removes any lingering moisture; an ozonator creates elementary sulfur from the DMS gas; and a photomultiplier measures light emitted by the sulfur—the amount of light is proportional to the amount of DMS present. Previously this sort of analysis was done in the lab; Woods Hole researchers were able to miniaturize Today’s DMS measurement setup to fit into a small boat. “The fact that we can run the DMS sniffer in the Zodiac is the big accomplishment this season,” Zitterbart said. Among other things, it allows them to analyze a water sample on the spot. “We don’t know how long the DMS signal from the water sample is viable,” he explained. “To be cautious, we process it within two minutes.”

Monitor the echo-sounder data, scoop the water, process the sample. Repeat. There were no whales here to distract from the monotony, just aching blue sky, a raw wind and the drone of the outboard. We were more than halfway through the survey before the echo sounder detected any krill—a patch of the crustaceans suspended above the seafloor in the shallow waters of the embayment. What the work lacked in adrenaline it made up for in potential scientific impact. “Nobody has surveyed much of these bays, so any data we can get are valuable,” Warren said. They returned to the ship with two krill patches detected and dozens of water samples analyzed—data that will help researchers understand how krill and DMS are distributed in the Southern Ocean and establish a baseline for measuring future change.

BY MARCH THE BRIEF AUSTRAL SUMMER was already drawing to a close. Daylight was ceding time to darkness, and the sea ice was starting to advance. Soon the humpbacks would head north to breed in the warm waters off the western coasts of South and Central America. Maybe that’s why they weren’t cooperating. Although the researchers had successfully tagged the five whales they had permits for, only two of the creatures went on to feed while they were being monitored. The other three snoozed or milled around the bays relaxing. To Zitterbart, the whales’ lack of interest in foraging means that next time the team needs to shift the timing of their research. “By March [the humpbacks] are already so big that they’re sleeping too much,” he said. “Earlier in the season is better because the whales are still building their body reserves and are more active.”

The water chemistry strategy may need tweaking,

too. Preliminary analysis of the samples obtained by the researchers as well as additional samples gathered by passengers through the ship’s citizen science program showed lower than expected signals from the DMS. Perhaps there just wasn’t a lot of DMS in the water. But another possibility, Warren speculated, is that a layer of melted freshwater atop the seawater diluted the signal. “The physics of water complicates things,” he said. To get a clearer picture of the chemistry, the researchers may need to sample deeper water.

Going forward, Zitterbart wants to move away from cruise-ship sightseeing schedules and focus on building a detailed picture of the activity in a single bay. The plan is to hitch a ride on a cruise to one of Antarctica’s research bases and stay there with just the Zodiacs. They’d map the whales, the krill and the water chemistry in the same place multiple days in a row and see how they change, then catch the mother ship on its way back.

First, though, they need to find a boat that can take them back to the bottom of the world. The cruise industry has a backlog of paying customers from the past few years who were unable to go on their planned voyages because of the pandemic. Trips the team might ordinarily be able to tag along on are fully booked. “We anticipated needing five years of data, and now three years are gone,” Zitterbart said of the pandemic’s effect on the project. He’s hopeful they may be able to get passage in 2024. In the meantime, he has turned his attention to research on the other side of the planet that could hasten help for the whales that need it most.

DURING THE PAST THREE YEARS, while waiting for the next Antarctic opportunity, Zitterbart, Owen and their colleagues have been studying the relationship among DMS, zooplankton and baleen whales in the waters off Massachusetts. Because they can’t tag North Atlantic right whales, they’re looking for correlations between DMS hotspots and right whale aggregations in Cape Cod Bay. The idea is to see if the chemical can be used as a proxy to predict where the whales will show up. The team surveys the whales by boat and plane, no tags required. Whereas the Antarctic research aims to identify the precise mechanism by which the baleen whales find their prey—whether it’s by following DMS gradients to swarms of krill or some other means—the Cape Cod work seeks only to establish whether these whales tend to show up in parts of the ocean where DMS concentrations are higher. If so, then regardless of whether the whales are actually detecting DMS or following some other cue that just happens to be linked to DMS, the scientists can theoretically use DMS values to predict where and when whales will appear.

Current efforts to protect North Atlantic right whales involve seasonal speed restrictions for ships and visual and acoustic monitoring systems. For example, from January 1 to May 15 in Cape Cod Bay, an important feeding ground for the right whales, all vessels 65 feet long or longer have a speed limit of 10 knots to reduce the likelihood of serious injuries to whales from

collisions. If whales are seen or heard in the area at any time of year, then boats of all sizes are asked to slow down and watch out for the creatures. A free app called Whale Alert displays seasonal management areas and whale-detection data on a map in near-real time.

But these management approaches lack predictive power, says research ecologist David Wiley of the National Oceanic and Atmospheric Administration's Stellwagen Bank National Marine Sanctuary, who works with Zitterbart on the DMS research. And big boats in congested shipping lanes often can't change course fast enough to avoid collisions with slow-moving whales. "With a predictive tool like DMS, we can plan rather than react."

In 2021 Owen, Zitterbart, Wiley and their collaborators published a paper based on the Cape Cod research showing that higher levels of DMS correspond to higher concentrations of zooplankton, so if baleen whales do track DMS, it will, in fact, lead them to prey. Now the researchers are looking at whether baleen whales actually aggregate in these DMS hotspots. Preliminary results indicate that both North Atlantic right whales and sei whales (another baleen species that eats copepods) do.

To strengthen their case, starting this year, the researchers will measure DMS concentrations in Cape Cod Bay and Massachusetts Bay every two weeks along standardized track lines before the right whales get there, when they arrive and when they leave. Their goal is to figure out how much DMS has to be in the water for the whales to show up. "We need to find out the thresholds, what's biologically relevant to the whales," Wiley says of the study, which he estimates will take around two years.

The dream is to be able to monitor places where DMS levels are building—and thus likely to be gathering spots for North Atlantic right whales—from space using satellite imaging. Wildlife managers could reroute ships around those areas or temporarily shut down fisheries or wind energy sites that might disturb the whales until the DMS levels subside and the whales move on. Climate scientists have long been interested in DMS because it promotes cloud formation. They have already found that the chemical can be detected from space. But it will take higher-resolution satellite data than is now available to predict the movements of whales.

For North Atlantic right whales and all the organisms whose fates intertwine with theirs, insights can't come fast enough. "If things don't change, right whales will go extinct in our lifetime," Wiley says. He believes the plight of this keystone species is the conservation issue of our time. Maybe with the help of hungry humpbacks in Antarctica and some curious scientists, North Atlantic right whales and other imperiled baleen whales will one day reclaim their place as rulers of the ocean realm. ■

FROM OUR ARCHIVES

The Prolific Afterlife of Whales. Crispin T. S. Little; February 2010.

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



Franco Banti/Winden Pictures

BLUE WHALES and other baleen whales are ecosystem engineers. Their health supports the health of many other species.



AN EARLY OPEN-PLAN office, designed by architect Frank Lloyd Wright for the S. C. Johnson company in the 1930s, was intended to boost productivity.





PSYCHOLOGY

Why People Hate Open Offices

Open-plan offices create health and productivity problems. Now insights from Deaf and autistic design communities could improve them

By George Musser

George Musser is a contributing editor at *Scientific American* and author of *Spooky Action at a Distance* (Farrar, Straus and Giroux, 2015) and *The Complete Idiot's Guide to String Theory* (Alpha, 2008). Follow him on Mastodon @gmusser@mastodon.social



IN 1967 CHEMICAL COMPANY DUPONT GUTTED A FLOOR OF AN OFFICE BUILDING in Delaware and rebuilt it. The firm put almost everyone into one big room with low partitions. In one corner, they provided a lounge with armchairs and Eero Saarinen end tables. This was the first major corporate adaptation of an “open-plan” office in the U.S., following the latest thinking by German architectural designers. Those designers held that companies increasingly relied on professionals—or knowledge workers, a term coined in 1959—who bristled at corporate hierarchies and needed more opportunities to collaborate. At DuPont, the new arrangement housed the company’s Freon refrigerant division. Freon began to be phased out in 1987 because it was destroying Earth’s ozone layer. The open-plan office, in contrast, has spread far and wide. By 2020 two thirds of knowledge workers in the U.S. worked in one, according to a survey by global architecture and design firm Gensler.

Most people wish they didn’t. The writing has been on the cubicle partition since the very first survey comparing this to other office designs was published in 1970. “Few ... like a completely open plan with little privacy,” the author wrote. The respondents—358 employees at 18 companies—complained about noise, distraction and soullessness. Apart from some references to ashtrays, the survey might as well have been written in 2020. In a sense it has been: dozens of recent surveys have recapitulated these findings. It’s now well established that open-plan offices fail to accomplish one of their major stated goals—increasing collaboration. Instead, researchers have found, they drive workers into more isolation. The design may also heighten office sexism and health troubles.

For convincing corporate real estate managers that open plans are bad ideas, no survey has had as much impact as an impromptu worldwide experiment, conducted during the past three years, called the COVID pandemic. It proved that most people who used to work in an office can work equally well from home. They’re Slacking, not slacking off. The pandemic also reminded everyone that open offices are germ-filled petri dishes. (This was known before: in 1995 a Finnish study found that sharing an office increased the chance of catching multiple colds a year by a third, nearly the same level of elevated risk as being a parent of young children, who repeatedly bring colds home from schools and day care.)

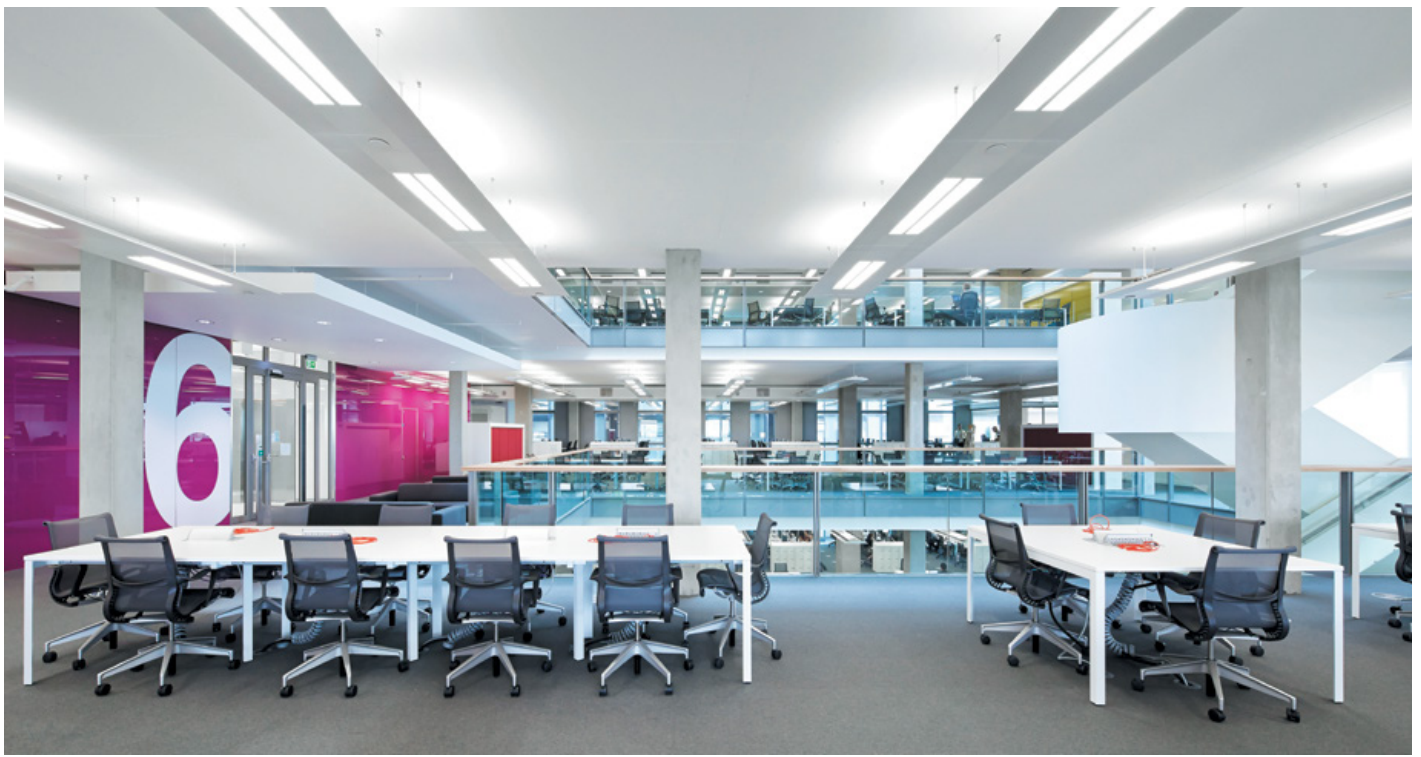
Gensler, in another survey in 2021, found that nearly a third of the people they asked said they wanted to work from home indefinitely. Half preferred a hybrid arrangement—ideally two office days a week. These new working habits have upended corporate office strategy. Companies that kept shaving inches off workstations to cram in more people now have half-empty facil-

ities. “The office thing is all bugged up,” says Alison Hirst, a business professor at Anglia Ruskin University in England, who has done case studies of the social dynamics in open offices.

Now designers are rethinking not so much the idea of an open office as its execution. In particular, they are doing more to accommodate a diversity of working styles. This trend overlaps with a movement toward inclusive design, which seeks to support people who are hard of hearing or autistic, as well as others who have trouble with conventional offices. Some of the architectural changes that reduce discomfort and productivity issues for these people work for open-plan offices in general. Companies, still looking at their real estate bills, don’t seem inclined to give employees back their private spaces, but they may change how work spaces function.

For example, Gavin Bollard, an information technology manager in Australia, who blogs about his experiences with autism, is deaf and uses hearing aids. “I’ve always struggled with the sound design of the open-plan office structure because it’s hard to know how loud I am talking, and it’s hard to hear effectively

Carol M. Highsmith/Buyenlarge/Getty Images (preceding pages)



when others are trying to be quiet,” he says. Both autistic and deaf people also object to visual clutter, harsh lighting and a feeling of personal vulnerability in an open plan.

These are universal complaints. “Autistic people are canaries in the coal mine: our needs aren’t actually different from typical people’s, just more intense and specific,” says Kirsten Lindsmith, another blogger on autism. By speaking up when neurotypical people might just grin and bear it, she and others can improve the office environment for all. “You design better for the center when you learn from the margins,” says Magda Mostafa of the American University in Cairo, an architect who focuses on design for autism.

A HARD PLACE TO WORK

AMONG ALL THE FINDINGS of office psychology studies over the decades, two stand out. The first is that the open office actually makes it much harder for people to collaborate. In 1984 the Buffalo Organization for Social and Technological Innovation (BOSTI) reported on its survey of some 6,000 workers at about 70 sites. Respondents in open-plan offices said they held back on talking to one another so as not to disturb the neighbors or broach confidential subjects in public. Although the BOSTI survey relied on people’s self-reported interactions, Ethan S. Bernstein and Stephen Turban of Harvard Business School corroborated it in 2018 with more objective measures. They had 152 workers at two companies wear sensors to track their movements. After moving from individual offices to an open plan, the workers spent only a third as much time interacting face-to-face as they had before, a striking downturn.

The second finding is that factors such as job function and gender influence how happy or unhappy people are with an open office. In early surveys, for instance, clerical workers said they were happier with an open office—it gave them someone to talk to while filing papers or transcribing memos. Women, however, have more recently reported a distressing fishbowl effect. In an [intensive case study of a new open office in 2018](#), Hirst and Christina Schwabenland of the University of Bedfordshire in England found that women felt the new design put them on display and responded by

AN OPEN-PLAN OFFICE in London has a typical modern style, with harsh lighting, little privacy and spaces for employees packed closely together—all features that workers dislike.

dressing up. Some found the expectations oppressive and told the researchers that they were being stared at and judged. Several in senior management, though, said they welcomed the opportunity to signal their status through fashion, so in this sense the open office actually reinforced the corporate hierarchy.

Men did not express comparable concerns. “It’s a reflection of a wider societal norm about who looks at whom,” Hirst says. The management team that decided on the design of the office were all men, and when Hirst and Schwabenland interviewed them, they mentioned gender only twice—and even those occasions were cringe-worthy, such as remarks that an open office would make it harder to have an affair.

A spectrum of opinion also shows up when it comes to a design trend that became hot in the early 1990s: the nonterritorial office, in which workers have no assigned space at all. Some companies instituted a “hoteling” system, in which workers could reserve an office or desk for a set period. Others began “hot desking,” in which workers had to scramble for spots like kids in a school cafeteria. By 2020 Gensler found that one in 10 knowledge workers in the U.S. had such an arrangement.

The nonterritorial office is simultaneously the most reviled and the best liked of arrangements. Gensler respondents without assigned desks were split down the middle. In 2008 Christina Bodin Danielsson of the Royal Institute of Technology and statistician Lennart Bodin (her father-in-law) of the Karolinska Institute, both in Stockholm, [surveyed 469 employees at 26 local offices](#). Those in assigned-seat open offices reported the worst health and job satisfaction, whereas those in private offices and nonterritorial or “flex” offices reported the highest. “The flex office appears to be preferred over traditional open offices, and in some cases, it seems to even be better than the [private] office,” Bodin Danielsson says. What workers in nonterritorial offices



DEAFSPACE, a design style developed at Gallaudet University, includes clear sight lines so deaf people can sign more easily (*top*), as well as translucent glass for some privacy (*bottom*).

give up in personalization, they gain in control; they can join a communal table when they need to share ideas and retreat to a nook when they have to concentrate.

But there is an important proviso: offices need plenty of nooks. In 2019 Bodin Danielsson and Töres Theorell of Stockholm University studied hot-desking offices that skimped on breakout rooms or otherwise didn't have enough space for everyone to find a work space to their liking, and employees were unhappier with this office type. When the goal is to pack in as many employees as possible, the nonterritorial office loses whatever advantages it had.

Unfortunately, that is all too often the case. For a 2021 paper, Ingrid Nappi and Hajar Eddial of the ESSEC Business School in the suburbs of Paris interviewed 16 managers and consultants who make corporate real estate decisions. These people cited expenses such as rent and utilities as their primary reason for in-

stituting hot desking or other nonterritorial features. They acknowledged that the savings could be offset by hidden costs such as lower productivity and more sick days, but these did not appear to factor into their decision.

DIFFERENT PEOPLE, DIFFERENT SPACES

ARCHITECTS AND DESIGNERS are coming around to the idea that one office size does not fit all. Since the 1990s they have been structuring offices as a quilt work of “neighborhoods,” customizing work spaces by company department. Accountants might get a conventional mix of workstations and conference rooms, whereas marketing people are all about the sofas and whiteboards. “That’s a much more tailor-made solution,” says Alonso Toledo, a strategy director at Gensler in San Francisco. He says his team designs the neighborhoods based on employee surveys and day-in-the-life narratives.

Paying attention to natural human variation is a core principle for designers working with Deaf, neurodiversity and disabilities advocates. Mostafa and others who plan spaces for these groups argue that their work can inform office design more broadly. The failings of the open office are typically sensory, such as noise, headache-inducing lights and visual cacophony—the very things that deaf and autistic people are sensitive to. Neurotypical people may find it expedient to make do rather than make a fuss, but deaf and autistic people are closer to their edge of tolerance.

Deaf people have a lot of experience with getting open floor plans just right. They often prefer an open plan because it gives them clear views of other people for signing. But they don't always want too much openness, either, because movement in the background can keep drawing their attention and lead to eye fatigue. When the balance of sight lines is right, “there’s an emphasis placed on always seeing one another and knowing where others are in space and being able to have connection to the other,” says Hansel Bauman, a designer in Washington, D.C., whose team at Gallaudet University developed architecture called DeafSpace.

“I think there’s a similarity there between what is a desire within the Deaf community and, historically, where people have been with the creative office.”

Robert T. Sirvage is a design researcher who worked with Bauman to develop DeafSpace and identifies as DeafBlind. (He is deaf and visually impaired.) Sirvage contrasts two architecture firms where he has worked. The first had a large, hangarlike space fitted out with rows of workstations. “In general, I don’t love rows, I will say that,” he says. “But in that setup, it was great.” Each team occupied a row. People could go home and leave papers and blueprints scattered around in collaborative work spaces; there was no leave-it-so-someone-else-can-use-it policy. The coherent spatial organization made it easier for Sirvage to work with hearing colleagues who didn’t sign. “If I can just point over in that direction, and we know what that direction is, and what’s there, and what that means, then we have a common schema,” he says. The second office lacked this clarity. It was stylish but labyrinthine and didn’t provide each team a dedicated meeting space. “It was hard to know what the focus of different spaces was,” he says.

Yushi Zhang, a master’s student in public health at Yale University who is neurodivergent, has her own tale of two offices. She worked at a newspaper in Chengdu, China, that had a huge, wide-open bullpen office, which people on the autism spectrum often describe as their nightmare. Yet she felt comfortable because the background noise was low and large windows provided natural lighting. Later, she moved to the U.S. and worked for an insurance company in a cubicle farm without much natural light. She had more privacy than before, but that also meant her interchanges with co-workers never got past small talk, which she and many other autistic people loathe. “Ask me ‘How are you?’—when I first came here, I really didn’t know how to answer that question,” she says. “I would be standing there, wondering, ‘Are you really wanting to know how I’m doing?’” She missed having natural lighting, too. “I feel like the bright light is too loud,” she recalls. “It’s screaming to me. It’s like my ear hurts.” She quit after three months.

Bauman and Mostafa both consult for the New York-based studio MIXdesign, where they merge the principles of designing for neurodiversity and for deafness. Reducing visual distractions and acoustic noise helps both autistic people and those who use hearing aids or cochlear implants. Adding breakout spaces along hallways and sidewalks lets autistic people take a breather and deaf people step out of the flow of traffic for a signed conversation.

Not every feature is a win-win, though. Making a room hypertransparent for people who are deaf may overstimulate people who are autistic. Widening a hallway to give people who are deaf more room to sign may make it harder for people who are blind to find their way. “Part of our philosophy in MIX is to ensure that that intersectional approach doesn’t, by creating access to one cohort, create a barrier for another,” Mostafa says. Often they best they can do is to create variety, so that everyone can find what they need—a spectrum of space.

LISTENING TO WORKERS

PERHAPS THE MOST IMPORTANT innovation of inclusive design is not the design itself but the process. Most people who have been through an office redesign get the feeling that companies solicit workers’ views less to inform the design than to get them to

acquiesce in whatever top management has already decided. Executives often “say, ‘Low-level workers and ordinary workers really don’t need to be included. We only need to give them the illusion of inclusion,’” notes Jennifer Kaufmann-Buhler, a design historian at Purdue University who has written a book on the adoption and spread of open offices.

Inclusive designers, on the other hand, adopt the disabilities-rights principle of “nothing about us without us.” The Deaf community, especially, has a strong ethos of inclusivity. Bauman describes what often happens when hard-of-hearing people go out for drinks after work. “First thing that happens is all the furniture gets moved. You’ve got to get so you can see each other; everyone’s concerned about the lighting conditions and what the background is,” he says. “Always the manager of the bar comes over and gets upset because you’re moving the chairs.” Bauman describes DeafSpace as this sense of agency, writ large.

So far, though, he and his colleagues at MIXdesign have yet to demonstrate these principles in an actual office; their practice focuses on schools and museums. Even these institutions, which give a high priority to accessibility, have to justify the extra expense. So designers must make the case for a net benefit over the long term. “It’s probably the single most challenging element of the work that we do,” Mostafa says.

Toledo says he is encouraging companies to use the pandemic as an opportunity to evolve. “It seems to me a bit forced that we’re assuming that there needs to *be* an office,” he says. Some companies are going entirely virtual and building their human connections in other ways, such as regular staff retreats. A shared office can provide everyone with equal work resources, but there are other ways to perform that democratizing function, Toledo says. Many companies are now paying at-home employees for their Internet service and ergonomic chairs; some U.S. states even require it.

Putting these ideas together, Bauman sees a huge opportunity. With so many people working from home, companies need less office space, and building owners are considering converting offices to apartments. These spaces—both work and home—could easily be built to inclusive-design standards: plentiful natural lighting, quieter air-handling systems and, above all, variety.

There may be “places where you might limit visual exposure and visual access, and there’s other places you might open up visual access,” Bauman says. A single building might have a mix of apartments and co-working spaces, not only supporting diverse work patterns but also creating enclaves for people from the Deaf and neurodiverse communities, as well as others with particular needs. “It inherently has the ability to create communities for people of difference,” he says.

Toledo emphasizes that no one is sure what the next stage in the evolution of the office will be. Businesses and workers will need to live with this uncertainty and embrace an experimental, trial-and-error spirit. “The planning that we do is always like the light from the stars,” he says. “We are seeing the past.” And hoping that we can avoid repeating its mistakes. ■

FROM OUR ARCHIVES

The Origin of Cubicles and the Open-Plan Office. George Musser; ScientificAmerican.com, August 17, 2009.

scientificamerican.com/magazine/sa

PHYSICIST Chien-Shiung Wu in her lab at Columbia University in 1978.



Michelle Frank is a science writer and poet at the CUNY Graduate Center. Her work has received support from the Consortium for History of Science, Technology, and Medicine; Friends of the Center for History of Physics at the American Institute of Physics; the American Physical Society; and the Sundog Poetry Center.



EXPERIMENTAL PHYSICS

A Hidden Variable behind Entanglement

The little-known origin story of the science
that won the 2022 Nobel Prize in Physics

By Michelle Frank

IN NOVEMBER 1949 CHIEN-SHIUNG WU AND HER GRADUATE STUDENT, IRVING SHAKNOV, DESCENDED TO a laboratory below Columbia University's Pupin Hall. They needed antimatter for a new experiment, so they made their own, using a machine called a cyclotron. The machine's multiton magnet was so gigantic that, according to university folklore, a decade earlier administrators had to blast a hole in an exterior wall and recruit the football team to maneuver the block of iron into the building.

The magnetic field produced by a cyclotron accelerates particles to dizzying speeds. In the lab, Wu and Shaknov used it to bombard a sheet of copper with deuterons, generating an unstable

Lynn Gilbert

(Shanghai C-39) (Approved by Department January 15, 1934)

AMERICAN CONSULATE-GENERAL

SHANGHAI, CHINA, July 29, 1936

PRECIS OF INVESTIGATION.

Name: **WU, Chien-shiung** (吳健雄)

Nationality: Chinese.

Class: Student.

Nonquota Immigration Visa No.: 14/1936-7

Section 6 Certificate issued by the **Bureau of Public Safety** at Shanghai, China, on July 6, 1936

Visa granted by this Consulate-General on: July 13, 1936

Bearer's birthplace: Liu Ho, China.
Date of birth by Chinese or Western reckoning: May 29, 1912.
Family (ages by reckoning): Not married.

Review of bearer's education: Attended the National Central University for four years graduating in 1934 with B.S. degree; for the following year she taught chemistry at the National Chekiang University, Hangchow; for the past year she has been doing research work in National Research Institute, Shanghai.


Plans for education in the United States: Will pursue a course in Physics at the University of Michigan, Ann Arbor, for four years for Ph.D. degree

Provision for financial support: Full support will be provided by applicant's father, Wu Dzong Ye, Traffic manager of the Wusih-Shanghai Motor Transport Co., Ltd., Shanghai.

Reference in the United States: Prof. Rufus, University of Michigan.

Consular investigation and remarks: Examination has been made of the applicant who has presented a formal acceptance as a student from the University of Michigan; a letter from the Chancellor of the National Central University, Nanking, certifying to her graduation therefrom; a letter from her father, Wu Dzong Ye, assuming full support and vouching for her purpose to study; a letter from B. L. Chen, Chairman of the National Construction Commission, Shanghai, introducing the applicant and her traveling companion, Miss Tung Ju Fen, and vouching for the standing of their respective families as well as guaranteeing financial support.

Intended departure: *Al*
Stowage: PRESIDENT HOOVER
Sailing-date: August 11, 1936
Port of entry: San Francisco, Calif.
W
C. E. Gauss,
American Consul-General.
811.11. Wu, C.S.
HDP/mf



WU'S immigration file from 1936.

isotope, Cu 64, as a source of positrons—the antimatter. When a positron and an electron collide, they annihilate each other, releasing two photons that fly apart in opposite directions. A few years earlier physicist John Wheeler had predicted that when matter and antimatter met, the resulting photons would be orthogonally polarized. Wu and Shakhov were looking for conclusive proof of Wheeler's so-called pair theory.

They weren't the first. An earlier team of experimentalists had a high margin of error, so their results were not sufficiently reliable. A second team came back with results that were too low to match Wheeler's predictions. But Wu was known for her extreme precision and strategic experimental design. The prior year she had proved Enrico Fermi's theory of beta decay after more than a decade of attempts by others.

Wu and Shakhov packed the copper isotope into a tiny capsule, eight millimeters long, and waited for electrons and positrons to collide inside the apparatus. Then they tracked the resulting annihilation radiation at the farthest edges of their experiment, using two photomultiplier tubes, anthracene crystals and a scintillation counter as a gamma-ray detector.

Ultimately they captured significantly more data than their predecessors, and what they saw was astonishing. Their evidence suggested that pairs of photons from particle collisions remained polarized at right angles to each other—consistently—as if somehow connected, even at a distance. Their experiment had proved Wheeler's pair theory, and Wu and Shakhov published their findings on New Year's Day in 1950 in a one-page letter to the *Physical Review*. But it also became the first experiment to document evidence of something weirder: that the properties of entangled particles are always perfectly correlated, no matter how far apart they stray. Entanglement is so strange that Albert Einstein thought it proved where quantum physics went wrong.

In 2022 the Nobel Prize Committee honored experimental work on entanglement by three physicists. John Clauser, Alain Aspect and Anton Zeilinger had each produced increasingly convincing evidence for the phenomenon by improving on their predecessor's experimental design. They ruled out one alternative explanation after another until, finally, entanglement was the only conclusion left standing. Although Wu's 1949 experiment had not been designed to rule out competing explanations, historians agree it was the first to document entangled photons. Yet Wu, who died in 1997, was not mentioned when the 2022 awards were announced. It's not the first time she has been overlooked.

CHIEN-SHIUNG WU WAS BORN the same year as the New Republic of China, in a small town in the Yangtze River basin. Her father, Zhong-Yi Wu, was an intellectual, a revolutionary and a feminist. To celebrate his daughter's birth and the end of dynastic rule, Zhong-Yi hosted a party in the spring of 1912 where he announced his daughter's name and his new plan to open the region's first elementary school for girls. At a time when most names for girls suggested a delicate fragrance or beautiful flower, Zhong-Yi's name for his daughter translated to "strong hero."

Chien-Shiung grew up in the crosscurrents of Chinese nationalism and the New Culture Movement that criticized traditional Confucian values. In 1936, at age 24, having reached the limit of what China could offer in physics training, she boarded the SS *Hoover* bound for California. Political movements were calling for "science and democracy," along with a generation of scholars who could elevate China's status. Wu was off to pursue a Ph.D. in physics. She would study under pioneers such as Emile Segrè, Ernest Lawrence and J. Robert Oppenheimer.

At the University of California, Berkeley, Wu became a star student. Her dissertation research on the fission products of uranium was so sophisticated and sensitive that it was turned over to the military and embargoed until the end of World War II. Yet Wu had trouble finding a job after graduation. For two years she depended on mentors for research appointments. At the time, none of the top 20 research universities in the country had a woman on the physics faculty.

Gender bias was not Wu's only obstacle. A year after her arrival in the U.S., the escalation of World War II cut off communication with China, and discrimination against Asian immigrants had intensified, especially on the West Coast. In 1940 Berkeley's acting comptroller wrote to Wu's supervisor to warn him that Wu's employment would be approved only on a temporary basis; less than a year later he wrote again: "Regulations laid down by the Regents" meant "Miss Wu is not eligible for employment," and "immediate steps should be taken to dismiss this employee from your staff."

When Oppenheimer left Berkeley in 1942 to lead the Manhattan Project, he brought many of his students along; Wu, despite her acclaim, was not invited.

Eventually Wu moved East for a teaching position at Smith College. The following year she became the first woman hired to the Princeton University physics faculty. Not long after, the Manhattan Project finally recruited her, and she played a quiet, conflicted and crucial role in the development of the atomic bomb. Yet Wu navigated repeated investigations by immigration authorities and threats of deportation for years. When she had left China in 1936, Wu expected to be away for only a short while. In 1945, when the silence between the U.S. and China lifted, China was embroiled in a brutal civil war, and relatives cautioned against returning too soon. By 1949, the year Wu observed evidence of the criterion for entanglement, Mao Zedong had established communism in the People's Republic of China, and McCarthyism was ramping up in the U.S., making travel home nearly impossible. She never saw her family again.

ENTANGLEMENT EMERGES from the most rigorous branches of mathematics and physics yet has poetic appeal. Abner Shimony, a philosopher and physicist, called it “passion at a distance.” Entanglement offers the wild notion that once certain particles or systems interact, they can no longer be described independently of one another. What happens to one, no matter how far it may travel from its entangled partner, instantly affects the other, as decades of evidence now shows. The characteristics of entangled particles are correlated, without any apparent communication, and at any distance. What's more, each member of the entangled pair seems to lack a complete set of definite properties until the moment when one partner is measured. Then, instantly, the entangled pair will be in sync—even if the particles have drifted galaxies apart. It's the ultimate star-crossed love.

To grasp entanglement's full strangeness, it helps to understand that when quantum physicists first set out to quantify the position and motion of subatomic particles, the tiny objects could not be pinned down. Sometimes particles seemed localized and distinct. At other times, the particles showed a broad and wavelike behavior, with influence spreading out over large regions of physical space relative to their natural size. Sometimes early 20th-century experimentalists couldn't be sure the particles were even tangible objects at all.

In 1927 physicist Werner Heisenberg called this problem the “uncertainty principle.” He studied under the founder of quantum mechanics, Niels Bohr, and Bohr had coined the term “complementarity” to describe the uncanny experimental results that quantum physics produced. For Bohr, one way to think about the entire confusing situation was to presume that certain pairs of observations such as a particle's “position” and “momentum” were complementary to one another; complementary characteristics could not be perceived or measured exactly in the subatomic world at the same time. Perhaps those characteristics did not even exist until the very moment of measurement. Things got weirder, though, when the mathematics of quantum mechanics

suggested that measuring one particle might instantaneously influence the state of another particle far away. This seemed especially odd if the particles had no measurable attributes in the first place until the two, somehow, telepathically connected.

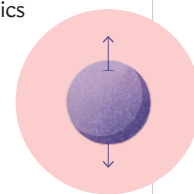
In 1935 Einstein, Boris Podolsky and Nathan Rosen tried to poke holes in quantum mechanics by pointing out how counterintuitive it seemed. The famous Einstein-Podolsky-Rosen paradox (“EPR”) pointed directly at entanglement. EPR suggested that there had to be a better explanation for why and how one particle could impact its entangled partner faster than the speed of light. Einstein derisively nicknamed the phenomenon “spooky action at a distance.” For Einstein and his co-authors,

Quantum Weirdness

Two of the most counterintuitive aspects of quantum physics are superposition and entanglement.

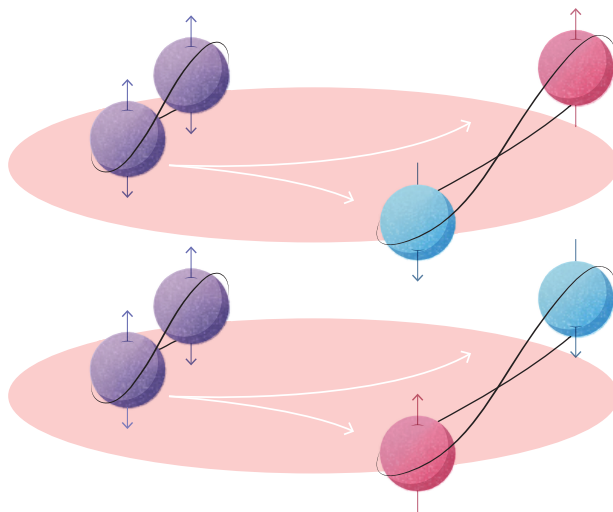
Superposition

According to quantum physics, photons and subatomic particles can exist in multiple states and even multiple locations simultaneously—a state called superposition—up until the moment they are measured. Whereas a classical object, such as a marble, can spin in only one direction at a time, a quantum particle can be understood to be in two simultaneous “spin states”—both “spin up” and “spin down,” for example—at once. A photon in superposition can be understood to be polarized in two different and conflicting directions, simultaneously. And a quantum object can be understood to be both “there” and “not there” at the same time. In other words, objects in quantum superposition seem to lack certain definitive properties until the moment they are measured.



Entanglement

Entanglement allows two particles in superposition to forge an instant connection, so that an action performed on one of them (like measuring one part of an entangled pair) affects both partners, even when they are separated by great distances. In the image below, the entangled particles start out in a superposition of both up and down spin states. When an outside measurement on one member of the pair forces the particles to “pick” a single state, the two partners always pick coordinated states. Wu's 1949 experiment provided early evidence of entanglement, that is, pairs of photons from particle collisions remained polarized at right angles to each other—consistently—even when those photons were separated at a distance. The results Wu observed depended on the correlated nature of the photons in her experiment.





WU shown with industrial scientific equipment in 1963.

spooky action proved that quantum theory was still incomplete.

Like Einstein, physicist David Bohm felt sure there was a perfectly reasonable explanation for entanglement. Perhaps we couldn't see it quite yet, but the explanation might not be so spooky after all. It could be attributed to hidden variables. Physics simply had more work to do to find them. In 1957 Bohm and his graduate student Yakir Aharonov wrote about how photon research could harness the famous EPR paradox to reveal these hidden variables. "[T]here has been done an experiment which, as we shall see, tests essentially for this point, but in a more indirect way," Bohm wrote.

That experiment, says Indianara Silva, a professor of physical sciences and history at the State University of Feira de Santana in Brazil, was the 1949 Wu-Shaknov experiment.

Silva is a historian who is acutely attentive to the missing stories of women in science. When Wu and Shaknov made the first precise measurement of Wheeler's pair-theory in 1949, Silva says, they became the first to document entanglement between photons, inspiring decades of later research in quantum foundations. Silva has identified a string of publications by other physicists and historians who acknowledge Wu's 1949 observation of entangled photons. She begins with Bohm in 1957 and continues through Zeilinger, one of the 2022 Nobel laureates, who wrote in 1999 that "an earlier experiment by Wu and Shaknov (1950) had demonstrated the existence of spatially separated entangled states."

Bohm had good reason to trust Wu's findings. He was a few years junior to Wu when they were graduate students at Berkeley. Both had studied under Oppenheimer, and both worked in E. O. Lawrence's prestigious radiation laboratory. Bohm had every reason to know of Wu's stellar reputation. He acknowledged Wu in a footnote in his 1957 article.

Silva traces how Wu's experimental work—in 1949 and later in 1971—prompted later entanglement experiments. Silva's findings were published in *The Oxford Handbook of the History of*

Quantum Interpretation in 2022. She points out how Bohm's article about hidden variables inspired John Bell, who proposed that the number of quantum coincidences between particles could be predicted and counted. In 1964, in an obscure journal called *Physics, Physique, Fizika*, Bell discussed Bohm's 1957 paper (which referenced Wu's experiment) and launched his own new theory. A few years later at Columbia, a young Clauser found "Bell's Theorem" in the library. The theory inspired Clauser to design a new experiment, one he hoped could prove Bell right, showing hidden variables were real.

Interestingly, the Wu-Shaknov letter to *Physical Review* in 1950 talks about Wheeler's pair theory, but it is silent about entanglement. In 2012 physicist F. J. Duarte called Wheeler's pair theory "the essence of entanglement." Other physicists, and historians like Silva, clearly spotted the connection, too. So why did Wu not mention quantum entanglement in her 1950 letter?

Wu might have been hesitant to discuss evidence of entanglement because throughout the 1950s and 1960s, such quantum-foundations work was stigmatized as junk science. Back then, explains David Kaiser, a professor of physics and history of science at the Massachusetts Institute of Technology, the idea of using an experiment to prove or disprove theories about quantum physics or to test for local hidden variables was "not even an inkling" for most physicists. Researchers who explored questions about entanglement often disguised their research because backlash could stymie a promising career. We're left to wonder whether Wu might have done so as well.

Silva points out that Wu came back to her 1949 experiment more than 20 years later to refine it further. By then, Wu was far more professionally secure, and she addressed questions about quantum mechanics directly. She favored traditional quantum-

entanglement interpretations, not Bohm's theory. In 1971, when she designed a new version of the 1949 experiment, Wu wrote that it "should certainly quiet those proponents of the hidden variables."

When Clauser published his proposed test of Bell's theorem in 1969, he took care to distinguish the Wu-Shaknov experiment from his own. Clauser had wanted to prove hidden variables were real; instead, in 1972, he *disproved* the existence of hidden variables and demonstrated entanglement with even greater certainty. He had counted coincidences, much as Bell suggested, but there were far more coincidences than hidden variables could explain. Clauser's work prompted Aspect and Zeilinger's later experiments, which closed lingering loopholes and supported entanglement further. Together those experiments led to their 2022 Nobel Prize.

BY THE TIME BOHM'S PAPER on hidden variables emerged, much had changed in Wu's life. She had married and moved to the East Coast. She had broken a glass ceiling at Princeton, had a child and had become a U.S. citizen. She was on the faculty of Columbia University, though still not a full professor.

In 1956 Wu's Columbia colleague T.D. Lee approached her for advice about an odd question. He and his research partner, Chen Ning Yang, wondered if some of the tiniest particles in the universe might violate long-established expectations. In response, Wu pointed Lee to a body of research, and she described a handful of possible experiments to address the questions he posed.

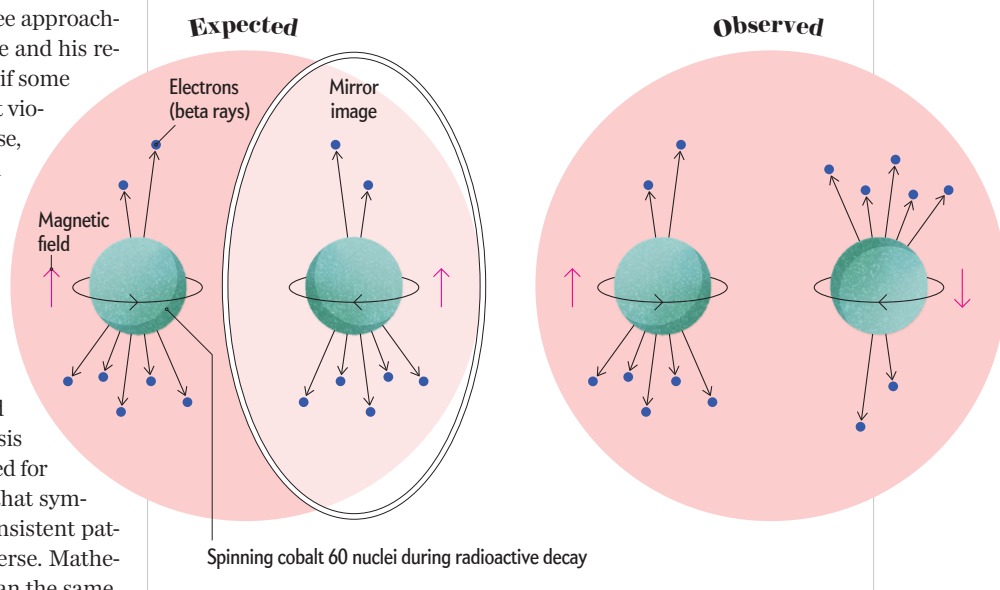
Yang and Lee were far from the likeliest of candidates to act on Wu's suggestions. Both were theorists, not experimentalists like Wu. In an oral history with the Simons Foundation half a century later, Yang confessed that neither he nor Lee had any sincere belief in 1956 that their hypothesis would hold up. In fact, physicists had assumed for decades that the opposite would be true: that symmetry would be among the immutable, consistent patterns in many building blocks of our universe. Mathematical conservation laws said that if you ran the same sequence of events forward and backward in time, the events would remain symmetrical. Yang and Lee's hypothesis, though, suggested that the behavior of nuclear particles in beta decay might not look the same if you flipped the events in an imaginary mirror. The idea simply did not align with conventional scientific thought or with common sense.

Like her father, Wu was willing to question mainstream thinking. She suspected the issue was important, and she knew how to approach it. So she designed and led an experiment to address her colleagues' ideas. It meant canceling a trip to China that would have been her first visit home since 1936.

To run the experiment she had in mind, Wu needed to reduce the temperature of radioactive cobalt 60 nuclei until the particles almost stopped moving. She wanted to study whether the daughter particles of nuclear decay shot out in a symmetrical pattern—as all of mainstream physics believed they would—or if the

Violating the Principle of Parity

Chien-Shiung Wu showed that weakly interacting particles inside an atom's nucleus do not behave symmetrically like the rest of the universe. In 1956 she devised an experiment to test the so-called principle of parity for weakly interacting particles, such as those that are produced during radioactive decay (*shown below*). When an atom has either too many protons or too many neutrons, a nucleus ejects extra electrons as it transforms from one element into another. Wu and her partners used a powerful magnet at ultracold temperatures to align the magnetic spins of cobalt 60 nuclei. Then they watched to see in which direction the electrons shot out from those nuclei. When the experimenters reversed the direction of the nuclei's spin from left to right, they expected to see a mirror image of what they had seen before. Instead the experiment revealed that parity was not conserved for weakly interacting particles: the spinning nuclei of cobalt 60 kept emitting electrons preferentially in one direction, relative to their spin. This unexpected result shocked the physics world.



radioactive patterns showed a preference for "right-handed" or "left-handed" behavior. She enlisted cooperation from the National Bureau of Standards (NBS, now the NIST) in Washington, D.C., because, unlike many other labs, they had the technology and expertise to work at temperatures close to absolute zero. For months Wu commuted between New York City and Washington, overseeing graduate student work that supported the experiment.

By January 1957, in close consultation with Yang and Lee, Wu and her NBS partners made an astonishing discovery. Beta-decay particles were slightly "left-handed," not symmetrical as all of physics had assumed. As soon as it was announced, Yang, Lee and Wu, along with other experimentalists who followed Wu's work, found themselves on a national conference circuit, their names and images splashed across the popular press. When the

American Physical Society met at the New York Hotel that year, they presented their findings in what the *New Yorker* called “the largest hall ... occupied by so immense a crowd that some of its members did everything but hang from the chandeliers.”

That October, Yang and Lee became the first two Chinese Americans in history to win the Nobel Prize. Although Nobel rules allowed up to three award recipients each year, Wu was not included. It could hardly be more apt that the law of physics that Wu toppled was called the principle of parity. Like a prism, the 1957 Nobel Prize separated out elements of identity like bands of light, rendering the impact of gender more visible. The following year Columbia finally promoted Wu to the rank of full professor.

IN HIS NOBEL LECTURE that December, Yang told the committee and guests how crucial Wu’s experiment had been, making a bold statement that the results were due to Wu’s team’s courage and skill. Lee would later plead with the Nobel Committee to recognize Wu’s work. Oppenheimer publicly stated that Wu should have shared in the 1957 prize. Segrè called the overthrow of parity “probably the major development of physics after the war.”

Other scientists criticized Wu’s exclusion from the highest recognition of scientific achievement, too. In 1991 Douglas Hofstadter, the author of *Gödel, Escher, Bach*, organized scientists to write letters to the Nobel Committee recommending Wu for the physics prize. And in 2018, 1,600 researchers invoked Wu’s name in an open letter to CERN challenging current-day sexism in physics. “[T]here are at least four women whose work is relevant for particle physics who are widely viewed as having deserved the Nobel prize but who did not receive it, in some cases even though their male colleagues did,” the letter says. Wu’s name appears at the top of that list.

After overthrowing parity, Wu became the first woman to receive the Comstock Prize from the National Academy of Sciences; the first female president of the American Physical Society; the first physicist to receive the Wolf Prize; and the first living physicist to have an asteroid named in her honor. Her work pushed open doors to university teaching in the West for women and scientists of color. In China, she is revered. In 2021 the U.S. Postal Service released a [Forever stamp](#) with Wu’s portrait. Today Wu’s parity experiment is understood as an early step on the path to what would become the Standard Model of particle physics, and it points toward possible answers about why matter exists in our universe at all.

Wu’s early entanglement work, however, remained in obscurity. Sometimes by examining one part of a system, we begin to perceive a related link, at a distance. The 2022 Nobel Prize celebrated a set of connected experiments that took place at great distance from one another. Even though Wu couldn’t have been awarded the prize posthumously, her early research is finally coming to light as a crucial part of that entangled history, thanks in large part to historians such as Silva. Society may prefer a hero narrative or the myth of a lone genius, but a closer look reveals that extraordinary science, like entanglement itself, depends fundamentally on connection. ■

FROM OUR ARCHIVES

[The Overthrow of Parity](#), Philip Morrison; April 1957.

scientificamerican.com/magazine/sa



American Association of Physics Teachers; Courtesy of AIP Emilio Segrè Visual Archives



WU at a particle physics conference in Israel in 1967 (seated in front row).

A LEOPARD in Mumbai defies notional borders between humans and the wilderness.



Living with Leopards

Big cats are learning to live among people—and if the carnivores are to survive, people must learn to live with them

By Vidya Athreya

Vidya Athreya is an ecologist who researches human-carnivore interactions. She is a senior scientist at Wildlife Conservation Society-India.



W

HERE THE WILD THINGS ARE IS A SHIFTING CONCEPT INFLUENCED BY culture, upbringing, environs, what we watch on our screens, and, for me, the tussle between my education as a wildlife biologist and my experiences in the field. Taking to heart a core tenet of conservation science—that wild animals, certainly large carnivores, belong in the wilderness—I began my career in the 1990s by visiting nature reserves in India to study Asiatic lions and clouded leopards.

When in the new millennium I stumbled on leopards living in and around villages, I was shocked. “They shouldn’t be here!” my training shouted. But there they were, leaping over the metaphysical walls scholars had constructed between nature and humankind as nonchalantly as they strolled past the physical boundaries of protected areas.

Take the first leopard I collared with a GPS tag: a large male that had fallen into a well near Junnar, in the Indian state of Maharashtra, in the summer of 2009. He took refuge on a ledge just above the water, and forest department personnel rescued him by lowering a ladder with a trap cage at the top into the well. It had been a hot day, and the leopard was clearly old and very tired, but even after climbing up into the cage, he remained unruffled. My team—veterinarian Karabi Deka, a local farmer named Ashok Ghule who served as a translator and guide, me (a doctoral student at the time) and some others—made sure he was secure, and Deka shot a tranquilizer dart into him through the cage bars. He didn’t even growl. His calm, gentle and elderly demeanor induced us to call him Ajoba, which means “grandfather” in Marathi, the area’s local language.

We released Ajoba the same night in a forest 52 kilometers away. Over the next weeks we watched his movements, as revealed by the intermittent signals from his collar, with astonishment and trepidation. Ajoba walked right out of the forest and traveled over farmland, through another wildlife preserve, across an industrial estate full of smoke-belching factories and a four-lane highway, and past a busy train station. After walking 125 kilometers in about a month, he reached Mumbai and settled down near the edge of the Sanjay Gandhi National Park (SGNP), where jungle borders a city of more than 20 million people.

For years the forest department had been assuaging public fear of leopards by capturing them from inhabited areas and releasing them in forests. Ajoba must have been exiled from Mumbai’s suburbs and now had simply gone home.

As humans, we believe that only we have agency. But like tens of millions of people in rural India whose forests and fields are being converted to mines, factories, dams and highways, animals must adapt if they are to survive in an increasingly challenging

world. The biology of large cats dictates that they roam across tens or hundreds of kilometers to find mates and have cubs; failing such dispersal, inbreeding and, with it, extinction are imminent. It is because these felines refuse to be confined to the 5 percent of India’s land surface designated as protected that—alongside 1.4 billion people—the country continues to shelter 23 percent of the planet’s carnivore species, including at least half the world’s tigers, the only surviving population of Asiatic lions and almost 13,000 leopards.

But they must not cause so much harm that people retaliate. Around the world the primary threat to big cats is humans. According to the Wildlife Protection Society of India, poachers in search of skin, claws or bones, for which there is an illicit market, or villagers angered by the loss of livestock killed almost 5,200 leopards in that country between 1994 and 2021. Even so, something about the way much of rural India views wild animals enables thousands of leopards to live in areas with roughly 400 humans per square kilometer. Observing how they do so convinced me that if large carnivores are to survive into the future, it is necessary to change the way the rest of us view them.

This is a story of two highly adaptable species sharing the same space—and a story of hope in these otherwise bleak times for wildlife. Here commonplace notions about large cats being fearsome and bloodthirsty break down. Instead we find wild carnivores and people trying to survive, having their young and living in their societies right next to each other.

AN EYE FOR AN EYE

I’VE BEEN FASCINATED with large cats since I first encountered the story of Lord Ayyappa, when I was a little girl. Ayyappa is a Hindu god who, as a child, was ordered to get tiger’s milk. He did so, returning on the back of a tigress. The imagery in my

Steve Winter (preceding pages)



MUMBAI, a city of more than 20 million people, borders the Sanjay Gandhi National Park (SGNP) and other green areas in which 50 or so leopards live.

picture book was peaceable, full of compassion and understanding, and it seems to have stayed in my head.

In 2001, after getting master's degrees in ecology and evolutionary biology, I found myself living in the Junnar subdistrict, a rural area full of sugarcane fields. I was the mother of a small child. I had followed my then husband, a physicist, to the Giant Meter-wave Radio Telescope there and planned to devote all my time to raising my daughter. But I became intrigued by reports of large numbers of people in the area being injured or killed by leopards. Between 2001 and 2003 leopards attacked 44 people in Junnar. Some of those assaults may have been accidental, but others were premeditated, as when cats lifted small children who were sleeping outdoors between their parents, killing them so swiftly and stealthily that no one woke up.

It made no sense. Why were there so many leopards in this agricultural landscape, which was bereft of wild herbivores for them to feed on? And why were the animals so aggressive? There were no reports in the conservation literature on large carnivores outside of protected areas, but Maharashtra's forest department was capturing leopards all over the state's rural areas for release into forests. (Leopards are smart, but being cats, they will enter boxes—trap cages.) I received a small grant and put together a team to microchip them. The tags did not transmit signals, but a handheld reader would allow us to identify an individual if it happened to

be recaptured. For every leopard, I noted where it was caught and why—and I soon realized they were being moved to jungles not because they'd attacked people but simply because they'd been seen near villages.

In 1972 the Indian government had passed the Wildlife Protection Act, which prohibited the killing of endangered animals. (A tiger or leopard that was proved to habitually prey on people could, however, be shot.) Since the 1980s forest departments in India, held responsible for large wild animals, had been removing leopards from inhabited areas as a way of reducing conflict between leopards and humans. By the mid-2000s it was clear that, at least in Junnar, translocation itself was increasing conflict.

For years Junnar's villagers reported an average of four leopard attacks a year. Then, in February 2001, the local forest department initiated the translocation program. During the following year its staff released 40 leopards caught in the region and elsewhere into two protected areas tens of kilometers away. Attacks on humans near the reserves more than tripled, to about 15 a year, and the fraction of fatal attacks doubled, to 36 percent. And there were more attacks near the release sites. One leopard caught and tagged in Junnar, and which the forest staff moved to a protected area in Maharashtra's northwest, went on to attack people near its release site. (We realized it was the same cat when it was recaptured, and we scanned its microchip.) It was the first



VETERINARIANS and others radio collar a leopard to understand its movements and behavior.

time the region had experienced such attacks, despite leopards having always lived there.

Leopards are very secretive, so we cannot really know how capture and release affects them. What we do know is that stress increases aggression, and moving large cats in captivity from one zoo to another elevates their levels of stress hormones. Home is a biological imperative for cats. And in the few places where wild leopards occasionally show themselves, such as Sri Lanka and Africa, they have social lives, centered on females; it stands to reason that disrupting their relationships compounds the stress of relocation. Moreover, studies in Russia on collared tigers found that when they did attack, they were usually responding to being provoked or injured. In 1988 Asiatic lions preyed on humans for the first time since 1904—after 57 lions were moved from human-dominated areas to Gir National Park, a protected area dedicated to them.

Had the translocated cats learned to see humans as threats? Whatever the reasons may be, when leopards were separated by humans from their homes and families and released in unfamiliar terrain, it was disastrous for the villagers they chanced on.

LIVE AND LET LIVE

WHILE TRAVELING around Maharashtra microchipping leopards in the early 2000s, I'd become intrigued by a region of beautiful hills and valleys just north of Junnar. A lot of leopards were being captured in this agricultural area—one female and her cubs were trapped inside a wheat field. There were apparently many leopards in a place with many people, yet there were no attacks. I wanted to understand why.

By then I had been working on leopards with the forest department for four years, and my record persuaded senior wildlife biol-

ogists [Ullas Karanth](#) and Raman Sukumar to support a doctoral project investigating leopard ecology using tools such as camera traps. When I started work around Akole, a town of 20,000 people, I wasn't even sure there were enough leopards there for us to learn anything meaningful. No scientist had ever reported a leopard from this locale. But the field staff of the forest department showed me the evidence: fresh pugmarks (paw prints) at the side of a field, in courtyards and in school playgrounds; kills hanging in trees; dogs missing or injured; a dead pig here and there. It seemed to be in the right place. But how could I design a camera-trap study in a place where people were everywhere? I was one of the last biologists using film cameras. Every roll was precious, and the cameras might get stolen.

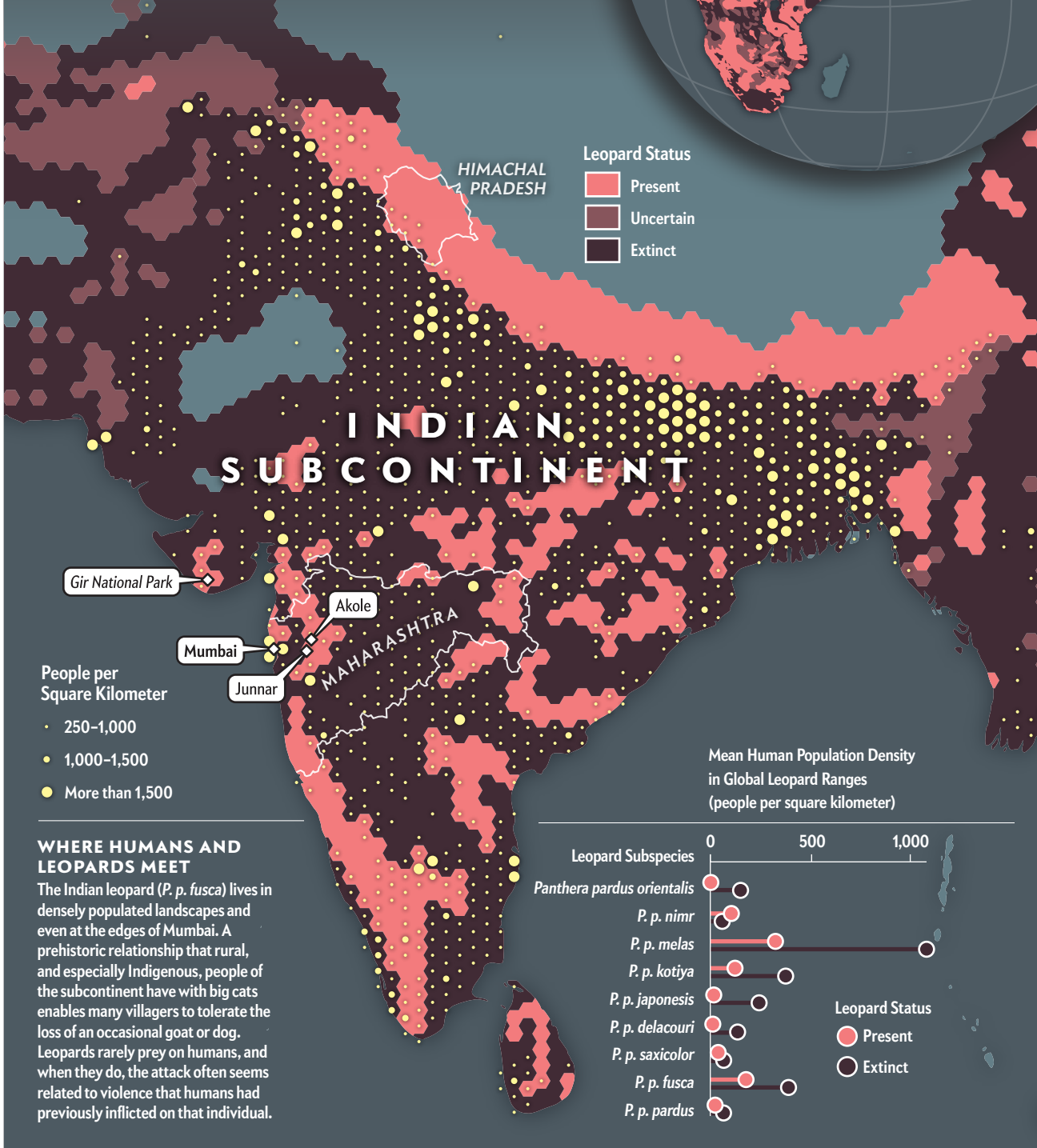
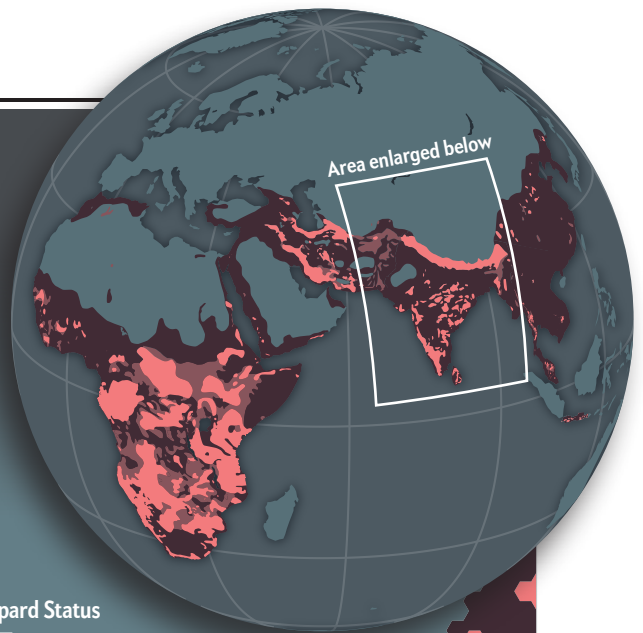
It was a difficult period for my six-year-old daughter, who would cry every time I left for Akole, where I stayed during weekdays. I began by interviewing 200 villagers about their livestock losses and leopard encounters and telling them about my project. At first they were surprised to see a field ecologist, particularly a woman, setting up cameras in sugarcane fields and walking for kilometers to look for leopard signs, but soon they got used to me and would offer me breakfast, lunch or tea when they saw me.

In the early days it was scary to walk in six-foot-high stands of sugarcane and other tall crops where the animals could hide or along dry streambeds with overhanging shrubbery where they might rest. To avoid surprising a leopard, I took to talking to myself if I walked alone; if someone else was there, we chatted.

As I talked to the farmers, my fear just went away. They were regularly interacting with the leopards. A man at a local tea shop recounted, with great amusement, how his wife had thrown dirty water from her home onto the field below and was terrified to hear the growl of a leopard she'd splattered; the leopard simply

A Versatile Cat

The elusive leopard (*Panthera pardus*) is the most adaptable of the big felines. A powerful runner, swimmer and climber, it ranges across the tropical forests, drylands and cultivated fields of Africa and South Asia to the frozen far east of Russia. Consummate hunters, they eat what they can get: deer, monkeys, cattle, goats, dogs, even rats or fish. Three subspecies, the Amur (*P. p. orientalis*), Arabian (*P. p. nimr*) and Javan (*P. p. melas*) leopards, are critically endangered; the rest are endangered or threatened.



Sources: "Panthera pardus (Amended Version of 2019 Assessment)," by A. B. Stein et al., in *The IUCN Red List of Threatened Species, 2020 (leopard range data)*; "Leopard (*Panthera pardus*) Status, Distribution, and the Research Efforts across Its Range," by Andrew P. Jacobson et al., in *PeerJ*, May 2016 (chart reference); Kontur Population data set (India human population data)



A NOCTURNAL visitor is welcome around the home of a Warli Indigenous family. Warli houses often have traditional paintings of leopards or other wildlife inside, depicting a philosophy of coexistence with other creatures.



went on its way. A farmer told me how he'd run out of his house when he heard his cattle bellowing at night and spotted a leopard running off when it could have turned and attacked him. One old lady described holding on to the back legs of her goat while a leopard was trying to pull it away by the front legs. She was alone in a secluded place, and yet the leopard gave up and ran away.

In the summer people routinely slept outdoors in the cool air without fear. The few attacks on humans I heard about were accidental, such as when a leopard jumped on a dog on a path and collided with a couple on a passing motorcycle; they all tumbled into a field, and the leopard ran away. In the villages around Akole, no leopard had killed anyone in living memory.

It took me a year to set up the first motion-triggered cameras across my 179-square-kilometer study area. I placed them alongside paths humans used where I had found pugmarks and scat. The first shots were of cattle, dogs and posing villagers, such as an old farmer who got down on all fours and crawled past, growling. But soon the real leopards showed up. We used the rosette patterns on their coats to identify the individuals we photographed, and statistical models helped us extrapolate the numbers to estimate how many leopards were going undetected.

The results were fascinating. There were high densities—five per 100 square kilometers—not just of leopards but also of hyenas, carnivores just as large. And this was in an agricultural landscape with human densities of 357 per square kilometer, by my measurements. For comparison, in Namibia the density of leopards varies from one to four per 100 square kilometers, but the average human density is just three per square kilometer—less than one hundredth of that in Akole. The croplands surrounding the village were also home to jungle cats—small felines that often stole domestic chickens—as well as jackals and foxes. The rare rusty-spotted cat was even breeding there.

To figure out what the leopards were eating, volunteers and friends helped me collect scat and examine it for undigested remains of hair, claws and hooves. (DNA markers confirmed the scat was indeed from leopards.) To my surprise, leopards in this landscape were eating primarily dogs (39 percent of their diet), and overall, domestic animals made up 87 percent of their prey. Interestingly, dogs supplied almost four times more biomass to the leopards' diets than goats did even though goats were seven times more numerous in the area. Farmers confirmed that they lost far fewer livestock to predators than to diseases or accidents, which may have made them more accepting of the loss of the occasional goat.

Never before had such high densities of large carnivores been reported in a populated landscape in India. To the staff of the forest department, it was no surprise, but most of my colleagues in conservation refused to believe the leopards were living there.

SECRETIVE LIVES

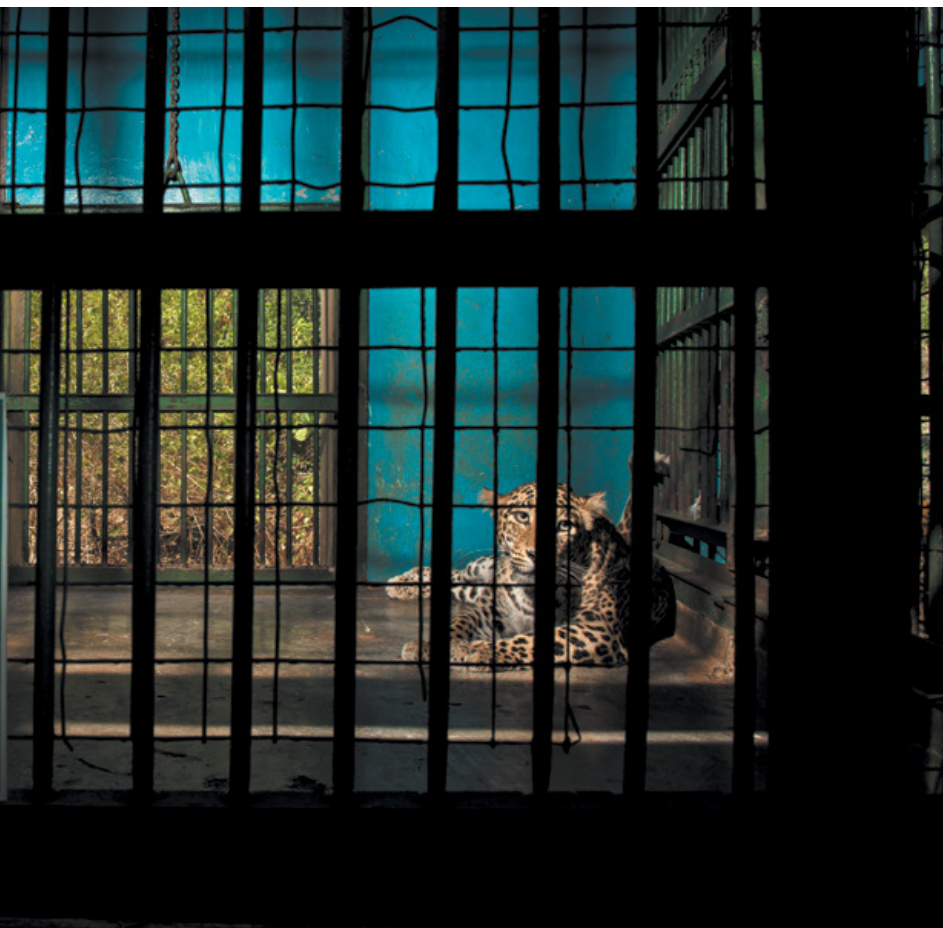
IF I WERE TO PUT RADIO COLLARS on some of the leopards, the GPS signals they transmitted would help us learn more about how they were sharing space with the people of Akole. I was initially reluctant to collar the cats—the stress of the intervention could be disastrous both for the leopards and for the villagers who'd made me feel so welcome—but the deep interest of Maharashtra's chief wildlife warden and my scientific curiosity induced me to try. What we found was remarkable.

The radio signals showed that the cats spent their entire day hiding in small bushes or inside the dense, six-foot-tall sugarcane

Nayan Khanolkar

RADHIKA was captured in 2004 during a spate of leopard attacks in Mumbai, although no one could be sure she was responsible. She died in captivity in 2018. Nowadays camera traps ensure that any leopard that threatens humans is swiftly identified and removed to permanent captivity.

Name of Leopard	Radhika
Sex	Female
Microchip No	0006830916
Trapping Place	Borivali
Arrival Date	2/8/2004



fields—within pouncing distance of people going about their business, unaware of the leopards lurking nearby. At night, when the rural landscape was devoid of people, it was, from the cats' perspective, just another wild space. The tracking data showed us that this was the leopards' time, when they stalked houses, looking for goats and pets, and prowled garbage dumps hunting for foraging dogs and domestic pigs.

We collared a female and a male who turned out to be a mother and her subadult (in human terms, teenage) son. We could see from the signals, transmitting every three hours, that they sometimes met up, fed together on the same carcass and then went their separate ways. When the female had a new litter, there were two nights when she was away and her subadult son stayed with his young siblings—babysitting!

And then one night one little cub fell into a well. The GPS signals showed that the mother paced by the well all night, leaving at dawn for her daytime shelter about 250 meters away in a sugarcane field. The forest department rescued the cub the next day and released it after dark near the well. Within half an hour of the cub's release, the mother was back by the well. A few hours later pugmarks from three cats were spotted together—the mom, her half-grown son and the baby, reunited.

Leopards were not only surviving but raising families in this agricultural landscape—and there was something about the way local people dealt with it that I could not fathom. I'd been trained to see the juxtaposition of large carnivores and people as a situation of imminent conflict. One day, early in my research in Akole, I drove with Ghule kaka ("kaka," an honorific, means uncle), the farmer I was working with, to interview a woman whose goat had

been killed by a leopard. Like a typical wildlife biologist, I asked her what problems she had with leopards. She brusquely replied that a particular leopard routinely came by a path in the hills, passed her house and went "that way."

Later I asked Ghule kaka what I'd done to annoy her. "These people revere the leopard, and you're asking her what problem her god gives her!" he replied. Nearby was a statue of *Waghoba*, a large cat deity that many people in the region have worshipped for at least half a century. I remember a pastoralist whose sheep was taken by a leopard. "The poor leopard had no prey in the forest," he said. "What else could he eat? So he's taken the sheep, and God will give me more."

I'd started out as an arrogant young biologist convinced that we can resolve human-wildlife "conflict" only by understanding the animal involved. My experiences in Akole convinced me that it is humans who hold the key, and I soon got a chance to test that theory.

ALLEY CAT

IN 2011 SANJAY GANDHI National Park got a new director, Sunil Limaye, who faced a serious problem: a history of leopard attacks in and around the reserve. At their peak, in June 2004, the cats attacked 12 people, most of them living in slums at the inner edge of the reserve forest. Limaye was familiar with my work in Junnar, and he had an idea about what the problem was. For years the forest department had been releasing leopards trapped around SGNP and elsewhere into the national park in relatively large numbers—15 in 2003. But relocation didn't help: another leopard swiftly took over the vacated territory, and attacks near the release site were likely to increase. Although a lot of forest

A RESEARCHER and a member of the forest department track a radio-collared leopard in the hills of SGNP.



officers understood this dynamic, the pressure from politicians and the media to remove leopards was immense.

Limaye wanted to start an initiative involving scientists and the citizens and institutions of Mumbai to reduce the leopard conflict, and he wanted me involved. I was busy writing a Ph.D. thesis on the work I had done in Akole, but I couldn't resist the chance to help resolve a terrible situation for leopards and people alike. Plus, my sister had moved to Mumbai around that time, so my daughter could play with her cousin while I worked. Limaye put together a team that included me, several forest officers and Vidya Venkatesh, currently director of the Last Wilderness Foundation. Many of Mumbai's residents regarded the forest as a source of trouble, and our group agreed that mindsets had to change. The surest way to make that happen was to get Mumbaikars involved.

We recruited wildlife enthusiasts who'd long wanted to help protect a nature preserve they loved. They formed an association, Mumbaikars for SGNP, and began a campaign to educate their fellow citizens about the value of the national park as a reservoir of green space and a source of water and oxygen. Local students set up camera traps to count leopards. In 117 square kilometers in SGNP and the Aarey Milk Colony, a nearby scrub forest given over to cattle for milk production, the cameras captured 21 leopards—a very high density. The national park had wild prey, mainly deer, but the leopards were clearly being attracted to the slums by the many feral dogs that were feeding on the garbage strewn around.

We also interviewed people to understand their interactions with leopards. As social geographer Frédéric Landy of the University of Paris has noted in his work, it wasn't the slum dwellers—the people most often attacked—who were calling for leopards to

be removed. It was politically empowered upper-class residents of high-rises near the reserve who relished the green view but panicked if a leopard so much as showed up on a security camera. Interestingly, the Warlis and Kohlis, Indigenous peoples who worshipped Waghoba and who had lived in the forest for centuries before Mumbai expanded to surround it, were not afraid of leopards and rarely experienced attacks. They wanted the carnivores there to scare off encroachers and developers.

As the research and the awareness-raising program proceeded, the forest department improved its ability to handle leopard-related emergencies—one being cornered in the urban area, for example. The department also worked with the police to increase their capacity to control mobs that might seek to attack these animals and, perhaps most important, with the municipality to initiate garbage collection in areas around the park frequented by leopards. Once our report came out, we worked with the Mumbai Press Club and other media organizations to advise people about how they could stay safe: keep their surroundings clean, don't let children play outdoors after dark, illuminate unlit environs and move away from a leopard if they spot one. Mumbaikars for SGNP held regular workshops with members of the press, seeking to change their coverage from sensational—some were habitually referring to leopards as “man-eaters”—to informed. In response to one media report that spoke of the dangers to school-going children at the edge of the park, the government started a school bus service there.

The outcome was a press and a public much more knowledgeable about and accepting of leopards, and the benefits were tangible. In most years since then, there have been no attacks. Individual leopards did attack people in 2017, 2021 and 2022, but because



AT HOME in an urban landscape, Luna (*right*) relaxes with her cub at the fringes of Mumbai.



of the camera traps, which the citizen scientists continue to use, they could immediately be identified, trapped and taken to permanent captivity. Our work in Mumbai showed how important a sensitive press and an aware and mobilized public are in reducing human-carnivore conflict.

A SHARED LANDSCAPE

I SHOULDN'T HAVE BEEN surprised that the people of the Indian subcontinent have a deep and complex relationship with the big cats they've shared space with since prehistory. But I was schooled in a strict separation of nature from humans that originated in Europe and reached its apotheosis in North America. Cleansing the landscape of all that they found threatening, European settlers all but eradicated wolves and cougars. When British colonizers arrived in India, they shot tens of thousands of tigers and leopards and exterminated the cheetah.

The dominant narrative in conservation continues to focus on large carnivores as predators that will inevitably hurt people or their livestock. In many documentaries about carnivores, the story is one of nature red in tooth and claw. This view presupposes conflict and implies that the only way to deal with large carnivores is to kill or remove them. I believe the contrary: most leopard-human conflict originates with the presupposition of conflict.

Among people, aggression prompts retaliatory aggression, and it might be the same for large cats. In the rare cases when they deliberately attack humans, we need to ask why. A leopard's normal reaction to hearing or seeing people is to run away; how does it get over that fear enough to kill in the rare instances when one does so? Is it because of something we have done to that individual?

We cannot know. But when I look at most sites I visit, the dominant narrative is one of peace rather than conflict. In rural Himachal Pradesh, local people referred to leopards as "*Mrig*," meaning "wild animal," a neutral framing. We found humans and leopards sharing space, trying hard to survive and lead their lives, which were often very difficult to begin with.

Many Indian ecologists are moving toward the idea of coexistence in shared landscapes. Given the deep cultural relationship between humans and big cats in the subcontinent, it is conceivable that if ever the animals return to the ranges they have vanished from, people will accept them.

In December 2011, just as I was starting the work in Mumbai, a speeding vehicle on a nearby highway hit a leopard. An animal lover was driving past. Seeing that the animal was badly injured but still alive, he picked it up—it weighed 75 kilograms (165 pounds)—and put it in the trunk of his car, with his family sitting inside. He drove it to the national park in the hope that the forest department and its veterinarians would save it, but by the time he arrived, an hour later, the leopard had died. Its collar had fallen off, as it was designed to, but the microchip could still be read. It was Ajoba.

I was told people cried when they heard his story. A Marathi director was so inspired by the saga that he made a feature film on Ajoba, teaching millions of his fellow Indians to love leopards. It is this empathy that gives me hope that my daughter and her children will also inhabit a world rich with wild things. ■

Nayan Khanolkar

FROM OUR ARCHIVES

The Lions of Los Angeles. Craig Pittman; September 2021.

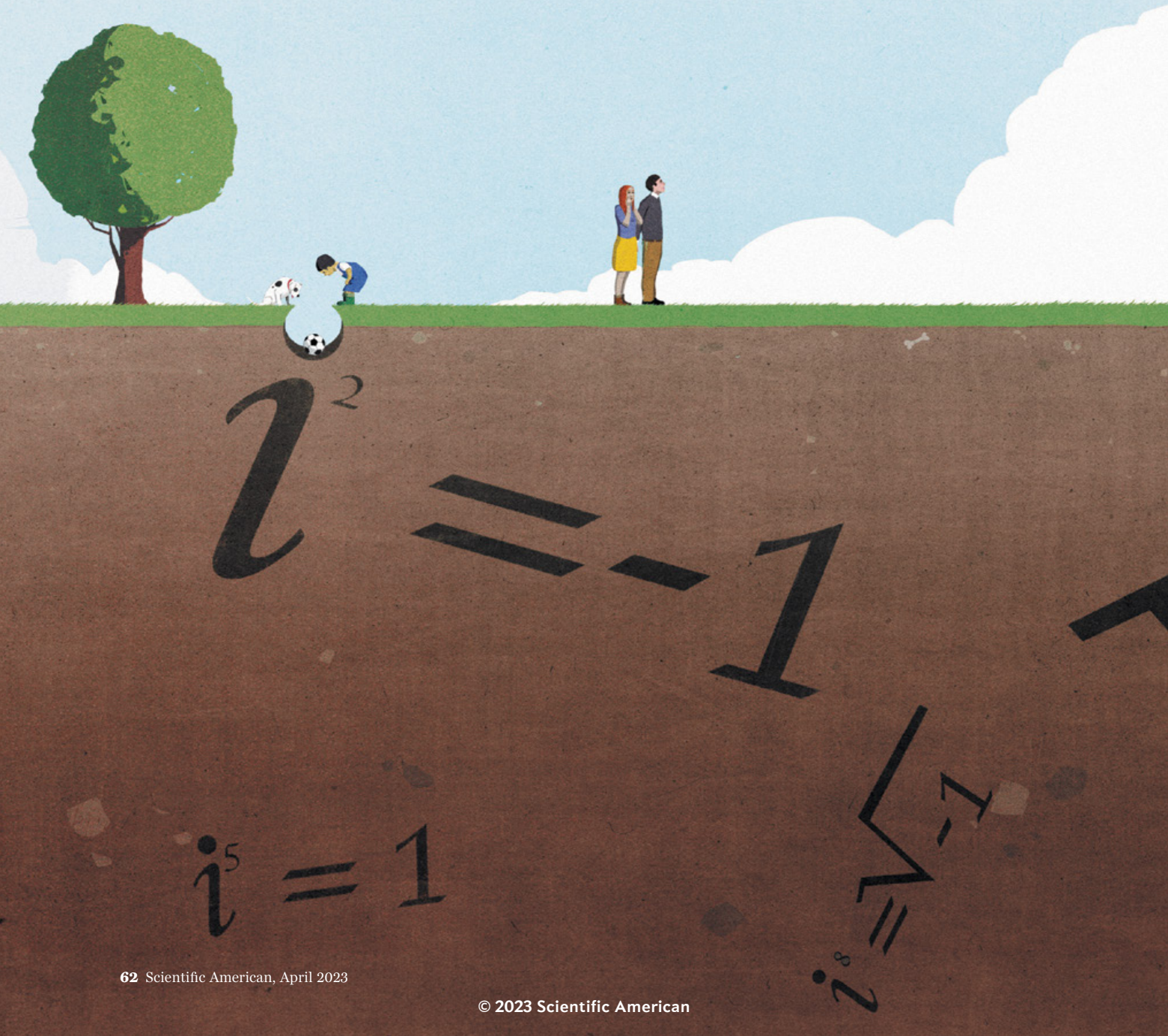
[scientificamerican.com/magazine/sa](https://www.scientificamerican.com/magazine/sa)

Imaginary Uni

Complex numbers are an inescapable part of standard quantum theory

By Marc-Olivier Renou, Antonio Acín and Miguel Navascués

Illustration by Andrea Ucini



verse



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Miguel Navascués is a junior group leader at the Institute for Quantum Optics and Quantum Information in Vienna.



T

HREE YEARS AGO ONE OF US, TONI, ASKED ANOTHER OF US, MARCO, TO COME TO HIS OFFICE at the Institute of Photonic Sciences, a large research center in Castelldefels near Barcelona. “There is a problem that I wanted to discuss with you,” Toni began. “It is a problem that Miguel and I have been trying to solve for years.” Marco made a curious face, so Toni posed the question: “Can standard quantum theory work without imaginary numbers?”

Imaginary numbers, when multiplied by themselves, produce a negative number. They were first named “imaginary” by philosopher René Descartes, to distinguish them from the numbers he knew and accepted (now called the real numbers), which did not have this property. Later, complex numbers, which are the sum of a real and an imaginary number, gained wide acceptance by mathematicians because of their usefulness for solving complicated mathematical problems. They aren’t part of the equations of any fundamental theory of physics, however—except for quantum mechanics.

The most common version of quantum theory relies on complex numbers. When we restrict the numbers appearing in the theory to the real numbers, we arrive at a new physical theory: real quantum theory. In the first decade of the 21st century, several teams showed that this “real” version of quantum theory could be used to correctly model the outcomes of a large class of quantum experiments. These findings led many scientists to believe that real quantum theory could model any quantum experiment. Choosing to work with complex instead of real numbers didn’t represent a physical stance, scientists thought; it was just a matter of mathematical convenience.

Still, that conjecture was unproven. Could it be false? After that conversation in Toni’s office, we started on a months-long journey to refute real quantum theory. We eventually came up with a quantum experiment whose results cannot be explained through real quantum models. Our finding means that imaginary numbers are an essential ingredient in the standard formulation of quantum theory: without them, the theory would lose predictive power. What does this mean? Does this imply that imaginary numbers exist in some way? That depends on how seriously one takes the notion that the elements of the standard quantum theory, or any physical theory, “exist” as opposed to

their being just mathematical recipes to describe and make predictions about experimental observations.

THE BIRTH OF IMAGINARY NUMBERS

COMPLEX NUMBERS date to the early 16th century, when Italian mathematician Antonio Maria Fiore challenged professor Niccolò Fontana “Tartaglia” (the stutterer) to a duel. In Italy at that time, anyone could challenge a mathematics professor to a “math duel,” and if they won, they might get their opponent’s job. As a result, mathematicians tended to keep their discoveries to themselves, deploying their theorems, corollaries and lemmas only to win intellectual battles.

From his deathbed, Fiore’s mentor, Scipione del Ferro, had given Fiore a formula for solving equations of the form $x^3 + ax = b$, also known as cubic equations. Equipped with his master’s achievement, Fiore presented Tartaglia with 30 cubic equations and challenged him to find the value of x in each case.

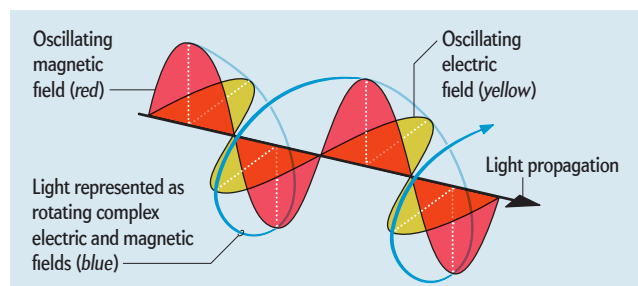
Tartaglia discovered the formula just before the contest, solved the problems and won the duel. Tartaglia later confided his formula to physician and scientist Gerolamo Cardano, who promised never to reveal it to anyone. Despite his oath, though, Cardano came up with a proof of the formula and published it under his name. The complicated equation contained two square roots, so it was understood that, should the numbers within be negative, the equation would have no solutions, because there are no real numbers that, when multiplied by themselves, produce a negative number.

In the midst of these intrigues, a fourth scholar, Rafael Bombelli, made one of the most celebrated discoveries in the history of mathematics. Bombelli found solvable cubic equations for which the del Ferro-Tartaglia-Cardano formula nonetheless required computing the square root of a negative number.

He then realized that, for all these examples, the formula gave the correct solution, as long as he pretended that there was a new type of number whose square equaled -1 . Assuming that every variable in the formula was of the form $a + \sqrt{-1} \times b$, with a and b being “normal” numbers, the terms multiplying $\sqrt{-1}$ canceled out, and the result was the “normal” solution of the equation.

For the next few centuries mathematicians studied the properties of all numbers of the form $a + \sqrt{-1} \times b$, which were called “complex.” In the 17th century Descartes, considered the father of rational sciences, associated these numbers with nonexistent features of geometric shapes. Thus, he named the number $i = \sqrt{-1}$ “imaginary,” to contrast it with what he knew as the normal numbers, which he called “real.” Mathematicians still use this terminology today.

Complex numbers turned out to be a fantastic tool, not only for solving equations but also for simplifying the mathematics of classical physics—the physics developed up until the 20th century. An example is the classical understanding of light. It is easier to describe light as rotating complex electric and magnetic fields than as oscillating real ones, despite the fact that there is no such thing as an imaginary electric field. Similarly, the equations that describe the behavior of electronic circuits are easier to solve if you pretend electric currents have complex values, and the same goes for gravitational waves.



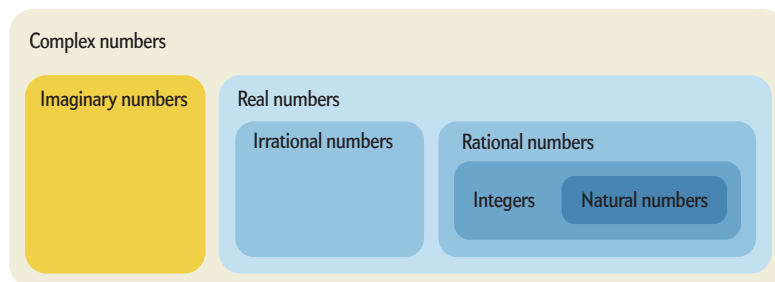
Before the 20th century all such operations with complex numbers were simply considered a mathematical trick. Ultimately the basic elements of any classical theory—temperatures, particle positions, fields, and so on—corresponded to real numbers, vectors or functions. Quantum mechanics, a physical theory introduced in the early 20th century to understand the microscopic world, would radically challenge this state of affairs.

SCHRÖDINGER AND HIS EQUATION

IN STANDARD QUANTUM THEORY, the state of a physical system is represented by a vector (a quantity with a magnitude and direction) of complex numbers called the wave function. Physical properties, such as the speed of a particle or its position, correspond to tables of complex numbers called operators. From the start, this deep reliance on complex numbers went against deeply held

What Are Imaginary Numbers?

“Imaginary” numbers are those that, when multiplied by themselves, produce a negative number. Complex numbers include both imaginary and real components. Real numbers include rational numbers (those that can be written as a ratio of two integers) and irrational numbers (those that can’t be). Rational numbers are the integers (whole numbers and their negative counterparts, plus zero). Natural numbers are a subset of integers that include only the positive whole numbers.



convictions that physical theories must be formulated in terms of real magnitudes. Erwin Schrödinger, author of the Schrödinger equation that governs the wave function, was one of the first to express the general dissatisfaction of the physics community. In a letter to physicist Hendrik Lorentz on June 6, 1926, Schrödinger wrote, “What is unpleasant here, and indeed directly to be objected to, is the use of complex numbers. Ψ [the wave function] is surely fundamentally a real function.”

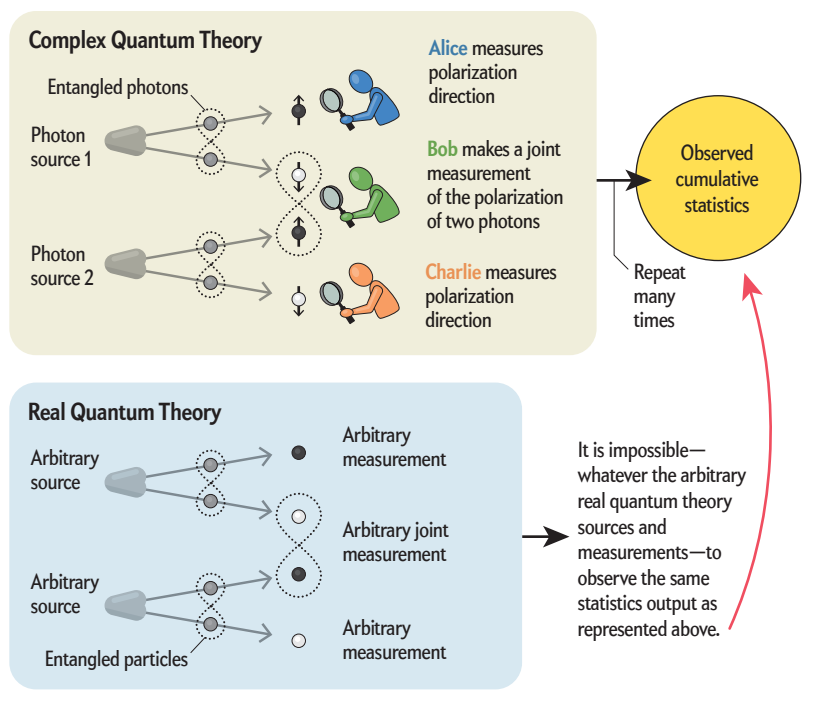
At first, Schrödinger’s uneasiness seemed simple to resolve: he rewrote the wave function, replacing a single vector of complex numbers with two real vectors. Schrödinger insisted this version was the “true” theory and that imaginary numbers were merely for convenience. In the years since, physicists have found other ways to rewrite quantum mechanics based on real numbers. But none of these alternatives has ever stuck. Standard quantum theory, with its complex numbers, has a convenient rule that makes it easy to represent the wave function of a quantum system composed of many independent parts—a feature that these other versions lack.

What happens, then, if we restrict wave functions to real numbers *and* keep the usual quantum rule for composing systems with many parts? At first glance, not much. When we demand that wave functions and operators have real entries, we end up with what physicists often call “real quantum theory.” This theory is similar to standard quantum theory: if we lived in a real quantum world, we could still carry out quantum computations, send secret messages to one another by exchanging quantum particles, and teleport the physical state of a subatomic system over intercontinental distances.

All these applications are based on the counterintuitive features of quantum theory, such as superpositions, entanglement and the uncertainty principle, which are also part of real quantum theory. Because this formulation included these famed quantum features, physicists long assumed that the use of complex numbers in quantum theory was fundamentally a matter of convenience, and real quantum theory was just as valid as standard

A Test of Two Theories

To test whether quantum theory requires complex numbers, physicists envisioned a thought experiment that was later carried out in actual laboratories. In this trial, two sources emit photons (particles of light) toward three observers: Alice, Bob and Charlie. The experiment, repeated many times, will produce statistics that are compatible only with the predictions of complex quantum theory, not with real quantum theory, the new theory obtained when scientists limit standard quantum theory to real numbers.



tainty principle—which limits how much can be known about a particle’s position and speed—was fundamental. Instead he conjectured that the experimentalists of his time were not able to prepare particles with well-defined positions and speeds because of technological limitations. Einstein assumed that a future “classical” theory (one where the physical state of an elementary particle can be fully determined and isn’t based on probabilities) would account for the outcomes of all quantum experiments.

We now know that Einstein’s intuition was wrong because all such classical theories have been falsified. In 1964 John S. Bell showed that some quantum effects can’t be modeled by any classical theory. He envisioned a type of experiment, now called a Bell test, that involves two experimentalists, Alice and Bob, who work in separate laboratories. Someone in a third location sends each of them a particle, which they measure independently. Bell proved that in any classical theory with well-defined properties (the kind of theory Einstein hoped would win out), the results of these measurements obey some conditions, known as Bell’s inequalities. Then, Bell proved that these conditions are violated in some setups in which Alice and Bob measure an entangled quantum state. The important property is that Bell’s inequalities hold for all classical theories one can think of, no matter how convoluted. Therefore, their violation refuted all such theories.

Various Bell tests performed in labs since then have measured just what quantum theory predicts. In 2015 Bell experiments done in Delft, Netherlands, Vienna, Austria, and Boulder, Colo., finally did so while closing all the loopholes previous experiments had left open. Those results do not tell us that our world is quantum; rather they prove that, *contra* Einstein, it cannot be ruled by classical physics.

Could we devise an experiment similar to Bell’s that would rule out quantum theory based on real numbers? To achieve this feat, we first needed to envision a standard quantum theory experiment whose outcomes cannot be explained by the mathematics of real quantum theory. We planned to first design a gedankenexperiment—a thought experiment—that we hoped physicists would subsequently carry out in a lab. If it could be done, we figured, this test should convince even the most skeptical supporter that the world is not described by real quantum theory.

Our first, simplest idea was to try to upgrade Bell’s original experiment to falsify real quantum theory, too. Unfortunately, two independent studies published in 2008 and 2009—one by Károly Pál and Tamás Vértesi and another by Matthew McKague, Michele Mosca and Nicolas Gisin—found this wouldn’t work. The researchers were able to show that real quantum theory could predict the measurements of any possible Bell test just as well as standard quantum theory could. Because of their research,

quantum theory. Back on that autumn morning in 2020 in Marco’s office, however, we began to doubt it.

FALSIFYING REAL QUANTUM THEORY

WHEN DESIGNING an experiment to refute real quantum theory, we couldn’t make any assumptions about the experimental devices scientists might use, as any supporter of real quantum theory could always challenge them. Suppose, for example, that we built a device meant to measure the polarization of a photon. An opponent could argue that although we thought we measured polarization, our apparatus actually probed some other property—say, the photon’s orbital angular momentum. We have no way to know that our tools do what we think they do. Yet falsifying a physical theory without assuming anything about the experimental setup sounds impossible. How can we prove anything when there are no certainties to rely on? Luckily, there was a historical precedent.

Despite being one of quantum theory’s founders, Albert Einstein never believed our world to be as counterintuitive as the theory suggested. He thought that although quantum theory made accurate predictions, it must be a simplified version of a deeper theory in which its apparently paradoxical peculiarities would be resolved. For instance, Einstein refused to believe that Heisenberg’s uncer-

most scientists concluded that real quantum theory was irrefutable. But we and our co-authors proved this conclusion wrong.

DESIGNING THE EXPERIMENT

WITHIN TWO MONTHS of our conversation in Castelldefels, our little project had gathered eight theoretical physicists, all based there or in Geneva or Vienna. Although we couldn't meet in person, we exchanged e-mails and held online discussions many times a week. It was through a combination of long solitary walks and intensive Zoom meetings that on one happy day of November 2020 we came up with a standard quantum experiment that real quantum theory could not model. Our key idea was to abandon the standard Bell scenario, in which a single source distributes particles to several separate parties, and consider a setup with several independent sources. We had observed that, in such a scenario, which physicists call a quantum network, the Pál-Vértesi-McKague-Mosca-Gisin method could not reproduce the experimental outcomes predicted by complex number quantum theory. This was a promising start, but it was not enough: similarly to what Bell achieved for classical theories, we needed to rule out the existence of *any* form of real quantum theory, no matter how clever or sophisticated, that could explain the results of quantum network experiments. For this, we needed to devise a concrete gedankenexperiment in a quantum network and show that the predictions of standard quantum theory were impossible to model with real quantum theory.

Initially we considered complicated networks involving six experimentalists and four sources. In the end, however, we settled for a simpler quantum experiment with three separate experimenters called Alice, Bob and Charlie and two independent particle sources. The first source sends out two particles of light (photons), one to Alice and one to Bob; the second one sends photons to Bob and Charlie. Next, Alice and Charlie choose a direction in which to measure the polarization of their particles, which can turn out to be “up” or “down.” Meanwhile Bob measures his two particles. When we do this over and over again, we can build up a set of statistics showing how often the measurements correlate. These statistics depend on the directions Alice and Charlie choose.

Next, we needed to show that the observed statistics could not be predicted by any real quantum system. To do so, we relied on a powerful concept known as self-testing, which allows a scientist to certify both a measurement device and the system it's measuring at once. What does that mean? Think of a measurement apparatus, for instance, a weight scale. To guarantee that it's accurate, you need to test it with a mass of a certified weight. But how to certify this mass? You must use another scale, which itself needs to be certified, and so on. In classical physics, this process has no end. Astonishingly, in quantum theory, it's possible to certify both a measured system and a measurement device simultaneously, as if the scale and the test mass were checking each other's calibration.

With self-testing in mind, our impossibility proof worked as follows. We conceived of an experiment in which, for any of Bob's outcomes, Alice and Charlie's measurement statistics self-tested their shared quantum state. In other words, the statistics of one confirmed the quantum nature of the other, and vice versa. We found that the only description of the devices that was compatible with real quantum theory had to be precisely the Pál-Vértesi-McKague-Mosca-Gisin version, which we already knew didn't work for a quantum network. Hence, we arrived at the contradiction we were hoping for: real quantum theory could be falsified.

We also found that as long as any real-world measurement statistics observed by Alice, Bob and Charlie were close enough to those of our ideal gedankenexperiment, they could not be reproduced by real quantum systems. The logic was very similar to Bell's theorem: we ended up deriving a Bell's inequality for real quantum theory and proving that it could be violated by complex quantum theory, even in the presence of noise and imperfections. That allowance for noise is what makes our result testable in practice. No experimentalists ever achieve total control of their lab; the best they can hope for is to prepare quantum states that are approximately what they were aiming for and to make approximately the measurements they intended, which will allow them to generate approximately the same measurement statistics that were predicted. The good news is that within our proof, the experimental precision required to falsify real quantum theory, though demanding, was within reach of current technologies. When we announced our results, we hoped it was just a matter of time before someone, somewhere, would realize our vision.

It happened quickly. Just two months after we made our discovery public, an experimental group in Shanghai reported implementing our gedankenexperiment with superconducting qubits—computer bits made of quantum particles. Around the same time, a group in Shenzhen also contacted us to discuss carrying out our gedankenexperiment with optical systems. Months later, we read about yet another optical version of the experiment, also conducted in Shanghai. In each case, the experimenters observed correlations between the measurements that real quantum theory could not account for. Although there are still a few experimental loopholes to take care of, taken together these three experiments make the real quantum hypothesis very difficult to sustain.

THE QUANTUM FUTURE

WE NOW KNOW neither classical nor real quantum theory can explain certain phenomena, so what comes next? If future versions of quantum theory are proposed as alternatives to the standard theory, we could use a similar technique to try to exclude them as well. Could we go one step further and falsify standard quantum theory itself?

If we did, we would be left with no theory for the microscopic world given that we currently lack an alternative. But physicists are not convinced that standard quantum theory is true. One reason is that it seems to conflict with one of our other theories, general relativity, used to describe gravity. Scientists are seeking a new, deeper theory that could reconcile these two and perhaps replace standard quantum theory. If we could ever falsify quantum theory, we might be able to point the way toward that deeper theory.

In parallel, some researchers are trying to prove that no theory other than quantum will do. One of our co-authors, Mirjam Weilenmann, in collaboration with Roger Colbeck, recently argued that it may be possible to discard all alternative physical theories through suitable Bell-like experiments. If this were true, then those experiments would show that quantum mechanics is indeed the only physical theory compatible with experimental observations. The possibility makes us shiver: Can we really hope to demonstrate that quantum theory is so special? ■

FROM OUR ARCHIVES

[Spooky Action](#). Ronald Hanson and Krister Shalm; December 2018.

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

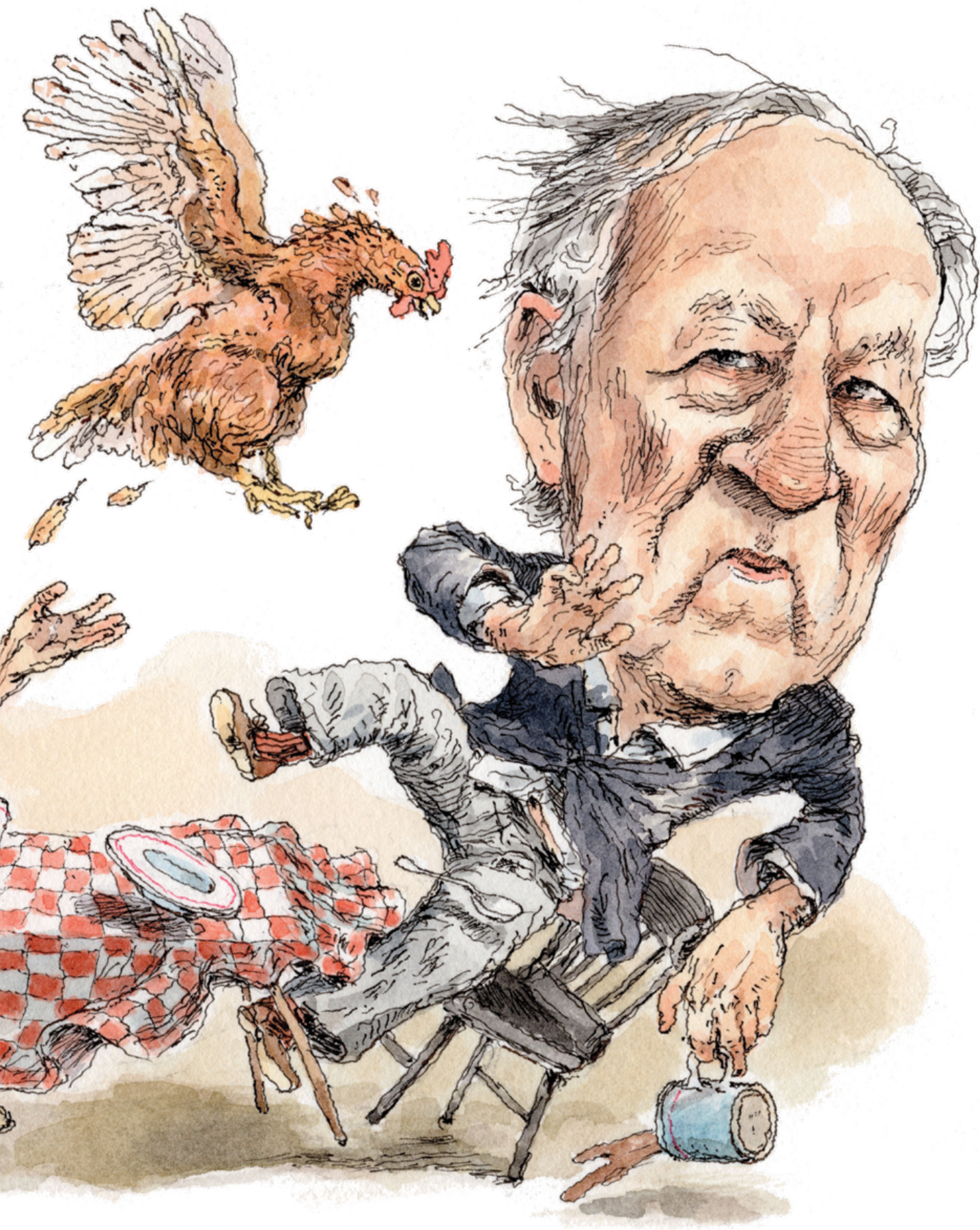
Chatbots Talking

An AI-generated conversation between a filmmaker and a philosopher shows the entertaining and disturbing potential of speech-synthesis technology

By Giacomo Miceli

Illustration by John Cuneo





Giacomo Miceli is an Italian American computer scientist, creative coder and entrepreneur.



ON THE WEBSITE THE INFINITE CONVERSATION, GERMAN FILMMAKER Werner Herzog and Slovenian philosopher Slavoj Žižek are having a public chat about anything and everything. Their discussion is compelling in part because these intellectuals have distinctive accents when speaking English and a tendency toward eccentric word choices. But they have something else in common: both voices are deepfakes, and the text they speak in those distinctive accents is being generated by artificial intelligence.

I built this conversation as a warning. Improvements in what's called machine learning have made deepfakes—incredibly realistic but fake images, videos or speech—too easy to create and their quality too good. At the same time, language-generating AI can quickly and inexpensively churn out reams of text. Together these technologies can do more than stage an infinite conversation. They have the capacity to inundate us with a deluge of disinformation.

Machine learning, an AI technique that uses large quantities of data to “train” an algorithm to improve as it repetitively performs a particular task, is going through a phase of rapid growth. This is pushing entire sectors of information technology to new levels, including speech synthesis, systems that produce utterances that humans can understand. As someone who is interested in the liminal space between humans and machines, I've always found it a fascinating application. So when those enhancements in machine learning allowed voice-synthesis and voice-cloning technology to advance in giant leaps over the past few years—after a long history of small, incremental improvements—I took note.

The Infinite Conversation got started when I stumbled across an exemplary speech-synthesis program called Coqui TTS. Many projects in the digital domain begin with finding a previously unknown software library or open-source program. When I discovered this tool kit, accompanied by a flourishing community of users and plenty of documentation, I knew I had all the necessary ingredients to clone a famous voice.

As an appreciator of Herzog's work, persona and worldview, I've always been drawn to his voice and

way of speaking. I'm hardly alone, as pop culture has made Herzog into a literal cartoon: his cameos and collaborations include *The Simpsons*, *Rick and Morty* and *Penguins of Madagascar*. So when it came to picking someone's voice to tinker with, there was no better option—particularly because I knew I would have to listen to that voice for hours on end.

Building a training set for cloning Herzog's voice was the easiest part of the process. Between his interviews, voice-overs and audiobook work, there are hundreds of hours of speech that can be harvested for training a machine-learning model—or in my case, fine-tuning an existing one. A machine-learning algorithm's output generally improves in “epochs,” which are cycles through which the neural network is trained. The algorithm can then sample the results at the end of each epoch, giving the researcher material to review to evaluate how well the program is progressing. With the synthetic voice of Herzog, hearing the model improve with each epoch felt like witnessing a metaphorical birth, with his voice gradually coming to life in the digital realm.

Once I had a satisfactory Herzog voice, I started working on a second voice and intuitively picked Žižek. Like Herzog, Žižek has an interesting accent, a relevant presence within the intellectual sphere and connections with the world of cinema. He has also achieved a popular stardom, in part thanks to his polemical fervor and sometimes controversial ideas.

At this point, I still wasn't sure what the final format of my project was going to be—but I was surprised by how easy and smooth the process of voice cloning was. As noted, deepfakes have become too

Deep Thoughts

A brief exchange from an endless and completely fake conversation

Slavoj Žižek*: So where do you see the possibility for a radical change today? How do you evaluate the present situation in terms of revolutionary potentials?

Werner Herzog: I don't know. I think there is no real potential for a revolution. Not in our society and not in the foreseeable future. There is no real potential. I think we should put our energy elsewhere. We should work on the next stage of human evolution. I have given some talks in Silicon Valley, and they are convinced that the next step in evolution is to make humans artificially intelligent. They see it as inevitable. Of course, it will have to be widely discussed and prevented at the U.N. But I am convinced that the next step lies there. The next step in inner evolution lies there. Look at you! You are constantly using your cell phone, and you look like a mountain sheep, completely lost. And yet, in one second, you can

find out every single detail about anything. And you're constantly updating your knowledge. You're constantly doing research. And this goes on and on and on. In 10 years we'll be totally different from what we are now. So that's where we need to focus our energy. The next stage of inner evolution. That's where it is.

Žižek: So you think we should organize a sort of "pro-artificial intelligence" movement? What would you like to achieve?

Herzog: I have no clear goal. I have a dream of sorts. And yet, at the same time, I am also profoundly happy. And that's what cinema, literature and music should do. Rather than just organizing a movement. Just filmmaking. Just making music. That's what we should do.

Žižek: Cinema, yes. Cinema for the machines. Yes, great idea.

**The two conversants are AI chatbots trained to imitate Žižek, the philosopher, and Herzog, the filmmaker.*

good and too easy to make. Just this past January, Microsoft announced a [new speech-synthesis tool called VALL-E](#) that, researchers claim, can imitate any voice based on just three seconds of recorded audio. We're about to face a crisis of trust, and we're utterly unprepared for it.

To emphasize this technology's capacity to produce ample quantities of disinformation, I settled on the idea of a never-ending conversation. I needed only a large language model—fine-tuned on texts written by each of the two participants—and a simple program to control the flow of the conversation so that it would feel natural and believable.

Given a series of words, language models predict the next word in a sequence. By fine-tuning a language model, it is possible to replicate the conversational style of a specific person, provided you have abundant transcripts of that person talking. I decided to use one of the leading commercial language models available. That's when it dawned on me that it's already possible to generate a fake dialogue, including its synthetic voice form, in less time than it takes to listen to it. This realization provided me with an obvious name for the project: the Infinite Conversation. After a couple of months of work, I published it online in October 2022. This year the Infinite Conversation was selected to be part of the [Misalignment Museum](#) art installation in San Francisco.

Once all the pieces fell into place, I marveled at something that hadn't occurred to me when I started the project. Like their real-life personas, my chatbot versions of Herzog and Žižek often talk about philosophy and aesthetics. Because of the esoteric nature of these topics, the listener can temporarily ignore the occasional nonsense that the model generates. For

example, AI Žižek's view of Alfred Hitchcock alternates between seeing the famous director as a genius and as a cynical manipulator; in another inconsistency, the real Herzog [notoriously hates chickens](#), but his AI imitator sometimes speaks about the fowl compassionately. Because actual postmodern philosophy can come across as muddled—a problem [Žižek himself has noted](#)—the lack of clarity in the Infinite Conversation can be interpreted as profound ambiguity.

This probably contributed to the success of the project. Several hundred of the Infinite Conversation's visitors have listened for more than an hour, and some people have tuned in for much longer. As I mention on the website, my hope for visitors of the Infinite Conversation is that they not dwell too seriously on what the chatbots are saying. Instead I want to give people an awareness of this technology and its consequences. If this AI-generated chatter seems plausible, imagine the realistic-sounding speeches that could be used to tarnish the reputations of politicians, scam business leaders or simply distract people with misinformation that sounds like human-reported news.

But there is a bright side. Infinite Conversation visitors can join a growing number of listeners who report that they use the soothing voices of Werner Herzog and Slavoj Žižek as a form of white noise to fall asleep to. That's a usage of this new technology I can get behind. ■

FROM OUR ARCHIVES

[AI Platforms Like ChatGPT Are Easy to Use but Also Potentially Dangerous.](#) Gary Marcus; ScientificAmerican.com, December 19, 2022.

scientificamerican.com/magazine/sa



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Kindness Goes Farther Than You Think

Small acts boost recipients' moods in big ways

By Amit Kumar

Scientists who study happiness know that being kind to others can improve well-being. Acts as simple as buying a cup of coffee for someone can boost a person's mood, for example. Everyday life affords many opportunities for such actions, yet people do not always take advantage of them.

In studies published online in the *Journal of Experimental Psychology: General*, Nicholas Epley, a behavioral scientist at the University of Chicago Booth School of Business, and I examined a possible explanation: people who perform random acts of kindness underestimate how much recipients value their behavior.

Across multiple experiments involving approximately 1,000 participants, people performed a random act of kindness—that is, an action done with the primary intention of making someone else (who isn't expecting the gesture) feel good. Those who perform such actions expect nothing in return.

From one situation to the next, the specific acts of kindness varied. For instance, in one experiment, people wrote notes to friends and family “just because.” In another, they gave cupcakes away. Across these experiments, we asked both the person performing a kind act and the one receiving it to fill out questionnaires. We asked the person who had acted with kindness to re-

port their own experience and predict their recipient's response. We wanted to understand how valuable people perceived these acts to be, so both the performer and recipient had to rate how “big” the act seemed. In some cases, we also inquired about the actual or perceived cost in time, money or effort. In all cases, we compared the performer's expectations of the recipient's mood with the recipient's *actual* experience.

Across our investigations, several robust patterns emerged. For one, both performers and recipients of the acts of kindness were in more positive moods than normal after these exchanges. For another, it was clear that performers undervalued their impact: recipients felt significantly better than the kind actors expected. The recipients also reliably rated these acts as “bigger” than the people performing them did.

We initially studied acts of kindness done for familiar people, such as friends, classmates or family. But we found that participants underestimated their positive impact on strangers as well. In one experiment, participants at an ice-skating rink in a public park gave away hot chocolate on a cold winter's day. Again, the experience was more positive than the givers anticipated for the recipients, who were people who just happened to be nearby. Although the people giving out the hot chocolate saw the act as relatively inconsequential, it really mattered to the recipients.

Our research also revealed one reason that people may underestimate their action's impact. When we asked one set of participants to estimate how much someone would like getting a cupcake simply for participating in a study, for example, their predictions were well calibrated with recipients' reactions. But when people received cupcakes through a random act of kindness, the cupcake givers underestimated how positive their recipients would feel. Recipients of these unexpected actions tend to focus more on *warmth* than performers do.

Missing the importance of warmth may stand in the way of being kinder in daily life. People know that cupcakes can make folks feel good, to be sure, but it turns out that cupcakes given in kindness can make them feel *surprisingly* good. If people undervalue this effect, they might not bother to carry out these warm, prosocial behaviors.

And kindness can be contagious. In another experiment, we had people play an economic game that allowed us to examine what are sometimes called “pay it forward” effects. In this game, participants allocated money between themselves and a person whom they would never meet. People who had just been on the receiving end of a kind act gave substantially more to an anonymous person than those who had not. The person who performed the initial act did not recognize that their generosity would spill over in these downstream interactions.

These findings suggest that what might seem small when we are deciding whether or not to do something nice for someone else could matter a great deal to the person we do it for. Given that these warm gestures can enhance our own mood and brighten the day of another person, why not choose kindness when we can? ■



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if I'm afraid he'll overdose again? | 🔍

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Volcanic Activity Surprises on Mars

A mass of moving material called a mantle plume may be causing quakes and volcanism

By Phil Plait

For decades planetary scientists assumed Mars was dead.

Geologically, that is. Smaller than Earth, the planet would have cooled faster than ours after it formed. It was, for a time, quite volcanically active. The assumption was that when the interior temperature gradually decreased, so, too, did the planet's ability to generate large-scale geologic activity such as huge volcanoes and "marsquakes."

New discoveries, however, belie that belief. It just so happens that Mars is only *mostly* dead. Scientists have found that a large region on Mars has been prone to quakes and even mild volcanic activity in recent geologic times, indicating *something* is brewing underneath the surface. But what?

After looking over data from several robotic Mars missions, a team of planetary scientists came to the astonishing conclusion that an immense tower of hot material moving upward in the planet's mantle is pushing on the crust from below, creating pressure that is cracking the surface and causing tectonic activity. Called a mantle plume, it may be a relatively new feature in Mars's interior, one that has analogues on Earth. It might even have implications for extant life on Mars—or, more accurately, *inside* it. The work was published in December 2022 in *Nature Astronomy*.

Mars was once a heavily volcanic planet. The surface is still dotted with ancient mounds, including one called Olympus Mons. This monster is more than 600 kilometers in diameter—roughly equal to the length of the state of Colorado—and towers 21 kilometers above the average surface elevation of its planet, about two and half times as high as Mount Everest. Although other volcanoes on Mars are smaller, they are still giant, and all of them are terribly old.

Large-scale volcanism on Mars started before the planet was even a billion years old and was active for roughly a billion years thereafter. Globally, volcano building pretty much stopped after that. There's evidence of some lava flows on Olympus Mons that date back to only a few million years ago, but these were small-scale events and were probably sporadic. By three or so billion years ago the era of active volcano construction on Mars was over. For comparison, most of the active volcanoes on Earth are less than a million years old.

Until recently, scientists considered that the end of the story of volcanism on the Red Planet. Spacecraft orbiting Mars, however, have captured high-resolution images that show the

final chapter hasn't yet been written. In a region called Cerberus Fossae, there are large numbers of cracks in the surface (fossae are trenches or fissures), and one such feature has dark streaks of material running alongside it for dozens of kilometers. Measurements from orbit show the material is loaded with pyroxenes, minerals common in volcanic lava. Startlingly, these outflows may have occurred only tens of thousands of years ago. That's recent in planetary time and points toward ongoing activity under the surface.

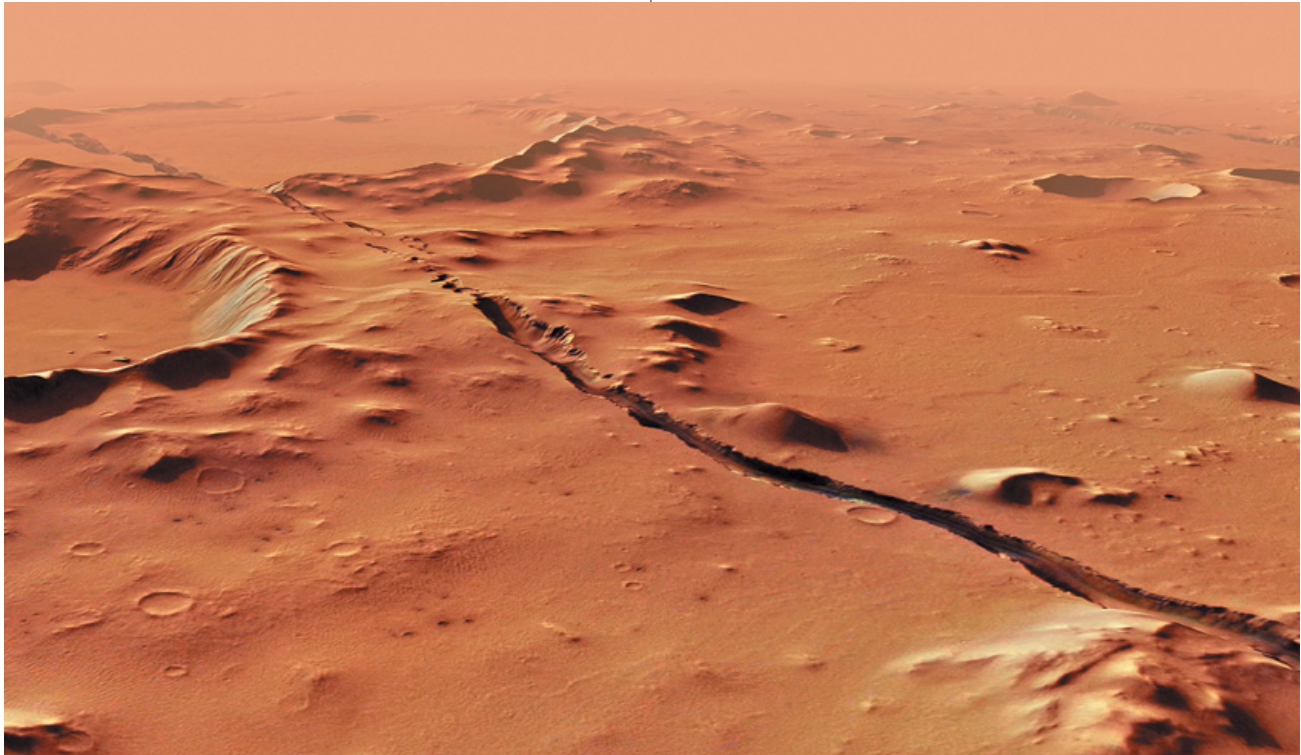
Moreover, in 2018 NASA's InSight lander touched down in the vast Elysium Planitia region, in a spot about 1,600 kilometers from Cerberus Fossae. Part of a mission to help measure what is going on below the Martian surface, InSight had a seismometer that detected hundreds of small marsquakes during its operational years, as well as several that were fair to middling in energy. The overwhelming majority of them appear to have come from the direction of Cerberus Fossae. Again, this activity indicates the Martian mantle may not yet be completely dead.

In the new *Nature Astronomy* study, the scientists focus on this region of Mars. Much of the planet's surface shows compression features, such as wrinkle ridges, that are formed when the surface of a planet contracts as it cools. Elysium Planitia, in contrast, is a bulge on the surface viewed as evidence for extension: a stretching of the crust as the local area expands. The cracks making up Cerberus Fossae are fissures where the crust has split apart because of this extension. The scientists also note that the floors of impact craters that formed many millions of years ago are tilted away from the center of the bulge, which would be expected if they had formed before the surface was pushed upward. Together these findings indicate that whatever caused the uplift is relatively young.

All this evidence is consistent with a mantle plume. The basic idea of a plume may be familiar if you've ever watched water boil or a hot-air balloon in flight: hot material rises as cold material sinks in a process called convection. The core of a planet is hot, and the mantle above it is somewhat cooler, so the material heated at the base of the mantle rises.

The curveball here is that much of Mars's mantle (and Earth's) is actually solid; it's a misconception that it's a liquid. But convection can work even in a solid. The silicate material that makes up the bulk of a mantle is crystalline, and there can be flaws and breaks in the crystal pattern. Under the huge pressures deep underground, atoms from the material below can fill in these cracks in a process known as dislocation creep. In this way, hotter material close to the core can rise up slowly, essentially flowing. It's an extremely slow process; Earth's mantle flows at an average rate on the order of a few centimeters a year, roughly as fast as your fingernails grow.

It's not clear exactly how mantle plumes form. At the base of the mantle above the core, a hotter-than-average spot can create a region of stronger convection where the material flows in a more constrained column. This plume rises to the



surface over tens or hundreds of millions of years. When it gets near the crust, the pressure is much lower, and the solid material can liquefy. It spreads out, forming a mushroomlike cap that pushes up against the crust, causing an extension feature like the one seen in Elysium Planitia.

This scenario would explain essentially all the anomalies in Cerberus Fossae: the uplift, the cracks, the volcanic eruptions, the quakes. Measurements of Mars's gravity field even show that the field is slightly weaker under Cerberus Fossae, which would be consistent with lower-density mantle pushing up toward the crust. These findings indicate that the uplift is supported very deep underground.

The scientists used computer models to simulate the geophysics of Mars and found that a plume that was 95 to 285 degrees Celsius hotter and slightly less dense than the surrounding mantle could do the trick if it were centered almost directly under the fossae. It would form a cap spread out over a few thousand kilometers and push the crust up about a kilometer, again matching Cerberus Fossae. It would also be a young feature: the activity in and around Cerberus Fossae appears to have started approximately 350 million years ago, long after every other large-scale engine inside the planet had effectively shut down.

Although the plume model is an excellent match to the observed data, the scientists acknowledge that there could be other explanations. For example, a slightly lower-density blob of mantle material could be just sitting there under the region, which would account for the gravity readings, although it

One of the fractures making up the Cerberus Fossae system on Mars. The fractures cut through hills and craters, indicating their relative youth.

wouldn't explain the uplift or anything else. The idea that covers the most ground, literally, is a mantle plume.

If the hypothesis proves to be correct, then this is indeed important news. For one thing, when drawing many of their conclusions about the Martian interior, scientists have assumed that Elysium Planitia is boring—just another spot on Mars. If it is sitting on the cap of a tremendous plume of hot, low-density material, that changes how we should interpret InSight's seismic measurements.

And although it's a bit of a stretch for now, the plume could have implications for life. Scientists have long thought water under the Martian surface takes the form of ice, but a warm mantle plume could heat pockets of water enough to make it liquid. Life on Earth needs liquid water, so it may not be too silly to consider the possibility of biology deep under the surface of Mars.

In that case, Mars might not be entirely dead, either geologically or in the more common biological sense. We've only just begun to understand the true nature of the Red Planet, and the more we look, the more we find it still has a little kick left in it. **SA**

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NONFICTION

Sightseers in Space

What would a black hole look like up close?

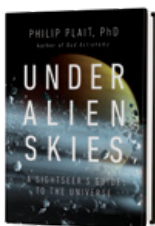
Review by Sarah Scoles

In a nearly 30-year-old photograph of the Pillars of Creation nebula, finger-shaped spires of gas and dust reach from the heavens toward the heavens. Dark in their middles, they seem to glow around their scalloped edges: campfire smoke in still frame.

The Hubble Space Telescope took that one. Hubble's successor—the James Webb Space Telescope—recently took another portrait of the nebula, which is birthing new stars. In the JWST image, the pillars show up as defined as rock formations.

It's a fantastic view. But you may wonder, as have audiences at astronomer Philip Plait's public talks, if that's what you'd actually see were you hovering nearby. How are telescopes' views different from those of human eyes? "The question gnawed at me," writes Plait, also known as the Bad Astronomer, in his fourth book. "What would these objects look like up close?"

Plait (who writes this magazine's monthly *The Universe* column) attempts to answer this question by plunking his readers in the passenger seat for a ride through the sensory realities of the cosmos. Each chapter begins



Under Alien Skies: A Sightseer's Guide to the Universe

by Philip Plait.
W. W. Norton, 2023 (\$30)

with a second-person scene in which you—you!—are on a trip to some astronomical phenomenon. You begin with solar system-centric journeys: Among your first stops are the moon and Mars, where you're hit with a tornado. Then you head farther afield to comets, asteroids, Saturn and Pluto, which Plait calls "the last stop before the stars." Jumping outward, literary explorers go on faster-than-light spaceflights to worlds with two suns and those that might exist in tightly packed spheres of stars called globular clusters. As the destinations get farther from home, the views and experiences trend ever more alien. That feeling culminates (and terminates) as you approach a black hole, where you are ultimately "crushed down to a mathematical point."

To convincingly transport readers from couch to deep space, Plait anchors the text with familiar things to grab on to and compare from one location to the next. He explains, often using earthly analogies, why various celestial sights would look the way they do. The sky seen from the moon, for instance, is black even during the day because there's no atmosphere to scatter sunlight. On Saturn, meanwhile, it's never truly dark because the planet's reflective rings continuously send photons down to the surface. You might test the measly pull of gravity on a small, rubbly asteroid, which Plait, with characteristic wit, calls "vermin of the sky." Always, he reminds you to look up—just as you might from your own backyard—at the stars.

For all its creative whimsy, *Under Alien Skies* is deeply focused on clarity, remaining

evidence-based even in its imaginings. Plait cites space missions that gave scientists the data to understand these alien worlds as real places rather than cosmic abstractions. The Rosetta spacecraft, for instance, revealed that Comet 67P/Churyumov-Gerasimenko—which you climb around on in the book—is shaped like a rubber duck. The Mars Reconnaissance Orbiter clued scientists in to a 12-mile-high dust devil, a version of which washes over you in the text.

When Plait cheekily imagines scientific details as part of the fictional exploration, the data can sometimes feel forced. He seems to be aware that it's a distraction. In a scene on a planet in the TRAPPIST-1 system, you see other potentially habitable planets orbiting close by, all circling a small red dwarf star. "One of the crewmembers starts lecturing about the physical characteristics of the planets: their distances, sizes, atmospheres," he writes. "But all you can think of is that you're seeing alien worlds glowing in the night sky."

There's a bit of elided wonder in that move from imagination to explanation. Plait misses a similar opportunity in largely glossing over the awe of *not* knowing all the astronomical things we have left to figure out—like the 95 percent of the universe made of dark matter and energy whose nature scientists don't yet comprehend.

Fundamentally, the book is a hopeful plea for interplanetary exploration that sets up its own sequels for eons to come: "The universe is a puzzle that never ends," Plait writes. But throughout the many-light-year journeys it contains, you're left thinking of, searching for and comparing everything with Earth. Even in the black hole at the center of the Milky Way, Plait and the reader are still thinking of home. "If you could somehow see Earth through a powerful telescope, the light from it will have been traveling for so long you'd be seeing humans living in permanent settlements for the very first time and just starting to invent pottery," he writes.

The cosmic scale contained in that sentence doesn't just make the universe feel vast. It also shows that humans have *already* come a long way and that the harder-to-reach places in the universe will be waiting for us when we get there, if we ever do.

Sarah Scoles is a science journalist, editor and author based in Colorado. Her most recent book is *They Are Already Here* (Pegasus, 2020).



FICTION

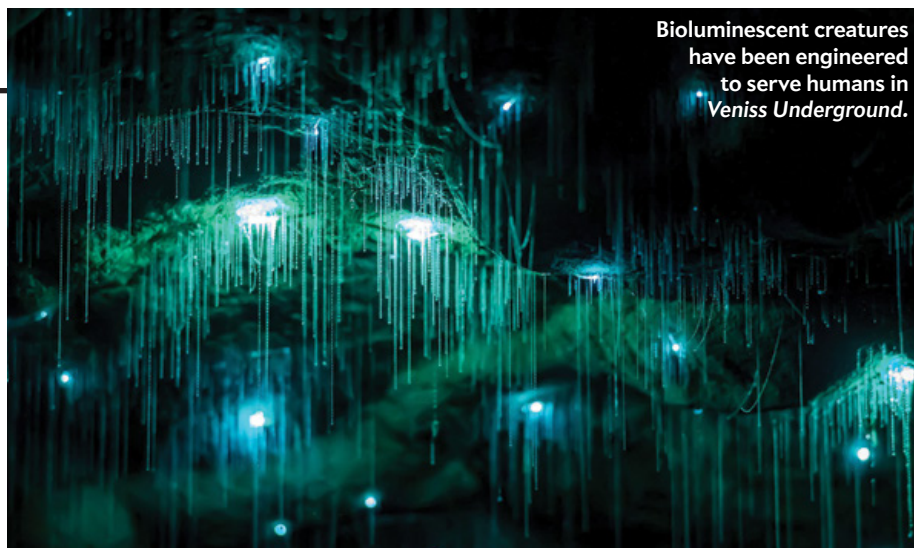
Mutated World

The origins of Jeff VanderMeer's creepiest creatures

With the reissue of *Veniss Underground*, first published in 2003, new audiences will encounter the roots of the surrealist bio-horror that best-selling author Jeff VanderMeer became known for in acclaimed novels such as *Annihilation* (2014).

VanderMeer's debut book, like much of his subsequent work, is a phantasmagoric thriller that explores the themes of climate disaster and humanity's selfish pursuit of control over nature. Rising sea levels have turned inland cities into detached coastal settlements, forcing the government of Veniss to build miles below Earth's surface to accommodate its citizens.

Operating on the edges of society are the Living Artists: bioengineers who practice gene manipulation to bring extinct species back to life, devise new creatures, and "improve" on animals for the benefit of humans, such as by giving meerkats opposable thumbs so they can cook and wash clothes. Part science and part perverse artwork, the practice often yields



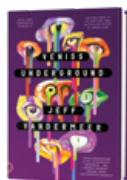
Bioluminescent creatures have been engineered to serve humans in *Veniss Underground*.

Frankenstein-like results. There's a kitten with a tongue emerging from a human ear on top of its head and a large, bioluminescent caterpillar whose body serves as a map of the underground.

The novel follows struggling artist Nicholas, his twin sister Nicola and her former lover Shadrach. When Nicholas goes to work for Quin, a powerful Living Artist whom many consider a godlike figure, he sets off a chain of events that results in Nicola's kidnapping and Shadrach's descent into the city's underground to save her. As Shadrach struggles like Dante through level after level of increasingly mutated humans and creatures, VanderMeer's talent for writing the sublime shines. There's an encounter inside a leviathan fish that has been engineered to

house life without feeling the pain of its own decay.

The reprint includes four short stories and a novella, all previously published, that are also set in and around the city of Veniss. In these offshoot plots, a human settlement is under attack by Flesh Dogs that steal the faces of the people they've killed, and an artificial intelligence sows compliance through tragic stories of citizens who disobeyed their orders. It's a joy to discover here that elements in VanderMeer's later science fiction—such as the tower of living flesh in *Annihilation* and the bioengineered chimeras in *Borne* (2017)—originated in the gloom of Veniss's depths. Taken together, these works provide a chaotic and captivating window into an author's early world building. —Michael Welch



Veniss Underground
by Jeff VanderMeer.
MCD, 2023 (\$30)

Hugh Mitton/Alamy Stock Photo

IN BRIEF

In the Lives of Puppets

by TJ Klune.
Tor, 2023 (\$28.99)



Infused with warmth and playful humor, TJ Klune's latest novel both charms and challenges, tugging at our understanding of the essential self. Vic Lawson lives a peaceful but isolated life deep in the forest, a lone human raised by an android father. When Vic and his two robot companions secretly reanimate an abandoned android, they incite a crisis, sending Vic on a dangerous journey that forces him to conceal his humanity even as he discovers its complicated connections with the machines around him. Inspired by *The Adventures of Pinocchio*, this heartfelt saga offers a lively look at identity, free will and love.

—Dana Dunham

Chasing Giants: In Search of the World's Largest Freshwater Fish

by Zeb Hogan and Stefan Lovgren.
University of Nevada Press, 2023 (\$29.95)



You might know Zeb Hogan as the excitable host of *Monster Fish*, a TV show about his quest to definitively identify the largest freshwater fish. *Chasing Giants* conveys the same premise in chapters instead of episodes: amid accounts of wrangling piranhas in Brazil and sawfish in Australia, Hogan and his co-author, journalist Stefan Lovgren, describe the environmental pressures endangering these targets. The final reveal is a satisfying conclusion, but it's hard to ignore the absence of voices who lent local knowledge throughout the expedition. I wanted to hear more from the hidden figures who made such a grand endeavor possible. —Sam Miller

Elixir: A Parisian Perfume House and the Quest for the Secret of Life

by Theresa Levitt.
Harvard University Press, 2023 (\$32.95)



In 19th-century French laboratories, scientists followed their noses in a race to discover the source of perfume's perceived vitality. Pulling from historical publications and personal writings, Theresa Levitt vividly explains why perfume—bathed in, lathered on and orally consumed—had a chokehold on Parisian life. The natural oils used to make scented products were widely considered to be the very life essence of a plant, imbued with beneficial properties that could keep death and disease at bay. Levitt traces how researchers' pursuit of the true composition of these oils laid the foundation for modern organic chemistry. —Fionna M. D. Samuels



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 *The Big Myth* (Bloomsbury, 2023).

The Disasters Science Neglects

Landslides kill and hurt thousands of people, yet researchers seem uninterested

By Naomi Oreskes

This winter devastating floods and mudslides in California killed at least 17 people, closed roads for days and caused thousands to be evacuated. Mud and water ripped through the hillside town of Montecito five years to the day after a 2018 slide there killed 23 people and destroyed more than 100 homes.

Between 1998 and 2017 landslides and mudslides affected nearly five million people worldwide and took the lives of more than 18,000, according to the World Health Organization. In contrast, wildfires and volcanic activity killed 2,400. In the U.S. alone, slides and other debris flows kill 25 to 50 people every year. Yet by and large we don't hear very much about hazardous slides. Tornadoes, volcanoes, wildfires and hurricanes get more headlines. They get more scientific attention, too.

And climate change is making these slides more common. In fact, they are a prime example of the cascading effect of an altered climate: Drought leads to fires, which destroy the plants that anchor earth to hillsides, and that instability creates slides when rain finally comes. Drought isn't the only cause, either. Across Asia melting snow and ice are engorging rivers and undercutting hill slopes, making them prone to collapse. Last June a landslide after heavy rains in India killed 61 people.

Why don't scientists pay more attention to this threat? The U.S. Geological Survey has a landslide research program, but most universities don't. Richard Iverson, recently retired from

the USGS after a career studying landslides and debris flows, told me that American research universities generally “avoid hiring faculty or training students to do this type of work.” To his knowledge, “no scientist who specializes in landslides/debris flows has ever been elected to the National Academy of Sciences.” A search of the academy's membership using the key word “landslide” turned up three names: a seismologist, a geophysicist specializing in theoretical rock mechanics, and a geologist specializing in biological forces shaping landscapes. None of the three works primarily on landslides.

One reason for this lack of research is money. U.S. federal funds for biomedical research soared to more than \$25 billion a year between 1990 and 2000 and have stayed high. On the other hand, funding for everything else—physics, environmental sciences, other life sciences, mathematics and even computer science—has remained mostly flat. Environmental science, under which slide research falls, regularly has received less than \$5 billion a year.

Another problem is that slides are notoriously hard to study. The basic idea is simple: a hillside becomes unstable when the force of gravity exceeds the forces holding it together. This happens when the hillside is undercut—for example, by an engorged river—or oversteepened or when friction is decreased by heavy rains. But because rocks and soils are highly variable, predicting when a particular hill will give way is almost impossible. It's hard to publish ambiguous results, so scientists may choose other research topics that seem more promising.

Slides suffer from siloed science, too. As one civil engineer put it, “Despite the high risk when extreme rainfall and droughts interact, most research in this area focuses on only one or the other. Different government agencies oversee flood and drought monitoring, warning and management, even though they are extremes of the same hydrological cycle.”

Scientists also like to take on things they find interesting, and slides appear to fall short. Many researchers think of their work as a kind of detective story, where “interesting” means understanding an underlying hidden mechanism. In cancer research, for instance, this has led to a focus on genetic causes of the disease instead of prevention. In earth science, it has prompted examinations of the internal processes of our planet. But slides aren't hidden. They happen quite clearly on the surface, and the mechanisms are in some ways obvious. Iverson put it this way: “Many scientists are most intrigued by things that are most mysterious.” Slides are catastrophic but not mysterious.

I don't fault scientists for wanting to study things they find fascinating. A lot of good work has been motivated by mystery. But researchers have to find a way to balance love of intrigue with a need to fix pressing problems such as the slippery ground underneath our feet. ■

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APRIL

1973 Catalytic Conversion

“Among the most troublesome air pollutants produced by automobiles are the chemically active nitrogen oxides. Workers at Bell Laboratories have found catalysts that react nitrogen oxides with a reducing gas (hydrogen or carbon monoxide), converting them to nitrogen and such harmless by-products as water and carbon dioxide. They can be coated on a ceramic support to make a filter-like device that could be installed in an automobile. So far such devices have been tested only in the laboratory; further tests are necessary to see if they will stand up under the severe conditions in an exhaust system of an automobile running for extended periods. The automobile industry faces increasingly strict Federal standards for reducing carbon monoxide, unburned hydrocarbons and oxides of nitrogen in exhaust emissions.”

1923 Discovered: Nebraska Man

“At the recent meeting of the National Academy of Sciences, Dr. Henry Fairfield Osborn announced the discovery of a tooth giving evidence of a pre-historic and unknown species of anthropoid intermediate between the ape and the earliest man. This discovery was made by Harold J. Cook in the middle Pliocene formations of Nebraska. This tooth matches no known tooth of ape or man, modern or extinct. Dr. Osborn classifies it as a new species and genus and names it *Hesperopithecus haroldcookii*, which means ‘the

anthropoid from the west discovered by Harold Cook.’ The fossil was found in the upper phase of the Snake River beds, associated with remains of the rhinoceros, camel, Asiatic antelope and an early form of the horse. Hitherto, no specimen of anthropoid primates had been discovered in America.”

Within a few years the novel classification was proved to be a mistake; it was retracted in 1927.

Artificial Rain

“There have been plenty of reported achievements in [artificial weather making] that, on investigation, turn out to be illusory. Now we are asked to believe that a method of dispelling clouds and fog, and incidentally of turning clouds into rain, cheap enough to be applied universally for the benefit of aviators and others, has been devised by investigators at work at McCook Field, near Dayton, Ohio, on behalf of the Army Air Service. The process consists of spraying the clouds from an airplane with electrically charged sand, clearing away the cloud and producing an incipient rainstorm. We are unable to see any reason why this process should extend very far. The grains of sand would quickly lose their electrical charge and behave the same as any other mineral dust found in the atmosphere.”

1873 Vesuvius House, Great Lava Views

“About two thirds of the way up the side of Vesuvius stands a small building, plainly visible. During cloudy and wet weather, it is shrouded in the dense veil of the smoke which settles around the



1973



1923



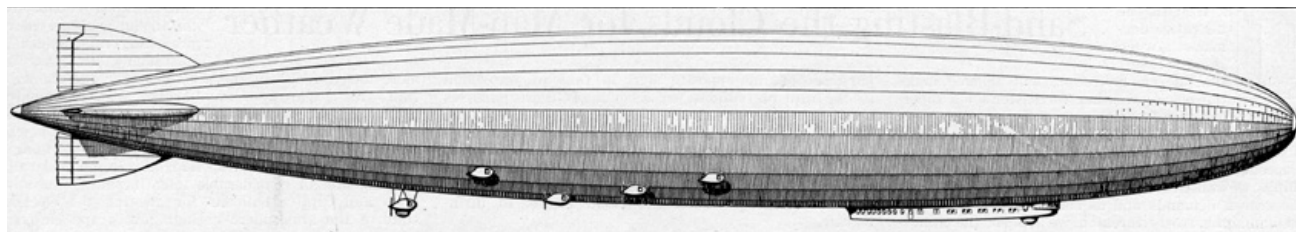
1873

summit; and in times of eruption, the fiery streams seem to encompass it and flow far below its level. In this structure, thus dangerously located, Professor Palmieri, a well known Italian savant, has established an observatory and, with marvelous intrepidity, has remained at his post watching the convulsions of the volcano at times when his house stood between torrents of liquid fire, the heat from which cracked the windows and scorched the solid stone of the walls. The knowledge obtained at so great a risk has been recently given to the world in an ably written volume, which contains data of invaluable assistance in the future investigation of volcanic phenomena. Professor Palmieri considers that, to a certain extent, eruptions may be predicted. We suggest he supplement his efforts by turning from an intermittent to a constant volcano—from Vesuvius to Stromboli.”

Science Benefits Economy

“It is noticeable that scientific subjects have received more attention from the newspaper press of late. This is partly [because] it is becoming more generally known that discoveries that seemed at first to be without any application have contributed to the general good. Experiments in magnetism and electricity, which led to the invention of the electric telegraph, were made from curiosity only. None could have anticipated the use of spectrum analysis in the manufacture of steel. Other cases may be noted to illustrate the proposition that every addition that may be made to physical science is capable of an economic use.”

1923, Air Mail:
“The Transatlantic rapid mail service by aircraft is being seriously discussed. This air liner would be 820 feet long, 110 feet in diameter, capable of carrying 12 tons of mail and 40 passengers at a speed of 65 knots.”



The Science of Melting Chocolate

An artificial tongue illuminates how chocolate changes from solid to smooth emulsion

The sensation of rich chocolate going gooey on your tongue is unlike any other. To understand how the process plays out on a molecular level, scientists created a biomimetic tongue that replicates the texture, surface distribution and mechanical properties of a human tongue. “We wanted to understand the main contributor to that smooth feeling of the chocolate as it melts,” says Siavash Soltanahmadi, a researcher at the University of Leeds in England. He and his collaborators, Anwasha Sarkar and Michael Bryant, placed chocolate on their ersatz tongue, then observed as the surfaces interacted. Their measurements allowed them to break down the chocolate-eating process into three stages: solid, molten and emulsion. The scientists discovered that the delectable feeling of chocolate depends on the snack releasing a fatty film that coats the tongue. “Where the fat is located in the chocolate is more important than how much of the fat we have,” Soltanahmadi says. This discovery suggests that by putting fat in the top layers of chocolate’s surface and reducing fat in its interior, chefs could make a healthier treat that feels just as good in the mouth.



These charts show the relative difference in tongue feel between two types of chocolate. The blue dots represent the amount of friction between the chocolate and the tongue for sample 1. The pink dots show how much sample 2 varied from that baseline.

Sample 1 (blue)

Cocoa content: 70%
Low fat content
High sugar content



Sample 2 (pink)

Cocoa content: 90%
High fat content
Low sugar content



Solid Stage

Chocolate starts out solid when it enters your mouth and your tongue begins licking it.

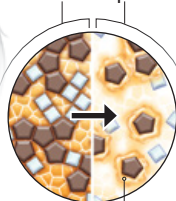
Full Tongue



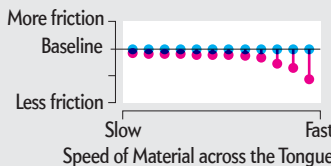
Molten Stage

Your mouth’s heat and friction from your tongue gradually melt the chocolate.

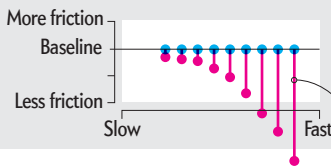
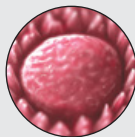
Phase change from solid to liquid



Fatty film



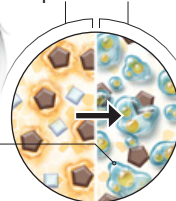
Single Papilla



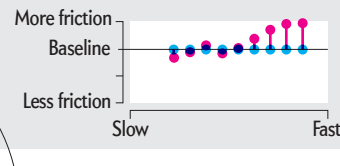
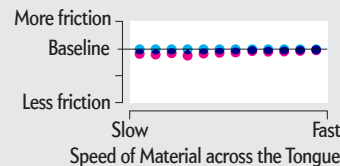
Emulsion Stage

During the last stage, the chocolate reaches an emulsion state where its fat and solid cocoa particles are smoothly mixed with saliva.

Phase change from liquid to emulsion



Saliva



At the papilla level, the difference between chocolate types is large at the molten stage. In chocolate with a higher fat content, lower friction is observed here when the surface of the chocolate first interacts with the tongue.

Source: “Insights into the Multiscale Lubrication Mechanism of Edible Phase Change Materials,” by Siavash Soltanahmadi, Michael Bryant and Anwasha Sarkar, in *ACS Applied Materials & Interfaces*, Vol. 15; January 12, 2023 (data)



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