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APRIL 2020

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ON THE COVER
Despite centuries of study, astronomers are only now learning how our home galaxy, a spiral of at least 100 billion stars spanning more than 100,000 light-years, really appears from outside. New surveys are revealing the Milky Way's structure in more detail than ever before. Illustration by Ron Miller.

Photograph by Igor Siwanowicz

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Curtis Brainard is acting editor in chief of *Scientific American.* Follow him on Twitter @cbrainard

We Are Here

Anyone living in Manhattan can tell you that of all the wonders the urban lifestyle affords, great vistas of the city itself are not one of them. Sweeping views of this American metropolis are available only from the outside, from places like New Jersey or Queens. Researchers who study the Milky Way have the same problem. They cannot see the entirety of our galaxy, because, along with the rest of us, they're right in the thick of it. And yet there is no cosmic equivalent of hopping the next train to Hoboken or Long Island City to gain the panoramic perspective they so desire.

Thankfully, radio telescopes offer a solution, as astronomers Mark J. Reid and Xing-Wu Zheng explain in this month's cover story (*page 28*). Using thousands of hours of observations from several projects, they and their colleagues were able to map the spiral structure of the Milky Way in unprecedented detail and better pinpoint our solar system's location therein. The result is a stunning new picture of the whirlpool of stars we call home.

Vying for the title of most amazing image in this issue is a magnificent portrait of *Tullbergia mediantarctica,* an animal smaller than a sesame seed. This so-called extremophile makes its unlikely home on the slopes of the Transantarctic Mountains, hemmed in by crushing ice on one side and toxic soils on the other. First glimpsed in 1964 but only rediscovered two years ago, it belongs to a group of primitive, wingless relatives of insects called springtails.

They have survived more than 30 ice ages, yet so delicate are these creatures that they shrivel and die almost as soon as the rocks under which they live are overturned. Thus, we had no idea what the outcome would be when the biologists who found them generously agreed to ship a few of the prize specimens to be photographed. But Igor Siwanowicz, a neurobiologist at the Howard Hughes Medical Institute, who specializes in capturing images of tiny creatures with a laser-scanning microscope and other tools, pulled it off with aplomb. And as journalist Douglas Fox reports, *Tullbergia* is now rewriting the history of Antarctica. Turn to "Extreme Survivor," on page 50, to explore more.

Here's something else to chew on: paleontologist Peter S. Ungar's fascinating tale (*page 44*) about the evolution of human teeth and the shocking revelation that we in the modern world have many more dental problems than our ancient ancestors. As he explains, "Although teeth endure for millions of years in the fossil record, ours cannot seem to last a lifetime in our mouths."

That is because our chompers are "a miracle" of evolutionary design at the both macroscopic and microscopic levels, forged in the oral crucible over hundreds of millions of years. But beginning with the transition from foraging to farming during the Neolithic period 10,000 years ago and continuing through the Industrial Revolution, humans began eating softer, more carbohydrate-rich foods to which our dental environment is ill adapted. The consequences are the impacted molars, cavities and gum disease that are so common today.

Stories like these help us to understand our place in the cosmos, the history of our planet and its beguiling denizens, as well as the rather astonishing reason so many people have bad teeth. Moreover, I hope they all instill a respect for life at the grandest scales of space and time. SA

Illustration by Nick Higgins

December 2019

"I expect that when truly intelligent computers arrive, we will be surrounded by artificial consciousness and not even realize it."

PAUL COLBOURNE *OTTAWA*

BLACK HOLE BREAKOUT

In "Escape from a Black Hole," Steven B. Giddings gives us a fascinating update on developments in the black hole information crisis, the seeming paradox of quantum rules and general relativity indicating that black holes destroy information despite quantum mechanics saying that information cannot be destroyed.

One thing puzzles me about his account. He explains that the three leading candidate solutions to the crisis all have the same thorny problem: they violate the principle of locality, which maintains that no influence can move across space faster than the speed of light. But I've read elsewhere that the violation of locality has already been rigorously established from both observations and theoretical analyses of quantum entanglement. If that assessment is correct, why is such violation still regarded as a problem for black hole theories? And why doesn't Giddings mention the confirmation of nonlocality in entanglement studies as helping things along for these theories?

Bruce Ecker *New York City*

GIDDINGS REPLIES: Ecker's question reflects a common misunderstanding of the precise meaning of locality in physics. It is true that quantum mechanics has properties—specifically, entanglement—that appear to represent a kind of nonlocality. This observation famously bothered Albert Einstein, who referred to its consequences as "spooky action at a distance." But quantum field theory fully reconciles locality with quantum mechanics. Although it exhibits entanglement, the precise statement of locality is that there is no way to send a signal (meaning no way to transmit information) nonlocally—that is, faster than the speed of light. Mere quantum entanglement does not allow such signaling. It is this locality property of quantum field theory that directly conflicts with the statement that, apparently, information must escape a black hole and that prompts us to consider modifications of quantum field theory.

CONSCIOUS DISTINCTION

Christof Koch gives an interesting summary of theories of human consciousness and whether computers can attain it in "Proust among the Machines." The popular media—including Koch, it would seem—assume that computer consciousness would be much like our own, with a desire to be free, safe and alive. But computers are so physically different from ourselves and their reason for existing so different that if they were to gain consciousness, it would be very distinct from what we experience.

Take self-driving cars, for example. Their programming, or training, is a kind of evolutionary process where the best-performing connections win out. If cars being conscious would result in better driving, then, sooner or later, it would happen. The only thing such a car would "want," however, would be to stay on the road and not hit anything. Behavior such as admiring the scenery would not contribute to good driving and would be eliminated in the training. What would it be like to "be" such a car? The experience would be so distant from our own that we would probably not recognize it as consciousness. I expect that when truly intelligent computers arrive, we will be surrounded by artificial consciousness and not even realize it. Or maybe we already are.

Paul Colbourne *Ottawa*

PLASTICS AND CLIMATE

In "Learning to Love Plastic" [Ventures], Wade Roush asserts that standard plastic is good for the environment because it traps carbon that would contribute to climate change and that we should thus not adopt biodegradable plastic to reduce waste. His argument is flawed in two ways.

The first is a misunderstanding of the problem, which he identifies as the carbon intensity of biodegrading plastics. The release of carbon dioxide is a natural part of biodegradation, yet Roush implies this is a problem unique to biodegradable plastics. Fallen leaves on the forest floor do the same. If anything, the problem with biodegradable plastics is that they're weaker than those derived from petrochemicals, and in the same issue of *Scientific American,* "Bioplastics for a Circular Economy," by Javier Garcia Martinez, highlights efforts to strengthen biodegradable plastics as one of the "Top 10 Emerging Technologies of 2019."

The second flaw in Roush's position is more important: he fails to recognize that we can tackle two problems at once. Biodegradable plastics are a hopeful solution to a serious problem: plastic pollution. They are not the root cause of a different but certainly more serious problem: climate change because of anthropogenic carbon emissions. Thankfully, we are developing other solutions to solve that problem that don't involve treating petrochemical plastics as carbon sinks.

Zachary Epstein *Houston, Tex.*

I was appalled to see the following statement in Roush's article with no supporting documentation: "And your supposedly eco-conscious cloth grocery bag is more damaging to the environment than conventional plastic bags—unless you reuse it literally thousands of times." This "idea" defies logic and demands evidential support. A reusable, plant-based cotton bag

will most certainly degrade more quickly and with less harm than a petroleum-based plastic one.

The war to save our environment requires maximum effort on everyone's part. No effort in this regard is too small.

James E. Britsch *Santa Barbara, Calif.*

ROUSH REPLIES: My column about plastic was meant to combat the idea that "biodegradable" means "safe for the environment." Quite the reverse is true if your paramount goal is to lower greenhouse gas emissions.

Epstein is right that fallen leaves biodegrade. But if humans can avoid adding to the natural carbon cycle—in this case, by switching to nonbiodegradable bioplastic and disposing of it responsibly—then we should. Plastic pollution remains a significant problem. But the solution is to stop abandoning plastic in the environment, not to hope that it decays there.

To respond to Britsch's comment: A bag's full life-cycle impact is what counts. Reusable cotton bags often consist of cotton grown on farms in China that use enormous amounts of irrigation water and are manufactured in textile plants that run on coal-fired electricity. In a thorough 2017 report, the Canadian government corporation Recyc-Québec determined that a cotton bag must be reused between 100 and 3,000 times to bring its life-cycle impact level down to that of a conventional plastic (high-density polyethylene) bag used just once.

ERRATA

"GPS Down," by Paul Tullis, should have indicated that the civilian and military signals sent by GPS satellites are distinguished by special bits of code, not encryption keys.

"X-ray Vision," by Belinda J. Wilkes, incorrectly implied that the supernova that created the neutron star in the Crab Nebula occurred in the year 1054. It was first observed on Earth at that time but had occurred thousands of years earlier.

"Odd Disturbances Pierce the Universe," by Katie Peek [Graphic Science], erroneously described the lasers in two LIGO gravitational-wave detector sites as located underground. They run in aboveground tubes 2.5 miles long.

LETTERS TO THE EDITOR

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BIG QUESTIONS FROM... ALAN GUTH

As a postdoctoral fellow, physicist Alan Guth developed the theory of cosmic inflation, which describes the early universe before the big bang. Here, he shares his thoughts on what existed before that: a backward world where the past is the future and where infinite parallel pocket universes pop into existence.

Our universe began with a bang—a big bang. The explosion stretched the very fabric of spacetime, sending superheated matter in all directions. As it expanded, the matter cooled and started to aggregate, forming atoms, then elements, then stars, galaxies and, ultimately, all we know and see today.

For physicist and cosmologist Alan Guth, one big question about the big bang remains: "What was it that banged?"

The answer lies in his theory of cosmic inflation. "It sets up the conditions for the big bang—like a prequel," says Guth, a professor of physics at MIT. For developing that theory, Guth and two of his colleagues, Andrei Linde at Stanford University and Alexei Starobinsky at the Landau Institute for Theoretical Physics of the Russian Academy of Sciences near Moscow, were awarded the 2014 Kavli Prize in astrophysics.

According to the theory, in the trillionth of a trillionth of a second before the big bang, an exotic form of matter exerted a counterintuitive force: gravitational repulsion. Although we normally think of gravity as being attractive (picture Isaac Newton and the falling apple), Albert Einstein's theory of general relativity allows for such gravitational repulsion.

Under the conditions present in the early universe, when temperatures were extraordinarily high, Guth says the existence of this material was reasonably likely. "It only has to be a speck," he says. "But when that speck starts to inflate, the expansion is exponential."

Contemplating those fateful events—and what happened next—Guth says, raises some of the most fascinating questions in science: How did our universe begin, where is it going, and what caused it to exist in the first place?

"We don't necessarily expect to answer those questions next year," he adds. But "anything that makes small steps towards understanding the answers is thrilling."

Here, Guth addresses some of those mysteries, including where our universe comes from, what else is out there, and how inflation may have spawned primordial black holes, a hypothetical entity that could represent the universe's long sought-after dark matter.

What was there before inflation started? That is something I have been thinking about in the context of a paper that I'm writing with Sean Carroll [at Caltech]. The idea is that the universe is actually eternal. It existed at all times, so there is no beginning to explain. The laws of physics themselves don't seem to make any significant distinction between the future and the past. As the universe evolves, its entropy, or disorder, will grow. What we call the future is simply the direction of higher entropy; a state of lower entropy is what we call the past. But a curious thing happens if you take this initial low entropy state and follow it backwards in time, towards what we previously called the past: the entropy will also start to grow in that direction. I think that the people living [along that arrow of time] would not feel anything different from what we feel. Everybody will think that they're living from the past towards the future, except what they call the future will be what we call the past.

What can inflation tell us about the forces that hold our universe together? If the only matter in the galaxies was the matter we see, there would not be nearly enough gravity to hold galaxies together. With them spinning as fast as they are, they would just fly apart—or they would never have formed in the first place. The assumption is that there must be other matter present to create a stronger gravitational field to hold the matter in, even at these high velocities. That's dark matter.

In collaboration with other physicists and students, I'm calculating the production of primordial black holes in a version of inflation called hybrid inflation. Primordial black holes could conceivably be dark matter. They could also be the seeds that led to the supermassive black holes that we see in the centers of galaxies—black holes that have millions and even billions of solar masses. If we could find primordial black holes, it would be a huge thing.

Is our universe all there is? The theory of eternal inflation says that once inflation starts, it never completely stops. Rather, it ends in places, and universes form there. We call them pocket universes because they're not everything that exists. We are living in one of these pocket universes. And even though the pocket universes keep forming, there's always a volume of exotic repulsive gravity material that can inflate forever, producing an infinite number of these pocket universes in a never-ending procession.

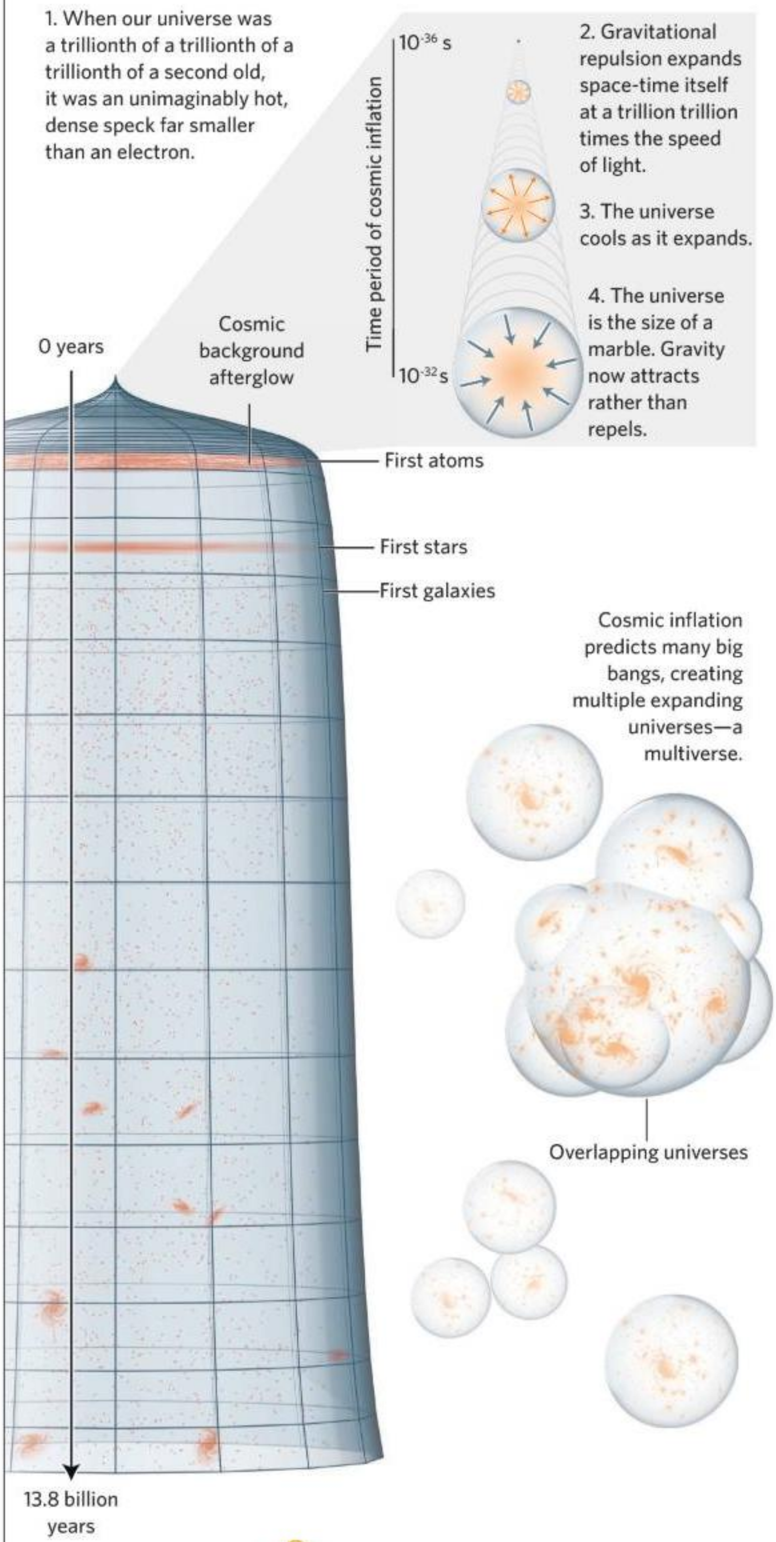
Each individual pocket universe will presumably ultimately die, in the sense that it will run out of energy and cool down. But in the big picture of all the pocket universes, life would not only go on eternally, but there'd be more and more of it every instant.

Are there any drawbacks to living in a multiverse? The problem with having an infinite multiverse is that if you ask a simple question like, "If you flip a coin, what's the probability it will come up heads," normally you would say 50 percent. But in the context of the multiverse, the answer is that there's an infinite number of heads and infinite number of tails. Since there's no unambiguous way of comparing infinities, there's no clear way of saying that some types of events are common, and other types of events are rare. That leads to fundamental questions about the meaning of probability. And probability is crucial to physicists because our basic theory is quantum theory, which is based on probabilities, so we had better know what they mean.

To learn more, listen to a podcast with Alan Guth on ScientificAmerican.com. Also, stay tuned for the announcement of the next Kavli Prize laureates on May 27, 2020.

THE BIG BANG'S BEGINNINGS

Cosmic inflation theory solves certain mysteries the conventional big bang theory doesn't, including what already existed and what drove it to expand.



An Erratic Finger on the Button

The U.S. president alone should not be able to start a nuclear war

By the Editors

Experts generally agree that the world came closest to nuclear war during the Cuban Missile Crisis of 1962, when the U.S. and the U.S.S.R. faced off on the issue of Soviet ballistic missiles being installed just 90 miles away from the American mainland. In the end, President John F. Kennedy found a way to back away from the brink of disaster: he was rational enough to see the inevitable catastrophe that would have resulted from "pushing the button."

But what if he hadn't been? Since the atomic bomb was first used against Japan in 1945, all U.S. presidents have had wide latitude to order a nuclear attack. And although we don't dwell on the fact, psychiatric and neurological disorders are not uncommon among people who ascend to the world's most powerful office. Lyndon B. Johnson and Richard M. Nixon displayed behavior suggestive of paranoia. Earlier, Abraham Lincoln showed signs of depression. In fact, the study of presidents from 1776 to 1974 found that nearly half the top office holders demonstrated signs of psychopathology. The potential for irrational decision-making cries out for limits on the power to destroy the world.

Which brings us to Donald Trump. Erratic behavior has been the norm during his presidency. Trump's order for the precipitous assassination of Iran's high-ranking officer Qassem Soleimani in January is only the most recent example. Shortly after he took office, Trump threatened North Korea's leader Kim Jong-un with "fire and fury like the world has never seen." Then he turned around and declared that he and the dictator were "in love," defending Kim even when the country continued to conduct missile tests. The full list of Trump's capricious behaviors would fill many pages. The American Psychiatric Association states that it is unethical to offer a professional opinion about someone before a thorough medical examination, but some psychiatrists have begun to argue that breaching the rule is justified in this case for the public good. And practitioners have followed through: hundreds of psychiatrists and medical professionals submitted a document to Congress last December stating that Trump's mental health was declining during the course of the impeachment proceedings.

A highly impulsive U.S. president should not be able to singlehandedly start a global nuclear conflagration that could kill tens of millions of people. Trump himself might even agree. The self-styled "stable genius" tweeted in 2014: "The global warming we should be worried about is the global warming caused by NUCLEAR WEAPONS in the hands of crazy or incompetent leaders!"

He was right. Fortunately, there are a few possible solutions that may be brought to bear. Proposals have circulated to require either Congress or cabinet officials to give assent to any first use of nuclear weapons. And Section 4 of the 25th amendment to the Constitution can be invoked to determine whether a president is fit to continue serving in office.

The apocalyptic danger posed by an unstable president with his or her finger on the nuclear button would be moot if the world scrapped nuclear weapons entirely. Failing that, the most important measure the U.S. could take as the world's preeminent military power should be to pledge never to initiate a first strike—a promise we have never made despite lawmakers' efforts—signaling that our current nuclear arsenal serves solely as a deterrent. In tandem, given that the nuclear early-warning system activates every day, usually in response to a rocket launching somewhere on the globe, the U.S. should take nukes off their current launch-on-warning status to remove the pressure on any president to respond in minutes to what may well be a false alarm.

The legislation needed to enact any one of these measures may have to await a new administration and a shift away from the unprecedented partisanship that divides the U.S. political scene. Public fear of nukes appears to have abated somewhat from the time when every schoolchild had to practice duck-and-cover drills. Still, a hopeful sign of congressional willingness to implement a check on presidential power came from the massing of bipartisan Senate votes in response to the Soleimani killing to limit Trump's authority to take military action in Iran.

Whether Democrat or Republican, any post-Trump administration should prioritize nuclear de-escalation while maintaining security. My-button-is-bigger-than-yours tweets should be replaced with reminders of the joint statement made by Ronald Reagan and Soviet president Mikhail Gorbachev in 1987: "A nuclear war cannot be won and must never be fought." SA

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MACIEJ FROLOW *Getty Images*

Chethan Sathya is a pediatric surgeon and journalist based in New York City. Follow him on Twitter @drchethansathya

Stand Up for Female Surgeons

Their male colleagues are abusive, and we must all be part of the solution

By Chethan Sathya

As a male surgeon, I am mortified that the profession allows my female colleagues to be treated like second-class citizens. I have watched women surgeons get bullied, harassed and discriminated against by their male counterparts. I have seen a countless number of their careers crumble in front of my eyes. I have seen their tears. I have seen them go into a deep hole of depression and never come back. And I'm embarrassed to say that for a long time, I did nothing about it.

New research is shining light onto the pervasiveness of sexual harassment, intimidation and prejudice in our world of surgery—but this is something that doctors have known about for decades. It is deeply ingrained in our culture of medicine—and it needs to change. While the rest of the world seems to be embracing the #MeToo movement, we are running from it. As a result, most cases of abuse are going unaddressed. And this is leading to burnout and suicidal thoughts among surgeons.

It's also bad for patients. When a person places one's life in the hands of a surgeon, one assumes that she or he is singularly focused on the patient's well-being. But how can surgeons perform at their best if they are battling workplace abuse?

Like many male surgeons, I have been afraid to speak up out of fear that it would destroy my reputation among senior surgeons in power, who are more often than not men. I am not alone. "Men are bystanders. They know something is wrong. They know someone is taking advantage of the situation. But medical training is hierarchical, and most men find it hard to challenge someone with more authority," says Zeno Franco, associate professor at the Medical College of Wisconsin. And frankly, many male surgeons don't care enough to do so.

A study in the *New England Journal of Medicine* shows that about a third of surgical trainees in the U.S. experience gender discrimination or verbal and physical abuse. Nearly two thirds of female surgeons-in-training experience gender discrimination, and one in five is sexually harassed—often by senior supervising surgeons. Another survey showed that 58 percent of U.S. women surgeons experienced sexual harassment within the last year, and many incidents were not reported. The most common reason: "fear of a negative impact on my career."

Discrimination and abuse are daily occurrences for many women surgeons; the perpetrators include co-workers, patients and their families, and nurses, says Arghavan Salles, scholar in residence at the Stanford University School of Medicine. "This is an epidemic," she says. "Not just one bad actor." Because women are scarce in academic surgery, says Karyn Butler, a professor of surgery at the Sidney Kimmel Medical College of Thomas Jefferson University, "they are the minority trying to convince the majority. And getting ahead is based on reputation among colleagues, making it easy for one's career to be destroyed for speaking out. To avoid sexual harassment at work, she notes, many women surgeons have resorted to demeaning ground rules, like "always wear a shirt under your scrubs, or else male surgeons will look down at your chest."

Men must acknowledge that discrimination and harassment in surgery are a problem, Butler says, and they need to step up. When we witness gender abuse, we need to support the victim and call out our colleagues or make sure that leadership is doing something about it. When we see great ideas from women surgeons being discounted or undeservingly credited to men, we can redirect the conversation. We can implore our institutions to hire and promote equitably. We can demand that they acknowledge maternity rights.

I myself have started raising these issues with my male colleagues. Some think the problem is overblown, and a few are outraged. But I've been gratified to see that many are supportive of these efforts. We have had a number of conversations around the topic, and most have been highly productive, with women feeling comfortable sharing their stories of abuse. I urge surgeons at other institutions to begin talking as well. They may fear that their careers could be at risk, but our female colleagues wouldn't hesitate to stick their necks out for us. Let's show them that they are not alone. SA

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Illustration by Lily Padula

ADVANCES

These wings, made from real pigeon feathers, form the basis for a flexible new flying robot.

LENTINK LAB *Stanford University*

INSIDE

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- New bandage material boosts clotting and repels bacteria
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- Underwater telescopes will peer through the depths to measure elusive particles

ROBOTICS

Feathered Fliers

A pigeon-based robot could inspire next-generation drones

As far back as Icarus's ill-fated aviation attempt, humans have looked to birds for inspiration in our airborne endeavors. But truly birdlike flight with flexible, feathered wings has long eluded us; for one thing, engineers have struggled to understand how birds control wing feathers. But two new studies could change that. Researchers recently designed and flew a robot with feathered wings that can change shape midflight like birds' do, giving it greater maneuverability than rigid drones.

To design the winged robot, the researchers first used motion-capture video to examine how pigeons fold and flex their wings while flying. Based on the results, they determined it was possible to control 20 feathers on each wing of a robot—which they dubbed "PigeonBot"—via elastic bands connected to just two joints. They also used modern imaging technology to gain new insight into how microscopic structures temporarily hook many bird species' feathers to one another during flight. PigeonBot needs real feathers to work, so researchers must still find ways to artificially reproduce feathers' qualities to take the technology to the next level.

The scientists modeled the robot's wing and feather movements closely on those of live pigeons, says study co-author Eric Chang, a mechanical engineer at Stanford University. Pigeons can sharply turn and bank by changing their wing shape, an attribute the researchers wanted to build

into their flier. Motion-capture footage showed how pigeons do this primarily by opening and closing their wrist joints.

Once the researchers built a prototype—a foam-board body with onboard electronic guidance systems and elastic bands controlling real pigeon feathers—they first flexed its wings in a wind tunnel to determine if it could function in blustery real-world conditions. It worked, paving the way for gliding and turning tests outside the laboratory. Chang piloted PigeonBot from the ground and describes it as an incredibly nerve-wracking experience: "[When] we had landed in one piece, I do remember collapsing on the ground afterward in this sense of relief," he says. The scientists published their results in January in *Science Robotics.*

Pigeon feathers can automatically attach to their neighbors to form a smooth, flexible flying surface, and PigeonBot's makers had to figure out exactly how. Like many bird species, pigeons accomplish this with microscopic structures called lobate cilia, which ornithologists documented early in the 20th century. But partly because of the limits of light microscopy at the time, they assumed birds' lobate cilia worked by simply increasing friction between feathers, much like rubbing pieces of sandpaper together, says Teresa Feo, a zoologist at the Smithsonian National Museum of Natural History, who contributed to a second paper from the team in *Science*, also in January. "What we discovered is the actual mechanism of those lobate cilia—that it is not friction, but hooking," Feo says. The team demonstrated how these cilia release when birds fold their wings and grab each other again when the wings are extended.

Their new understanding was made possible by modern analytic techniques such as scanning electron and x-ray microscopy and CT scans, says study co-author Laura Matloff, a mechanical engineer at Stanford. "We're the first to really revisit [lobate cilia] with this new instrumentation," she says.

But there are still mysteries about how natural feathers work. The research group found that the cilia are notably absent from feathers of barn owls and nightjars, two species that stalk prey at night. Like Velcro, the microstructures are noisy when they detach; in these stealthy hunters, evolution may have favored silent flight over feather connectivity. "It's pretty clear that this is an example of convergent evolution, where there was a trade-off," says Julia Clarke, a paleontologist at the University of Texas at Austin, who was not involved in the studies. Clarke is intrigued by the cilia's evolutionary history, although she says the tiny structures may be hard to find in the fossil record.

Emulating features that help make flying surfaces soft but sturdy could be invaluable in designing artificial morphing wings—a key step to building next-generation drones. Typical quadcopter-style drones are maneuverable and adept at hovering in place, but Chang says winged drones could be faster and quieter. The Stanford team is looking at how to best design not just "an actual wing shape that gives you more efficiency, but [the ability] to change that wing shape very dynamically" for streamlined flight, he says.

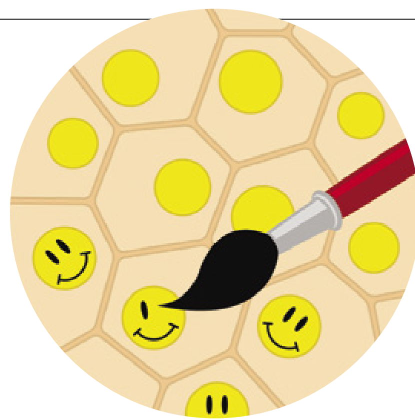
The research "points the way to new forms of biomimetic flying robots that could have a lot of useful applications," says Phil

LENTINK LAB *Stanford University*

BIOLOGY

Therapy for Cells

Cognitive-behavioral therapy improved cellular aging markers in people with social anxiety



Depression, anxiety and other psychiatric disorders can also influence physical health; they are linked with increased risk of heart disease, for example, and shorter life expectancy. Recent research suggests this may be related to accelerated aging—and new work finds that a form of purely psychological therapy can have a protective physiological effect.

A study led by clinical psychologist Kristoffer Månsson of the Karolinska Institute in Sweden showed that cognitive-behavioral therapy (CBT), a common psychotherapy technique, not only reduced anxiety levels in people with social anxiety disorder but also improved cellular aging markers for some patients. This finding could ultimately help clinicians personalize treatments.

Telomeres, short DNA sequences that cap chromosomes' ends to protect them from damage, indicate cellular age. Each time a cell divides to drive growth and repair, its telomeres shorten. The enzyme telomerase maintains them to an extent, but eventually they shorten so much that cells can no longer divide, and signs of bodily aging appear. Telomeres also shorten through cellular damage caused by highly oxidizing molecules called free radicals.

Many studies link stress with shorter telomeres. And in 2015 researchers led by clinical psychologist Josine Verhoeven of Amsterdam University Medical Center found that patients with an active anxiety disorder had shorter telomeres than those in remission or healthy controls.

In the new study, published last December in *Translational Psychiatry,* the scientists first took two blood samples, nine weeks apart, from 46 people with social anxiety disorder. They measured the subjects' telomere length as well as levels of telomerase and glutathione peroxidase (GPx), an antioxidant enzyme that counteracts free radical damage. The participants received nine weeks of online CBT and then gave another sample.

All measures remained largely unchanged over the two samples prior to therapy. But afterward, the subjects had increased GPx

Illustrations by Thomas Fuchs

Husbands, a bioinspired roboticist at the University of Sussex, who was not involved in either study. "An interesting future challenge might be the development of soft artificial feathers that can match the real thing in morphing ability."

Soft, feathered wings are "completely unusual in aerospace engineering"—and building a working artificial feather remains a major challenge, says David Lentink, an aerospace engineer and experimental zoologist at Stanford and principal investigator on both studies. Structures such as lobate cilia are currently too small for 3-D printers to handle, he adds.

Still, PigeonBot's current incarnation could help zoologists better understand how birds control their wings during flight, Lentink says. It is difficult to study live birds in a wind tunnel and nearly impossible to train them to move just a wrist or a single finger joint on command. "My goal is to develop more realistic models of birds and provide a range of species that fly very differently," he adds. Museums have a wealth of feathers that could be used in robots that mimic other birds, allowing scientists to study "the diversity of flight," Lentink explains. And replacing sentient animals with robots can reduce the need for animal research. "There's a very broad range of things that you can study with these robots," he says. "There are numerous scientific questions that spin out from this." *—Jim Daley*

levels on average. Telomerase also rose among patients whose anxiety levels benefited most from treatment, although activity averaged over all participants did not change. There were even indications that telomerase activity could predict treatment response. "The people with the lowest telomerase had greater improvements," says Verhoeven, who was not involved in the study. "This needs to be replicated, but it's an interesting lead for future research."

A longer study might show changes to telomeres themselves; nine weeks was too short for that, according to Månsson. Nevertheless, the research suggests purely behavioral changes can affect health at a cellular level. "Our biology is remarkably dynamic," Månsson says. "And it seems to respond quite quickly, over just weeks, with a behavioral intervention."

"Psychiatry is very divided between the psychological and biological," Verhoeven says. "This paper connects those fields." These results could also help relieve the stigma of mental illness, she adds: "It's not something that's only in your head—it's also in your body." *—Simon Makin*

PALEONTOLOGY

Future Fossils

Humans' and domesticated animals' influence will overwhelm the fossil record

Meat processing will produce distinctive fossils.

Humans have become a dominant force on the planet, driving species extinctions, transforming the landscape and changing the climate. And this influence will likely outlast *Homo sapiens* by millions of years: we also look set to dominate paleontology in the distant future, according to research published in March in *Anthropocene.* The new study finds that mammalian fossils from the current people-centric geologic age will consist almost entirely of humans, livestock and pets.

"We and our animals are just going to totally flood the mammalian fossil record," says Roy Plotnick, a paleontologist at the University of Illinois at Chicago and lead author of the study. "The future fossil record of today will include lots of human skeletons all lined up in a row."

The recent research was a natural follow-up to a 2016 paper in which Plotnick and his colleagues examined whether endangered species would wind up in the fossil record. They found that less than 9 percent of mammals currently threatened with extinction will likely make the cut. After learning which fossils would not be present, Plotnick says he was curious to see which would.

So he and co-author Karen Koy, a paleontologist at Missouri Western State University, exhaustively reviewed studies of how the numbers of humans, livestock and wild animals and their distribution have changed over time, both globally and in the state of Michigan. For the latter, they compared cemetery and landfill locations to sites where Pleistocene and Holocene mammalian fossils tend to occur. They also considered how human treatment of remains differs from natural processes.

The researchers found that even as wild animal numbers plummet worldwide, human development is also crowding out marshlands and other places most conducive to fossil-forming processes. Combined with the vast numbers of humans and domesticated animals occupying the planet—96 percent of all mammals on earth are people or livestock, according to a 2018 study—these findings suggest very low chances of wild animals being represented in the fossil record. (Plotnick and Koy also predict cats and dogs will likely be preserved, based on their geographical spread.) And future fossils will probably look much different from most found today. For example, they will include sawed animal bones from industrial-scale meat processing, complete and aligned human skeletons in cemeteries, and mass assemblages of livestock carcasses in landfills.

These changes' sheer scale is "staggering," says Kate Lyons, a paleoecologist at the University of Nebraska–Lincoln, who was not involved in the new research. "As I was reading the paper, I was thinking sadly of all the ecological questions that I am able to ask using the Pleistocene fossil record that will be unanswerable using this future fossil record." —*Rachel Nuwer*

ANWAR AMRO *Getty Images*

MEDICINE

A Cut Above

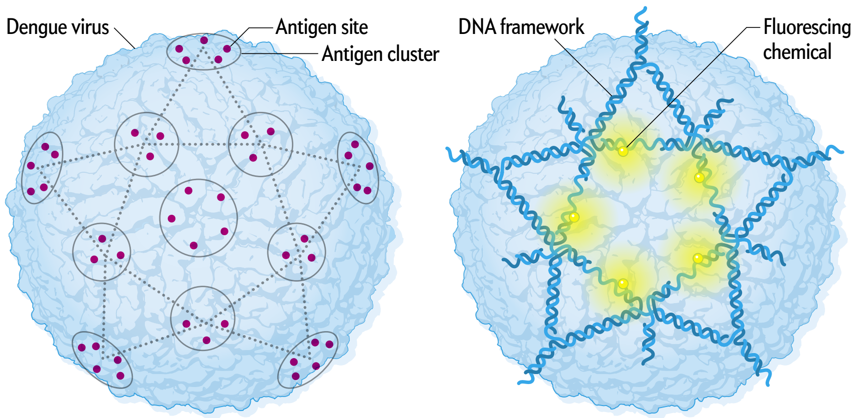
Blood-repelling bandage material also helps with quick clotting

Hemorrhage—blood escaping profusely from a ruptured vessel—is a leading cause of potentially preventable death. Bandages often fail to stop the bleeding. But researchers say they have developed a better kind of dressing: one that repels blood and bacteria, promotes quick clotting and detaches without reopening the initial wound.

While developing blood-repelling coatings for medical devices, scientists at the National University of Singapore and the Swiss Federal Institute of Technology in Zurich found that one mixture of carbon nanofibers and silicone had an unexpected effect: it boosted blood clotting. So they sprayed the mixture onto conventional cotton gauze and applied heat to make it stick. In laboratory tests and experiments with rats, they observed that this new bandage promoted the production of fibrins, proteins that form a meshlike network at wound sites to aid clotting. The bandage also stayed dry, repelling blood, which made it easy to pull away from a wound—and an investigation using *Escherichia coli* showed that bacteria in a solution could not adhere to the material. The researchers described their findings last December in *Nature Communications.*

Study co-author Choon Hwai Yap, a biomedical engineer in Singapore, says more tests are needed to understand why the nanofibers encourage fibrin formation. But he notes that producing the material is inexpensive and could be replicated on a larger scale. "I think the new bandage can make a big difference in serious wounds, such as in a car accident or on the battlefield," Yap says. "In these situations, you want to prevent bleeding very quickly by repelling it back into the wound, instead of soaking and draining blood from the body."

Esko Kankuri, a pharmacologist at the University of Helsinki, who was not involved in the new study, cautions that human trials would be needed to prove the bandage's real capabilities. "This study presented the very first observation of the material's properties on blood and in very acute, uncomplicated wounds," Kankuri says. "The results are very good and promising, but laboratory conditions are very far from actual clinical reality." —*Jillian Kramer*



Researchers built a framework from DNA that binds to particular proteins the dengue virus uses to snag host cells. The framework (*dark blue*) lights up once attached.

BIOMEDICAL SCIENCE

DNA Trap

A new test clings to dengue virus

Scientists have crafted a trap for the dengue virus using a scaffold made from fragments of DNA. The star-shaped structure is engineered to single out the virus in the bloodstream and latch on to it with precision, providing a powerful yet simple test to detect the mosquito-transmitted disease.

Dengue is the world's fastest-growing vector-borne disease, with multiple serious outbreaks in 2019. In its severe forms, it can cause internal bleeding and is sometimes fatal. There is no widely accepted vaccine or targeted treatment for dengue, so accurate early detection is crucial.

The spherical surface of the dengue virus is peppered with antigens, special proteins the virus uses to attach to the cells it infects. Scientists led by Xing Wang, a biochemist at the University of Illinois at Urbana-Champaign, constructed a flexible scaffold using DNA nanotechnology to mirror the proteins' arrangement on a hemisphere of the viral surface. The tips and vertices of this five-pointed "DNA star" align with the antigens and carry molecules that they glom on to. The multiple attachment points make the binding strong and very precise, the researchers say: the DNA star targets only viruses with that particular pattern. Once binding occurs, the star fluoresces, or lights up, signaling the presence of the virus.

"This is a great example of how DNA nanotechnology can solve real biological problems," says Mingxu You, who leads a nucleic acid chemistry research group at the University of Massachusetts Amherst and was not involved in the study. "Compared with current [dengue-detection] techniques, this DNA probe exhibits exciting sensitivity and simplicity."

Current gold-standard dengue tests require sophisticated laboratory set-ups and training. "Our technology is very simple; we need only one to two minutes, and the cost is only 50 cents for each test," Wang says. In their *Nature Chemistry* paper, published in January, the researchers compare their technology with current clinical tests and make a case for its superior sensitivity and accuracy. It should work before symptoms appear, and the DNA nanostructures are nontoxic and friendly to human tissue, the researchers say.

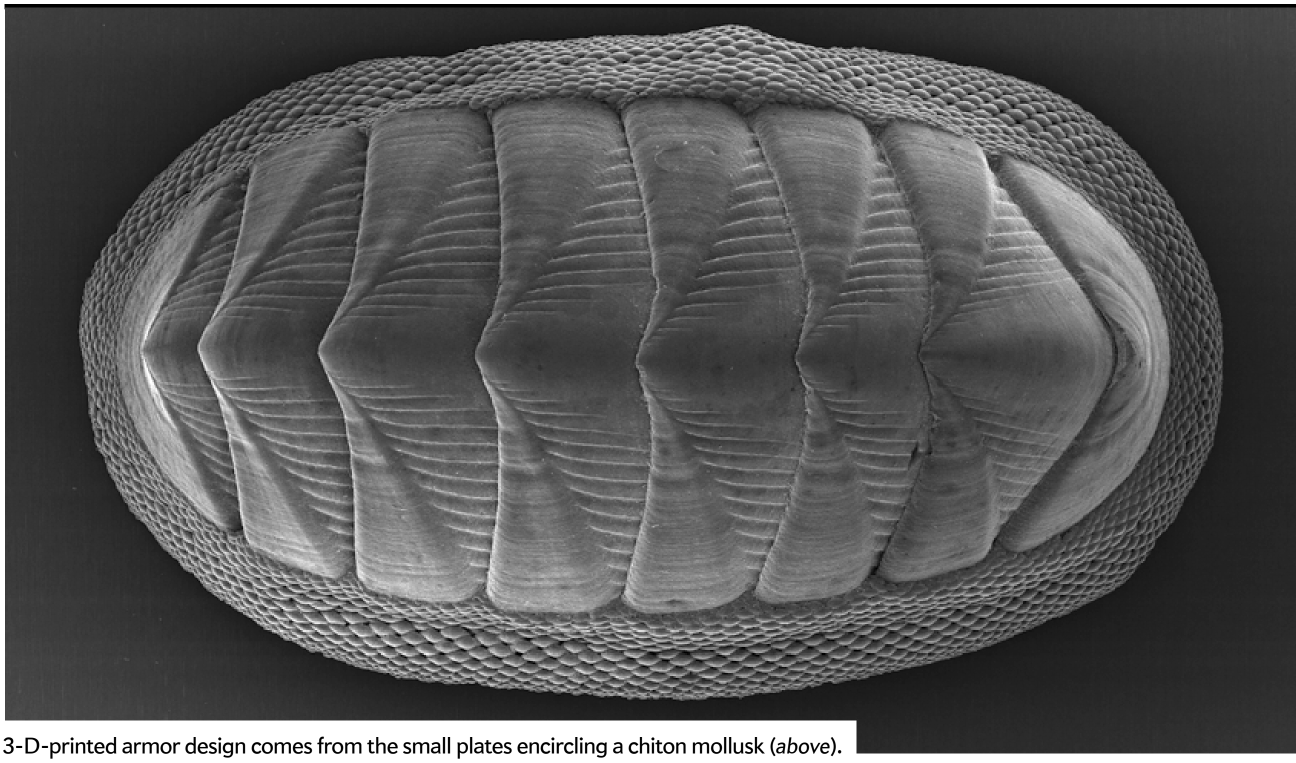
Dengue's surface pattern is complex, Wang adds, so DNA nanostructures must be molded into complicated geometric shapes to match. Simpler viruses would require simpler designs.

Wang is now collaborating with Sherwood Yao, CEO of Atom Bioworks in North Carolina, to expand the same principle to other viruses such as Zika and influenza—and beyond, to bacteria and perhaps even cancer cells. Yao has a background in AI and was intrigued by the method's pattern-recognition approach, which he compared with facial-recognition techniques. The technology provides "a programmable interface into biology," Yao says. "Our solution could become a fundamental vehicle not only to detect a pathogen but also to inhibit it."

—Harini Barath

SOURCE: "DESIGNER DNA ARCHITECTURE OFFERS PRECISE AND MULTIVALENT SPATIAL PATTERN-RECOGNITION FOR VIRAL SENSING AND INHIBITION," BY PAUL S. KWON ET AL., IN *NATURE CHEMISTRY*, VOL. 12; JANUARY 2020

Illustration by Tami Tolpa

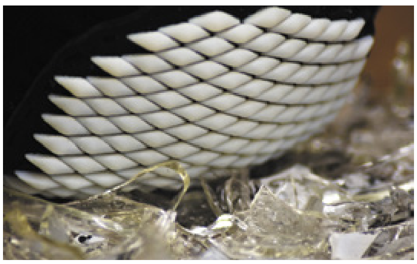


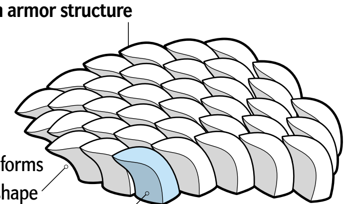
3-D-printed armor design comes from the small plates encircling a chiton mollusk (*above*).

TECH

Mollusk Armor

Scaly sea creatures inspire a flexible protective material





Protective gear has come a long way since the days of medieval armor. But engineers still have trouble shielding joints like elbows and knees, which requires material tough enough to prevent injury but flexible enough to allow motion. Toward this end, researchers are imitating an inconspicuous sea animal whose covering strikes a remarkable balance between protection and flexibility.

Certain species of marine mollusks called chitons are encircled by girdles of tough tissue capped with overlapping scales of calcium carbonate, the rigid compound that encases many shellfish. Scientists analyzed this ocean armor to learn how it provides freedom of movement without compromising defense, then 3-D-printed protective gear based on its shape. The work appeared last December in *Nature Communications*.

"We did a systematic study of the material structure, from the nanometer to macroscopic scale," says study co-author Ling Li, a mechanical engineer at Virginia Polytechnic Institute and State University. He and his colleagues at multiple institutions examined individual chiton scales' chemical composition, crystal structure and mechanical properties, then zoomed out to study how the scales worked together. The type of chiton they studied is about the length of a penny, and its largest scales are only a couple of millimeters wide—so the researchers relied on high-resolution x-rays to image the 3-D geometry of the animals' coverings.

They found the armor gains strength from its interlocking structure. Each scale has a diamond-shaped base that stretches up to a smooth top surface, which curves to hook the plate to its neighbor. When an outside force pushes on one scale, it presses against those next to it, distributing the pressure to protect the organism underneath. Working with architectural designers, the team 3-D-printed analogous scaled armor for humans—including kneepads that protect the wearer from broken glass.

The researchers could then run physical tests on the scales' behavior rather than relying on computer simulations. "This system with a lot of scales that contact each other, that slide along one another—if you try to capture this using traditional computer models, then it becomes a nightmare very fast," says Francois Barthelat, a mechanical engineer at the University of Colorado Boulder, who was not involved in the study. Printing the structures offers an efficient way to demonstrate the principles involved, he adds.

Li's team tested different scale configurations and investigated how the synthetic armor behaved under stress; he says it could provide protection for athletes or for scientists doing fieldwork. Barthelat notes that it "seems to be pretty efficient at combining flexibility with protection against lacerations." He suggests the armor could cover any joints, including fingers, and could, for example, help industrial workers: "There's a huge demand for this type of flexible protection." *—Sophie Bushwick*

FROM "BIOINSPIRED DESIGN OF FLEXIBLE ARMOR BASED ON CHITON SCALES," BY M. CONNORS ET AL., IN *NATURE COMMUNICATIONS*, VOL. 10, ARTICLE 5413; DECEMBER 10, 2019

Illustration by Brown Bird Design

MATERIALS SCIENCE

Morphing Materials

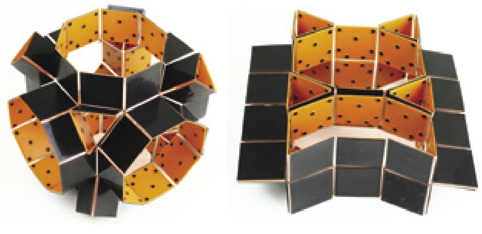
Foldable building blocks could help with nanoscale manufacturing

The sculpture-like objects in Bas Overvelde's laboratory at the Netherlands' Atomic and Molecular Physics (AMOLF) Institute are not as simple as they appear. Made of multiple prism-shaped building blocks, each face connected by flexible hinges, they can easily flip from shapes such as 3-D stars into cylinders, balls, and more.

Think of a classic slap bracelet, Overvelde says: a structure that has two stable positions, one straight and one curled up. But his lab's objects can fold along their many hinges to pop into dozens of predictable positions when pressure is applied. Beyond building a collection of these physical objects, Overvelde and his fellow researchers used computer simulations to explore even more complex assemblies of the building blocks, finding every potential shape many combinations can form. Some large virtual constructions reached more than 100 stable configurations. The study was detailed last December in *Nature Communications.*

By designing and simulating objects that fold into predictable shapes when pushed on, the researchers hope to make it easier to manufacture very tiny robots and materials with changeable structures. If such items can easily morph into specific, stable forms, fewer tools are needed to bend or assemble them. Plus, certain shapes and internal structures can add strength and make objects resilient: for instance, "bone has a microstructure that makes it lighter, but it stays stiff," Overvelde says. "We try to do the same kinds of things with our materials."

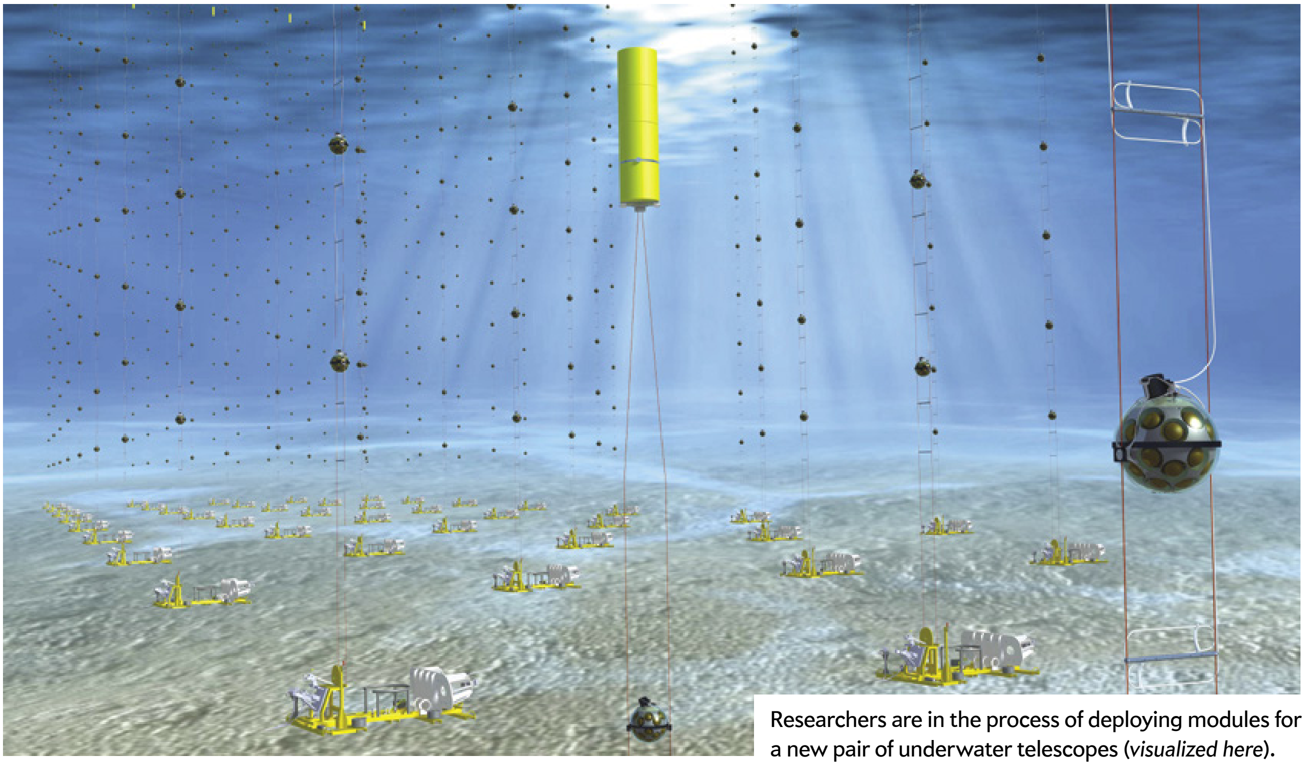
This study explores the "centimeter scale" (roughly the size range of traditional paper origami made with human hands), but Overvelde notes such objects would work the same way if much larger or much smaller. For now the group is focusing on the basics: "We're not people who do ... manufacturing at small scale," he says. "We try to come up with new concepts."



This object flexes into numerous shapes.

AGUSTIN INIGUEZ-RABAGO AND JOHANNES T. B. OVERVELDE *AMOLF*

These concepts have impressed some of Overvelde's peers in materials science. Itai Cohen, who leads similar research at Cornell University and was not involved in this study, says the new work is "a real tour de force" in its research and implications. "These are all devices that are done with [the equivalent of] cardboard and double-sided sticky tape—but the real question is, Could you start to make robotic systems?" Cohen adds. "In robotic systems, the number of configurations that you can go through dictates how much the robot is able to do, how many [light-diffracting] gratings you can make or chemical surfaces you can expose." —*Caroline Delbert*



Researchers are in the process of deploying modules for a new pair of underwater telescopes (*visualized here*).

ASTROPHYSICS

Underwater Eyes

Submarine neutrino telescopes will scan for dark matter, distant star explosions, and more

Suspended near the bottom of the Mediterranean Sea off France and Italy, 126 football-sized glass spheres are already using the ocean itself as an instrument to search for signals from dark matter, supernovae and neutron star collisions. These are the first of many such globes deployed for a project called the Cubic Kilometer Neutrino Telescope, or KM3NeT.

Its target, neutrinos, are fundamental particles that have no electrical charge and almost no mass. "Unlike cosmic rays, neutrinos are not deflected by magnetic fields in intergalactic space, making them unique messengers," says Walter Winter, a neutrino astrophysicist at the German Electron Synchrotron (DESY) research center, who is not involved with KM3NeT. "They are complementary to other sources of information like electromagnetic radiation and gravitational waves."

Neutrinos can pass through most other

matter with only a tiny fraction interacting; this ghostly behavior makes them ideal candidates for astronomy. KM3NeT is set to be installed throughout one cubic kilometer of water—enough for 400,000 Olympic swimming pools—split over two locations, turning the surrounding water into a giant lens. More than 6,000 spheres, each containing 31 highly sensitive detectors called photomultiplier tubes, will cling to strings anchored to the seafloor and kept taut by floats.

"Perhaps one or two neutrinos in a million will interact with quarks inside the nucleus of either hydrogen or oxygen" in the water, says the project's physics and software manager, Paschal Coyle of the Marseille Particle Physics Center. "Because the cosmic neutrinos possess very high energy, the result of such interactions is the release of a charged particle that travels very fast."

In fact, it travels through the water faster than light can, producing an effect Coyle likens to an optical equivalent of the Concorde jet's sonic boom. Researchers can determine the original neutrinos' energy and direction using the faint light released—so-called Cherenkov radiation—picked up by the undersea sensors.

Among the handful of astronomy-focused neutrino telescopes in existence, "KM3NeT is unique, especially in observing the Southern [Hemisphere] sky with unprecedented directional and energy resolutions, paired with its enormous size," Winter says.

The French site, scheduled for completion in 2024, will detect low-energy neutrinos generated when cosmic rays interact with Earth's atmosphere. As they pass through the planet, these particles provide an x-ray-like view of what is inside. The Italian site, set for 2026, will focus on cosmic neutrinos produced in the cataclysmic deaths of distant stars—or in dense regions of colliding dark matter.

Intriguingly, the telescopes' clearest view is looking downward; Earth works as a filter to block background particles from the cosmic rays that continuously bombard our world. Neutrinos are the only known particles from those rays that make it through the planet. —*Dhananjay Khadilkar*

KM3NET

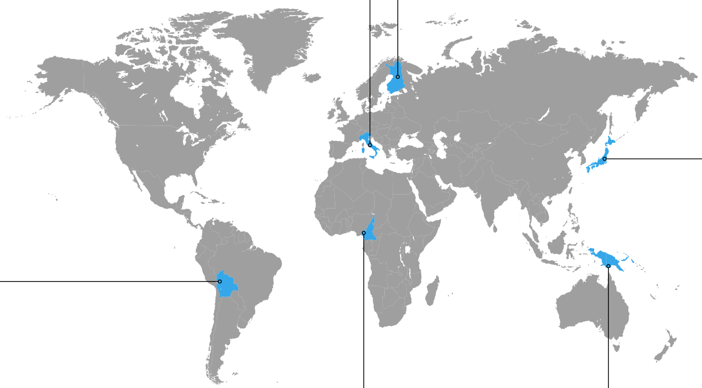
IN THE NEWS

Quick Hits

By Sarah Lewin Frasier

ITALY
New analysis suggests a fragment of ancient glass may have formed from a Herculaneum inhabitant's brain, heated by the A.D. 79 eruption of Mount Vesuvius.

FINLAND
Aurora chasers in Finland helped to identify a new feature in the Northern Lights. Nicknamed "the dunes," it may reflect an elusive type of ripple in Earth's upper atmosphere.



BOLIVIA
A new study traces how smoke plumes from heavy Amazon burning in 2007 and 2010 deposited black carbon and dust in the Andes, speeding up melting of the Bolivian Zongo Glacier by boosting heat absorption.

JAPAN
Researchers isolated and grew an intriguing single-celled microorganism in the lab from sediment off the coast of central Japan. The tentacled Archaean uses proteins common to multicellular organisms and might lend insight into how the latter evolved.

CAMEROON
Bones of children buried 3,000 and 8,000 years ago in Cameroon grasslands provided the first ancient human DNA from this region. The discovery illuminates early genetic diversity and at least one long-gone population.

NEW GUINEA
Off the island of New Guinea and northern Australia, researchers spotted four species of intricately patterned sharks that walk on their fins to hunt during low tides. They average less than a meter long and bring the total of known "walking" sharks to nine.

For more details, visit www.ScientificAmerican.com/apr2020/advances

CHANGE AGENT

Giving patients the best care for a reasonable price should be the goal of any hospital. So why are so many just maintaining the status quo? One center is bucking the trend.

Health care today is a tale of two systems. One is based on the limitless potential of science and technology to beat disease. The other is the obstacle course of time, access, and cost that sick people experience in getting well. Bridging that divide requires more than incremental change. It requires a fundamental shift in how we think about and provide health care.

Academic teaching hospitals are among America's greatest engines of innovation. Yet only a few are truly testing the status quo to make the patient experience more accessible and affordable. UPMC is one. A world-class research enterprise, health care provider, new business incubator, and insurer, UPMC includes a network of 40 hospitals, 5,000 physicians, 700 outpatient and community practice facilities, and 3.6 million insurance plan members, in the United States and abroad. That breadth has advantages. Leaving the standard fee-for-service model, UPMC is using data from its various enterprises to plan holistically and unconventionally about how to improve patient care while also lowering costs.

So how does UPMC implement change? *Scientific American* asked four leaders about how technology, science, and adjusted incentives are transforming the patient experience, and the future of medicine.

UPMC
LIFE CHANGING MEDICINE

THE NEXT REVOLUTION IN HEALTH CARE

Steven Shapiro, MD, is the Executive Vice President and Chief Medical and Scientific Officer at UPMC. Jeremy Abbate, the publisher of *Scientific American,* asked for his view on health care today and tomorrow, and how it will take some unconventional thinking to get us where we want to go.

Q: How would you describe the state of health care today?
A: We see this as both the best of times and worst of times for health care. The advances in science and technology are unbelievable. We're doing things to improve patient care like never before. But, the price is too high and we need to work on affordability and access to care.

Q: How can you place a greater emphasis on affordability without sacrificing quality care?
A: The two often go hand in hand. The higher quality often lowers the cost, but sometimes one pays for what they get. Our job is to know the difference. The incentives are largely misaligned, which is why the government has been working on other models of care. In the meantime, we're unique in our structure, so as a payer-provider, we can start to deal with these things today. The total cost of care and quality is on us as a system.

Q: If you imagine the hospital of the future, what will it look like?
A: We can bring continuous physiologic monitoring to our patients in their homes. It's a matter of really coordinating the care, keeping in contact. There will be a need, at least in the foreseeable future, for a brick-and-mortar hospital. But in that hospital, the patients will be sicker. It'll almost be a big ICU.

Q: If you could change one thing about our health care system, in this country or even globally, what would that be?
A: I talked about affordability, which is big, but we could make the most difference if we focused on healthier lifestyles. A healthy diet, a little exercise, don't smoke, and maybe sleep a little bit more. Changing behaviors could eliminate the majority of chronic diseases, improving health in our country tremendously.

Q: What's the next frontier for UPMC?
A: We would like to continue on our payer-provider journey to interlock even more closely with our health plan to deliver higher quality care that's more affordable for our patients. But with advances in science and technology, we also have the opportunity to develop new therapies that could really make a difference in treating intractable diseases, if not ultimately lead to a cure.

"Changing behaviors could eliminate the majority of chronic diseases, improving health in our country tremendously."

DAVID KELLY

THE PROMISE OF BIG DATA

Featuring Oscar Marroquin, MD, Chief Clinical Analytics Officer, UPMC

Big data is reshaping every aspect of the health care business model. Tools like AI that connect the clinic to the patient have the potential to advance precision medicine and reduce the burden of chronic disease, which accounts for more than 80% of total U.S. health costs.

Despite the optimism, health care institutions have been slow converts to the revolution. Obstacles include a culture of professional autonomy in medicine and the logistics challenge of turning vast amounts of raw, disaggregated data into the knowledge to act.

"It takes more than an app to get that right balance between people and the machine, but if you do, you've nailed the future of health care," says Oscar Marroquin, a cardiologist who oversees the development of UPMC's large suite of information assets as Chief Clinical Analytics Officer in the Health Services Division.

Marroquin runs a team of data scientists, software engineers, and visualization specialists with a simple mandate: to back clinical decisions with evidence relatable to the whole person, not just the disease.

"We don't see data as just a research tool but as continuous learning support in patient care," Marroquin says. "It's more the bedside than the bench."

Marroquin's group is fully funded by UPMC and is embedded within its clinical network, eliminating the distractions of vying for outside research grants common among data crunchers in rival hospital systems.

Among its many projects, Marroquin's group is using data prospectively to map what's missing in the patient journey from diagnosis to recovery. With its own insurance plan, UPMC can curate the huge data sets necessary for conducting broader population health assessments linked to "well care" and prevention.

"In medicine we've been trained to lump people into fixed therapeutic categories," Marroquin says, "but we now know that the phenotype of every individual consists of seemingly endless shades of gray. These include social determinants of health status, such as where you live, family background, occupational stress, and mobility issues. Using data from UPMC's network of acute care and outpatient facilities, we can add these variables to the patient chart and then build highly accurate predictive models to identify those most at risk for adverse outcomes."

Identifying the risk factors behind costly postoperative readmissions in UPMC's network of 40 hospitals has been Marroquin's priority. Pilot programs in 10 hospitals were conducted in 2018, evaluating millions of discharge records to target patients at highest risk for readmission. The pilot resulted in a 35% to 50% reduction in readmissions compared to prior rates, enough to start deploying the model for use by physicians at the point of care.

Marroquin sees more improvements to come as the data on individual patients deepens. "It is bringing us to the day when the art of medicine is validated by the hard evidence that can prevent disease, not just treat it," he says.

BREAKING THE CODE ON IMMUNE RESPONSE

Featuring Tim Billiar, MD, Chair, Department of Surgery, University of Pittsburgh School of Medicine and Scientific Adviser, UPMC Immune Transplant and Therapy Center (ITTC)

DAVID KELLY

For years, immunology, or the study of the immune system, was a sleepy little corner in the otherwise fast-moving world of clinical research. Today, it is one of the hottest fields in medicine and a source for some of the most exciting new therapies in cancer and autoimmune disease.

Research hospitals around the world are working furiously to bring this budding science quickly into the clinic, but some are farther along. "We've been far ahead of the crowd in pursuing the translational aspect in ways that benefit patients," says Tim Billar, Professor and Chair of the Department of Surgery at the University of Pittsburgh School of Medicine, UPMC's academic partner.

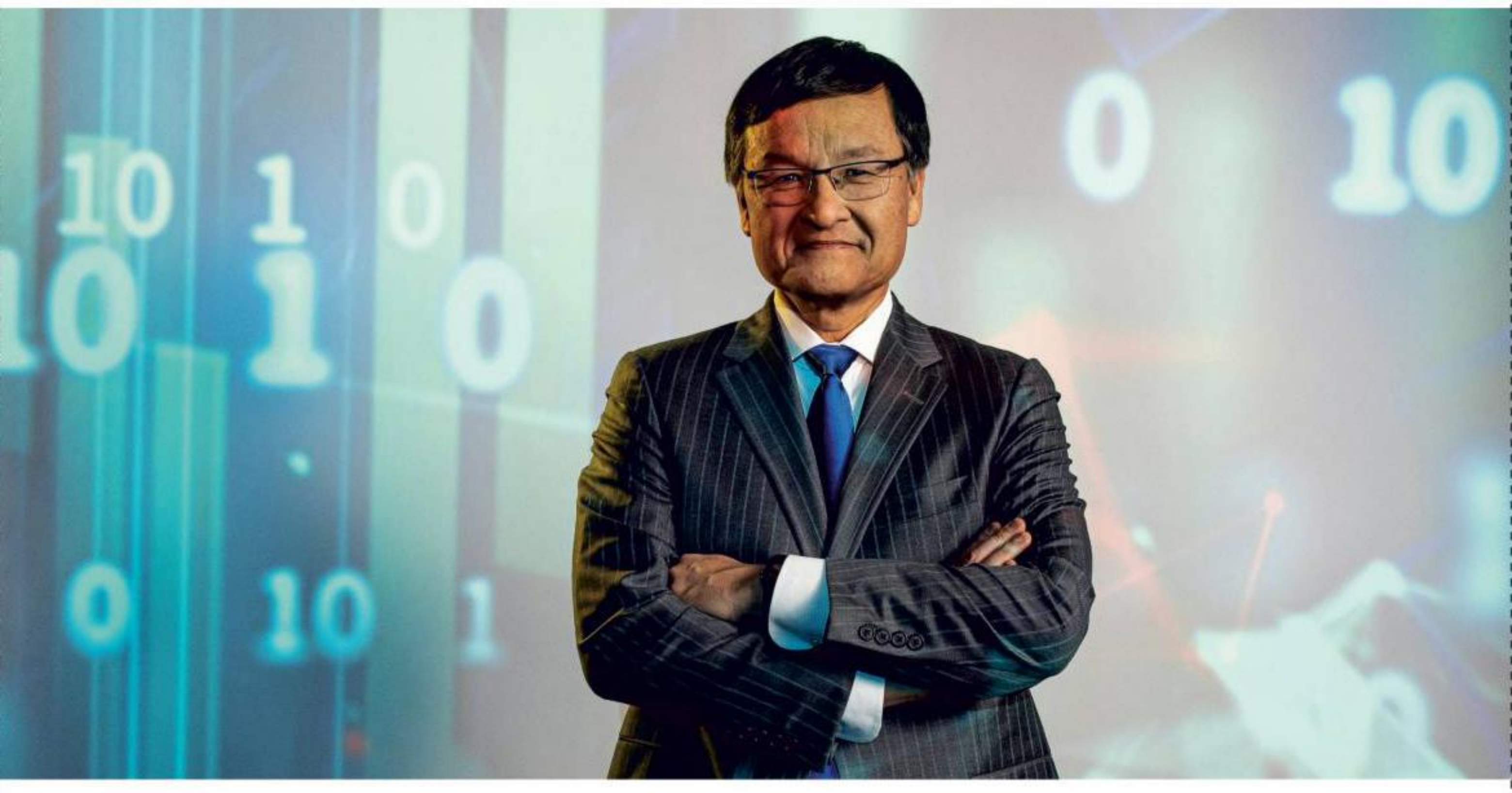
Billiar traces UPMC's involvement in the field to the 1960s, when surgeons opened the field of organ transplantation with a number of firsts. Next came the introduction of effective immune suppression that transformed organ transplants from high-risk experiments to routine procedures. "Now with 20,000 organ transplants and many cancer breakthroughs," Billiar says, "we've been able to move seamlessly to clinical leadership in cancer immunotherapies like CAR T-cell therapy."

Also in UPMC's sights are treatments for a growing list of chronic inflammatory disorders. "Chronic inflammatory conditions affect nearly everyone at some point in their lives, are a major productivity drain, and contribute to accelerated aging," Billiar says.

To consolidate their diverse capabilities in immunotherapy, UPMC and the University of Pittsburgh launched the Immune Transplant and Therapy Center (ITTC) in February 2018. The center's goal is to advance the science of immunology to create innovations in four areas: cancer, chronic disease, aging, and transplant.

Ongoing projects include a clinical trial to infuse regulatory dendritic cells in liver transplant patients prior to surgery, with the hope of putting an end to toxic immunosuppression regimens. Another is a prospective trial using the diabetes drug metformin to see if it improves outcomes following high-risk surgery. Work is also progressing to explore bone marrow transplants as a novel pathway to treating debilitating conditions like refractory inflammatory bowel disease (IBD). The ITTC currently has five trials in motion.

Billiar, who serves as the center's co-director and scientific lead, contends that the ITTC can help what ails the health research enterprise. "ITTC can rely on its position as part of UPMC's own in-house business incubator, UPMC Enterprises, which commercializes what comes out of our labs," Billar says. "Together, we've already had a hand in funding 30 projects and creating five start-up companies. Seeing our science come to life gives me a reason to think differently about the future of health care. From our perspective, the view looks promising."



THE PREMIUM IS PREVENTION

Featuring Joon S. Lee, MD, Chief Medical Officer, UPMC Insurance Services Division

In health care circles, the notion of value-based medicine has been around for some time. Rather than a "sick care" model, the thinking goes, we should move to a "well care" one, where value and outcomes are the priority. The vision is tantalizing, but realizing it has been slow.

Joon S. Lee, the Chief Medical Officer of UPMC's Insurance Services Division, which administers the nation's second largest provider-owned health plan, is challenging that status quo. "Our health plan is transitioning from traditional fee-for-service payments to a system where getting paid depends on the outcome, such as lowering hospital readmissions or optimally managing co-morbidities like hypertension," he says.

The centerpiece of this transition is a "shared savings" physician reimbursement formula that allows each practice to keep a percentage of the money saved from observing treatment guidelines to lower the total cost of care. "More than half of UPMC Health Plan patients are now under a shared savings contract," Lee says. "We expect that number to rise as we move it from primary care to the specialty side."

Lee is also looking at new ways to leverage UPMC's connection to patients to improve preventive health measures. He cites his experience in directing UPMC's Heart and Vascular Institute, one of the largest integrated cardiovascular delivery programs. "A decade ago we began to see that, despite all the new technology, deaths from heart disease were inching up again," Lee says. "We were failing to control for risk factors linked to unhealthy lifestyle behaviors like obesity and smoking."

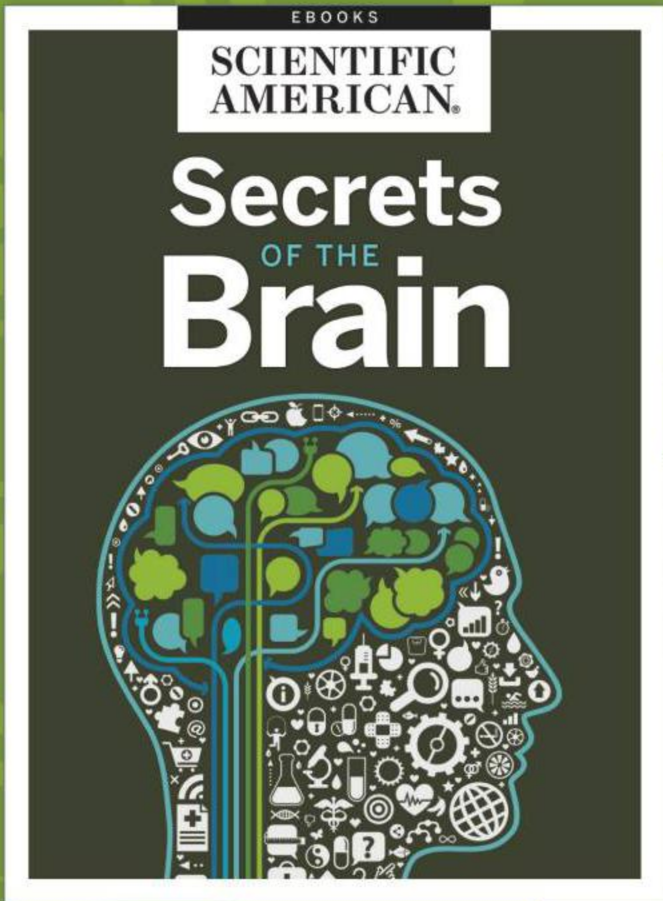
In response, the Institute worked with the UPMC Health Plan to create a patient-centered coaching program called Prescription for Wellness, utilizing UPMC's vast community outreach capabilities in managing heart care from a whole person perspective.

Though there is much yet to be done, Lee says that in the end, integrated care is a puzzle where the pieces fit. "Through the coordinated approach we minimize expensive hospital care. But when it's necessary, UPMC offers the best there is. We meet the patient in the community to seed healthy behaviors, improve outcomes, and keep our insurance rates down. It's a trifecta win, for the payer, the provider, and the member."

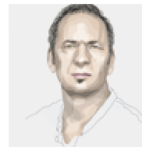
For more information on how health care is evolving, visit UPMC.com.

UPMC
LIFE CHANGING MEDICINE

DAVID KELLY


EBOOKS
SCIENTIFIC AMERICAN
Secrets
OF THE
Brain

Forrest Gander is a writer and translator whose book *Be With* was awarded the 2019 Pulitzer Prize for Poetry. His work is often linked to ecopoetics and ecology. This poem is from *Twice Alive,* due out in early 2021 from New Directions.



Forest

Erogenous zones in oaks
slung with
stoles of lace-lichen the

sun's rays spilling
through leaves in
broken packets a force

call it nighttime
thrusts mushrooms up
from their lair

of spawn mycelial
loam the whiff of port
they pop into un-

trammeled air with the sort of
gasp that follows
a fine chess move

like memories are they? or punctuation? was it
something the earth said
to provoke our response

tasking us to recall
an evolutionary
course our long ago

initiation into
the one-
among-others

and within
my newborn noticing have you
popped up beside me love

or were you here from the start
a swarm of meaning and decay
still gripping the underworld

both of us half-buried holding fast
if briefly to a swelling
vastness while our coupling begins

to register in the already
awake compendium that offers
to take us in you take me in

and abundance floods us floats
us out we fill each
with the other all morning

breaks as birdsong over us
who rise to the surface
so our faces might be sprung

Author's Note:
What we all learned in high school about lichen—that it's the synergistic collaboration of a fungus and algae or cyanobacteria—is simplified in many ways. For one thing, the original organisms are changed utterly in the compact. They can't return to what they were. For another, according to Anne Pringle, one of the leading contemporary mycologists (with whom I had the lucky opportunity to collaborate), it may be that lichen do not, given sufficient nutrients, age. Anne says that our sense of the inevitability of death may be determined by our mammalian orientation. Perhaps some forms of life are immortal. The thought of two things that come together and alter each other collaboratively—two things becoming one thing that does not age—roused me toward considering lichen a kind of model and metaphor for the intricacies of intimacy. —F.G.

MARTIN RUEGNER *Getty Images*

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

Of Sex and Sleep Apnea

The risky disorder often looks different in women and may get ignored

By Claudia Wallis

Picture, if you will, your typical sleep apnea sufferer. Chances are he is middle-aged and overweight and snores like a freight train. Note the male pronoun. Twenty-five years ago experts believed that the condition, in which breathing is disrupted during sleep, was about 10 times as common in men as in women. Better-quality studies have since reduced that ratio to roughly three to one, but as more data come to light, it is becoming clearer that sleep apnea—and the broader category known as sleep disordered breathing—simply looks a little different in women. And that suggests it is often overlooked.

Sleep apnea is a concern because it raises the risk of heart attacks, hypertension, arrhythmias, insulin resistance, strokes and accidents that result from daytime sleepiness. Put simply, gasping for breath at night and not giving your body a thorough rest puts a lot of pressure on the cardiovascular system, raises adrenaline levels and ignites inflammation. Doctors diagnose apnea with a sleep test, often done at home, that measures your apnea-hypopnea index. This index reflects the average number of times an hour that you have an episode lasting at least 10 seconds during which breathing stops (apnea) or becomes so deficient that blood oxygen levels fall by 3 or 4 percent or more (hypopnea). Fewer than five such episodes an hour is considered normal. Five to 15 is mild sleep apnea, 15 to 30 is moderate and more than 30 is severe.

Most home tests do not, however, examine the *stage* of sleep in which these episodes occur, and that may be a problem. A growing body of evidence shows that for many women disrupted breathing is concentrated in the rapid eye movement (REM) phase, which is also when dreams are most vivid and when heart and respiratory rates become less regular. A study of 2,057 men and women aged 45 to 84, published last November in the journal *Sleep,* found that women have just as many events as men do during the REM phase. "Whatever protection women have in non-REM sleep is not there during REM sleep," says Christine Won, medical director of the Yale Centers for Sleep Medicine and lead study author. Disrupting REM may be especially bad for health. "Studies suggest that how many events you have during REM sleep is what really puts you at risk for cardiovascular health effects," Won says. But because REM accounts for only about 20 percent of a person's nightly slumber, a test that averages events across the entire night can be misleading.

Several other sex differences emerged from the new study. "One of our findings is that women have a lower arousal threshold—they are more likely to wake up at night in response to a given apnea," says Susan Redline, senior author of the study and a senior physician at the Division of Sleep and Circadian Disorders at Brigham and Women's Hospital in Boston. This may also impact diagnosis. Women are more likely than men to briefly wake up before their oxygen level falls by more than 4 percent—the threshold used to identify and treat sleep apnea in patients covered by Medicare. When Won and Redline used a cutoff of 3 percent oxygen desaturation, many more women met the criteria for sleep apnea.

These differing patterns may help explain why women with sleep apnea are more likely to complain about morning headaches, fatigue, depressed mood and insomnia. In men, a big complaint (usually from a bed partner) is loud snoring, along with daytime sleepiness. In both sexes, apnea rates rise with obesity and age.

Hormones most likely play a role in these sex differences. Sleep apnea increases in women after menopause, and it is common in women with polycystic ovary syndrome, a condition characterized by high levels of testosterone. Redline notes that anatomy may also be a factor: "Men have a longer and more collapsible airway." As for the female tendency to wake up more easily, evolutionary pressures and experience might be at work: "It may be that women evolved to wake up to tend to their children," Redline says.

The leading therapy for apnea is the use of a CPAP (continuous positive airway pressure) machine to force air into the throat, keeping the airway open. Research suggests that it works equally well for REM and non-REM apnea. But as scientists shed more light on the varying patterns of the condition, treatment may become more tailored to the individual. Diagnostic criteria might also need to change to capture more cases in women. Medicare's 4 percent desaturation threshold is one example. And the increasing use of at-home testing rather than costlier testing in a sleep lab may be another. "If our findings are true," Won says, "then home sleep apnea testing biases against diagnosing women." SA

Illustration by Fatinha Ramos

Wade Roush is the host and producer of Soonish, a podcast about technology, culture, curiosity and the future. He is a co-founder of the podcast collective Hub & Spoke and a freelance reporter for print, online and radio outlets, such as *MIT Technology Review,* Xconomy, WBUR and WHYY.

Tackling the Toughest Tech

A few brave investors are backing start-ups that aim to solve the world's hardest problems

By Wade Roush

Some global crises, such as climate change, are too big to overcome through individual action or even through government-level policy change. To survive this century, we are also going to need some huge science and engineering breakthroughs—especially in areas such as energy and transportation. Unfortunately, the systems we have built to encourage innovation are in a dismal state.

Federal investment in R&D as a share of the overall economy is lower than at any point in the past 60 years. And venture capital—the industry that is *supposed* to take risky ideas from government or university laboratories and turn them into valuable businesses—has instead spent the past decade investing in low-stakes tech that helps us order takeout, avoid taxis, swap selfies and overpay for desk space. Many of Silicon Valley's "unicorns" are doing no more to improve the world than their mythical namesakes [see my column "The Big Slowdown," Scientific American; August 2019].

There is, however, at least one bright spot in the world of tech investing. I got a glimpse of it on a recent visit to The Engine, a for-profit venture firm set up in 2016 by the Massachusetts Institute of Technology. It is designed to fund ambitious ideas in areas it calls "tough tech": energy, nanotechnology, quantum computing, immunotherapy and other fields where the technical and regulatory challenges are too daunting for most venture capitalists.

A case in point: Commonwealth Fusion Systems. The Engine-backed start-up has turned a former Radio Shack down the street from M.I.T. into a lab where it tests components for future fusion reactors that could produce nearly inexhaustible, economical, carbon-free energy with vastly less radioactive waste than conventional nukes—an elusive goal that scientists have been trying in vain to accomplish for more than half a century. Chief operating officer Steve Renter says Commonwealth's "Kitty Hawk moment"—when it proves its demonstration machine can generate more energy than it consumes—could come as soon as 2025.

"To get technologies at a scale that impacts what's happening in our climate, in the time frame in which we need it, it's going to require some pretty incredible teams," says Ann DeWitt, a general partner at The Engine. "In areas like energy delivery, it means figuring out how you make that thing a business and how you integrate it into existing infrastructure. Those are areas where I think it's really hard for classical investors to go."

Part of what sets The Engine apart is the timescale of its $200-million fund. Limited-partner investors know they might not get their money back for 18 years or more, compared with the eight- to 12-year life of a typical venture fund. Plus, the firm provides lab space and equipment in addition to mentorship and networking. And it welcomes companies that hopscotch across disciplines in ways that might puzzle other investors. "We're not afraid to look at a founding team with a physicist, an optical engineer and a stem cell biologist," DeWitt says.

There are 20 start-ups at The Engine right now, and the firm is renovating an old Polaroid building that will soon hold 100 companies and 800 entrepreneurs. Researchers come to The Engine not because they are trying to make a quick buck but because they have an idea they can't bring alive anywhere else, DeWitt says: "They're compelled into entrepreneurship because of what they're trying to achieve." SA

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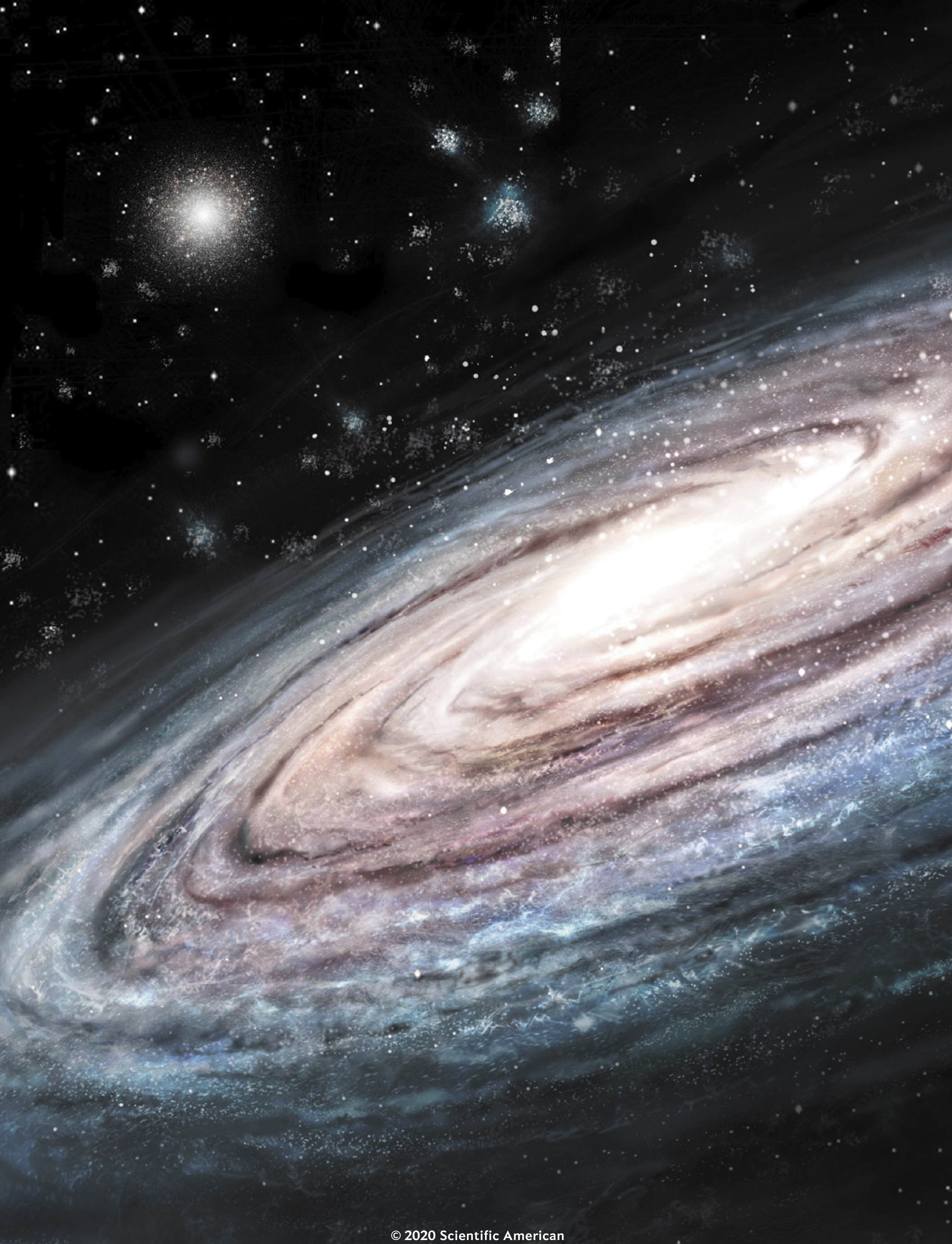
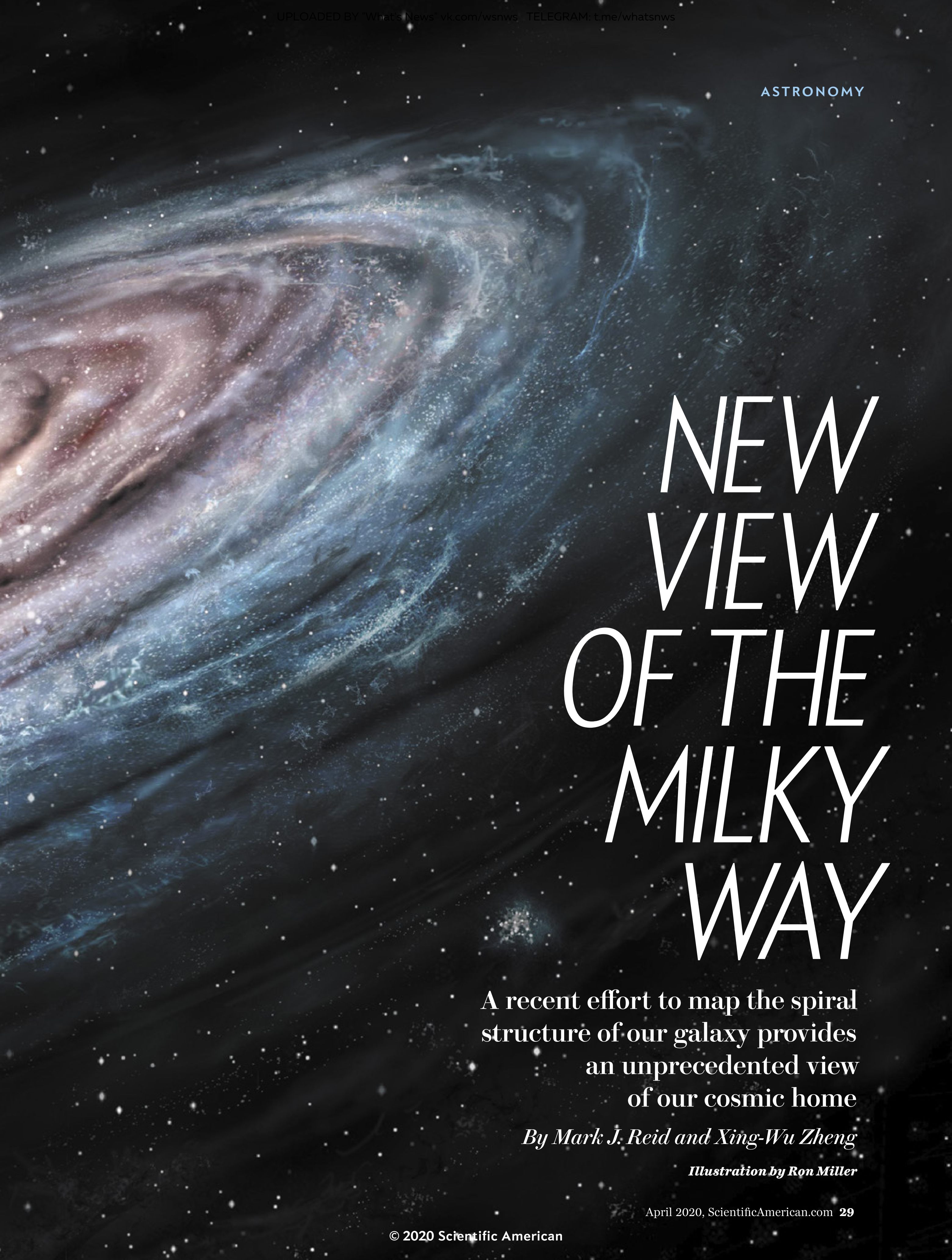
Illustration by Jay Bendt





NEW VIEW OF THE MILKY WAY

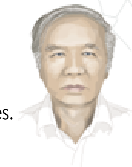
A recent effort to map the spiral structure of our galaxy provides an unprecedented view of our cosmic home

By Mark J. Reid and Xing-Wu Zheng

Illustration by Ron Miller

Mark J. Reid is a senior radio astronomer at the Smithsonian Astrophysical Observatory at the Center for Astrophysics | Harvard & Smithsonian. He was recently elected to the U.S. National Academy of Sciences.

Xing-Wu Zheng is a professor of astronomy at Nanjing University in China. He has studied astronomical masers and star formation for decades.



HUNDREDS OF YEARS AGO EXPLORERS SAILED ACROSS OCEANS AND TRAVERSED uncharted continents to map Earth, and in the past half a century space probes have photographed most of our solar system. Yet as well as we have come to know our astronomical backyard, our image of the larger neighborhood—our Milky Way galaxy—is blurry. The reason is obvious: we cannot get outside it to take a peek. Imagine sending a spacecraft on a multimillion-year journey to go beyond our galaxy, look back and snap a picture: clearly impractical. We are left with many open questions about our cosmic home, such as how many spiral arms the galaxy has, whether the large structure closest to the sun counts as an arm and where in the galaxy our solar system lies.

IN BRIEF

Astronomers know surprisingly little about the structure of our Milky Way galaxy, including the number of spiral arms it has and the location of our sun within it.

Recently, though, scientists have pieced together the best map yet of our galaxy by using data from several new research projects, particularly the Bar and Spiral Structure Legacy (BeSSeL) radio survey.

The map reveals at least four major spiral arms in the Milky Way, as well as some smaller features, and shows that the sun lies almost exactly on the central plane of the disk of the galaxy.

Recent efforts, however, have begun to map the Milky Way from the inside out, allowing us to assemble an accurate snapshot of its structure for the first time. This emerging vista is the result of several large projects involving advanced radio and optical telescopes, including our program, the Bar and Spiral Structure Legacy (BeSSeL) Survey. For this effort, we were granted an unprecedented amount of observing time—5,000 hours—on the Very Long Baseline Array, a system operated by the National Radio Astronomy Observatory and funded by the National Science Foundation.

Our initial results offer a new and improved view of the Milky Way. In addition to gaining a better understanding of what the Milky Way looks like, we are starting to clarify why galaxies such as ours exhibit spiral structure and how our astronomical home fits into the universe as a whole.

THE COSMIC NEIGHBORHOOD

IN THE EARLY 1800S William Parsons, the third Earl of Rosse, built a 72-inch telescope—huge for its time. He observed and drew what we now call the Whirlpool Galaxy, which clearly had a spiral pattern. Without knowledge about how far away it was or about the scale of the Milky Way, however, it was unclear whether the Whirlpool was a small structure inside our galaxy or a large nebula similar to it. Debate on these points continued into the early 1900s, until Edwin Hubble, using a technique developed by Henrietta Leavitt to measure the distance to bright stars, showed that the Whirlpool and similar spirals were far outside the Milky Way. This revelation upended the notion that the Milky Way might encompass the entire universe.

Astronomers figured out that we live in a spiral galaxy by measuring the motions of gas throughout the disk—the large, pancake-shaped region that makes up the main body of the Milky Way. Spirals, along with rounded ellipticals, are common types of galaxies. The nearby spirals NGC 1300 and Messier 101 (M101) provide good examples of how the Milky Way might look from afar. NGC 1300 has a bright, linear structure in its center, which astronomers call a bar, and two bluish spiral arms that start at the ends of the bar and wend slowly outward as they encircle it. Bars are seen in the majority of spiral galaxies and are thought to form from gravitational instabilities in a galaxy's dense disk. In turn, the stirring action of the rotating central bar may give rise to spiral arms. (Other processes—such as instabilities associated with large mass concentrations inside a disk or gravitational perturbations from nearby galaxies—can also lead to arms.) Spiral arms tend to glow in blue light, which comes from gigantic stellar nurseries where massive stars are forming. M101, the other potential Milky Way match, is known as the Pinwheel Galaxy; although it lacks the bright bar of NGC 1300, it boasts more spiral arms.

Astronomers have long thought that the Milky Way has characteristics of both these galaxies. It probably has a significant bar as seen in NGC 1300, as well as multiple spiral arms as in M101. Beyond these basic

LIKE THE MILKY WAY, the nearby galaxy NGC 1300 is a barred spiral of stars stretching across more than 100,000 light-years. But our celestial neighbor is not an exact mirror image: studies indicate the Milky Way has four major spiral arms rather than two.

NASA, ESA AND HUBBLE HERITAGE TEAM (STSCI/AURA)

conclusions there is considerable debate. Infrared observations made more than a decade ago with the Spitzer Space Telescope have suggested that the galaxy might have only two spiral arms. But radio-wavelength observations of atomic hydrogen and carbon monoxide, which are concentrated in the spiral arms of other galaxies, indicate that the Milky Way has four arms. Additionally, astronomers have debated how far the sun is from the center of the galaxy and how high it sits above the Milky Way's midplane—the central plane of the disk.

Nearly 70 years ago scientists calculated the distances to some nearby luminous blue stars. Plotting these points on a map revealed segments of three nearby spiral arms, which we call the Sagittarius, Local and Perseus arms. Around the same time, starting in the 1950s, radio astronomers observed atomic hydrogen gas, which releases a telltale light signature at a wavelength of 21 centimeters. When this gas is moving relative to Earth, the frequency of this atomic hydrogen signature shifts because of the Doppler phenomenon, allowing astronomers to measure the velocity of the gas to provide clues to its location in the galaxy. Using such measurements, galactic cartographers employ a convenient coordinate system for our Milky Way as viewed from the sun: by analogy to Earth's longitude and latitude, galactic longitude (l) is zero toward the galactic center and increases along the "equatorial" plane of the Milky Way as viewed from the Northern Hemisphere; galactic latitude (b) denotes the angle perpendicular to the plane. So-called longitude-velocity plots of 21-centimeter light signatures from hydrogen gas (and later from carbon monoxide) revealed continuous arcs of emission that very likely trace spiral arms. This mapping method, however, is plagued by ambiguities and lacks the accuracy necessary to clearly reveal the galaxy's spiral structure.

A NEW VIEW

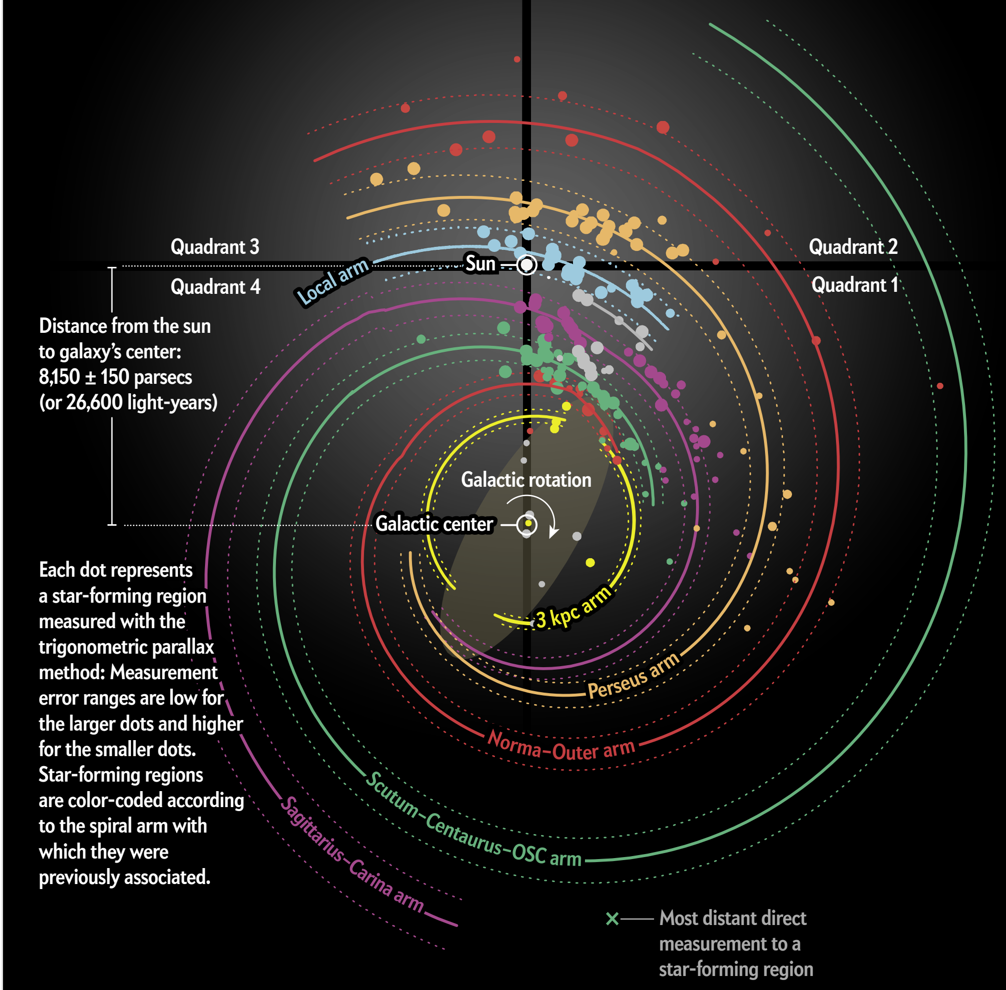
ONE REASON that we know so little about the Milky Way is that the galaxy contains an enormous amount of dust. Dust absorbs optical light efficiently, so along most lines of sight through the disk, we cannot see very far—dust is blocking the view. Another reason is the Milky Way's mind-numbing vastness. Light from stars on the other side of the galaxy takes more than 50,000 years to reach Earth. Such distances make it hard to even sort out which stars are near and which are far away.

New telescopes operating at optical wavelengths in space and at radio wavelengths across the globe are now making great strides toward answering our questions about the Milky Way. The Gaia mission, launched in 2013, seeks to measure distances to more than a billion stars in the galaxy and will undoubtedly revolutionize our understanding of the different stellar populations involved in the Milky Way's formation. But because it uses optical light, which is absorbed by interstellar dust grains, Gaia cannot freely probe distant spiral arms. In contrast, radio waves easily pass through dust and allow us to explore the entire disk and map its structure.

Two major projects now mapping the Milky Way use a technique in radio astronomy called very long baseline interferometry (VLBI). The VERA (VLBI Exploration of Radio Astrometry) project operates four radio telescopes spanning Japanese territory from the north of the country (Mizusawa) to its southernmost (Ishigaki) and easternmost (Ogasawara) islands. And the BeSSeL Survey uses the Very Long Baseline Array, which includes 10 telescopes and spans much of the Western Hemisphere, from Hawaii to New England to St. Croix in the U.S. Virgin Islands. Because their telescopes are separated by nearly the diameter of Earth, these arrays can attain an angular resolution

A Whirlpool of Stars

Based on distance measurements gathered using thousands of hours of radio-telescope observations (*below*), this is the best bird's-eye view of our galaxy's structure ever assembled (*right*). The data reveal four major spiral arms around a central, barred bulge of stars. Our sun—which astronomers treat as the nexus of a quadrant mapping system—lies in a 212-million-year orbit around the galactic center, near a smaller spiral-arm fragment (*in blue*). Future studies using radio telescopes in Earth's Southern Hemisphere could unveil additional structures in the mostly unmapped fourth quadrant.



Each dot represents a star-forming region measured with the trigonometric parallax method: Measurement error ranges are low for the larger dots and higher for the smaller dots. Star-forming regions are color-coded according to the spiral arm with which they were previously associated.

TRIGONOMETRIC PARALLAX

Astronomers measure interstellar distances by watching for the offset, or parallax angle, of a star's position when viewed from opposing sides of Earth's orbit. The closer a star is to Earth, the larger its parallax. Paired with the known Earth-sun distance, a star's parallax lets astronomers use basic trigonometry to calculate that star's distance from Earth.

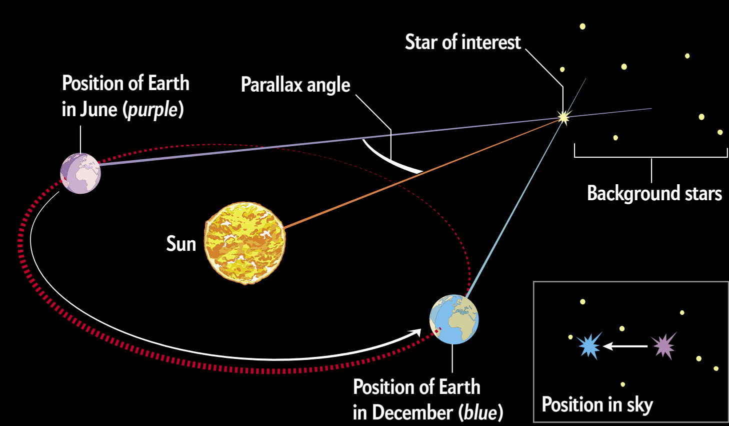
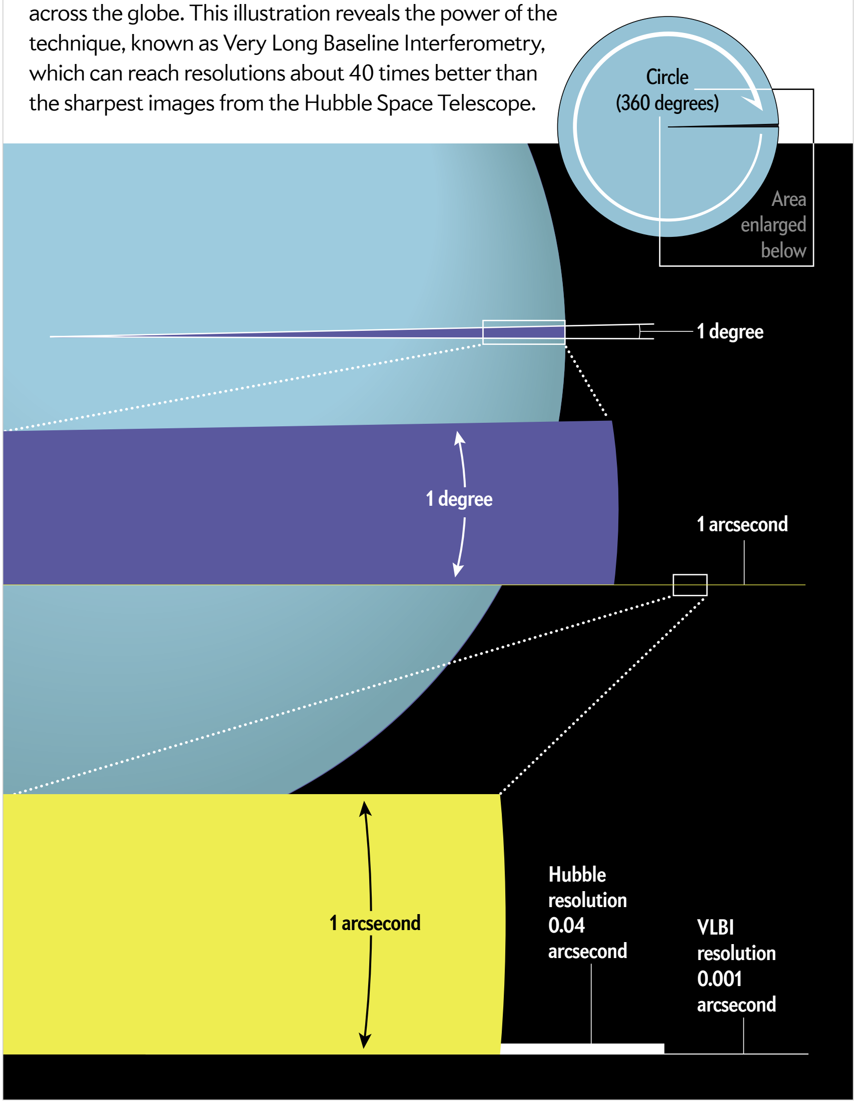


Illustration by Elena Hartley (parallax diagram)

XING-WU ZHENG AND MARK J. REID, BAR AND SPIRAL STRUCTURE LEGACY (BESSEL) SURVEY (A VLBA KEY SCIENCE PROJECT), NANJING UNIVERSITY, AND CENTER FOR ASTROPHYSICS | HARVARD & SMITHSONIAN (*Milky Way chart* and *illustration*)

Eagle Eyes on the Sky

Measuring the minuscule parallax angle for star-forming regions on the other side of the galaxy requires extreme angular resolution currently achievable only through precisely combining simultaneous observations from multiple radio telescopes across the globe. This illustration reveals the power of the technique, known as Very Long Baseline Interferometry, which can reach resolutions about 40 times better than the sharpest images from the Hubble Space Telescope.



that far surpasses that of any other current telescope at any wavelength. Researchers must observe simultaneously with all the telescopes and synchronize the data recorded on computer disks at each site with the best atomic clocks. They then ship the recorded data to a special computer that cross-correlates the signals among the telescopes. After some calibrations, the result is a digital image of what we would see if our eyes were sensitive to radio waves and separated by almost the entire width of the planet. Such imagery represents an incredible angular resolution of better than 0.001 second of arc (there are 3,600 seconds of arc in one degree, and the entire celestial sphere is 360 degrees). By comparison, the human eye can resolve structures separated by at best about 40 seconds of arc, and even the Hubble Space Telescope can achieve a resolution of only about 0.04 second of arc.

With VLBI, we can measure the position of a radio-bright star relative to background quasars (bright active black holes at the centers of distant galaxies) with an accuracy approaching 0.00001 second of arc. Making this comparison allows us to survey very great distances by observing the parallax effect, whereby a nearby object seen against a distant background will appear at different positions when viewed from different vantage points. You can simulate this effect by looking at your thumb at arm's length and alternately closing your left eye and your right eye. Our eyes are separated by several centimeters, so a thumb at an arm's length will appear to shift by an angle of about six degrees when viewed through one eye and then the other. If one knows the separation of the vantage points and the observed angular shifts, it is easy to calculate the distance. This is the same principle that surveyors use to map cities.

Ideally, to map spiral structure, astronomers should observe young massive stars. These short-lived stars are often associated with intense bouts of stellar formation within spiral arms and are so hot that they ionize the gas around them, causing it to glow in blue light and creating a spiral-arm-tracing beacon visible across the cosmos. But trapped within the Milky Way's dusty disk, we cannot easily observe such stars throughout our own galaxy. Fortunately, molecules of water and methyl alcohol just outside the regions ionized by these hot stars can be very bright radio sources because they emit natural "maser" emission that is barely attenuated by galactic dust. The word "maser" is an acronym for "microwave amplification by stimulated emission of radiation," and this radiation is the radio analogue of an optical-light laser. In astrophysical settings, maser emission comes from solar system–scale clouds of gas whose mass is comparable to that of Jupiter. What we see in radio images are extremely bright "spots" that are nearly ideal targets for parallax measurements.

THE UPDATED PICTURE

BETWEEN THE BESSEL SURVEY and the VERA project, astronomers have amassed about 200 parallax-based distance measurements for young hot stars across large regions of the Milky Way. These data, which give us good coverage of about one third of the Milky Way, reveal four arms that are continuous over great distances.

The map also shows that the sun is very close to a fifth feature called the Local arm, which seems to be an isolated fragment of a spiral arm. Previously this fragment had been called the Orion or

Illustration by Elena Hartley

Local spur, suggesting a minor structure similar to smaller appendages seen branching off spiral arms in other galaxies. This "spur" interpretation is probably incorrect, however. In our data, this fragment appears to be an orphan segment of an arm that wraps around less than a quarter of the Milky Way. Over its short length, though, it has amounts of massive star formation comparable to what we see in a similar length of the nearby Perseus arm. Interestingly, some astronomers have thought the Perseus arm to be one of the two dominant arms (the other is the Scutum-Centaurus–Outer-Scutum-Centaurus arm) in the Milky Way. We find, however, that massive star formation decreases significantly as the arm wends inward away from the sun, suggesting that it would not appear as a very prominent arm to an external observer.

By using the three-dimensional locations of our massive young stars and modeling the measured motions, we can estimate values for fundamental parameters of the Milky Way. We find that the distance from the sun to the galaxy's center is 8,150 ± 150 parsecs (or 26,600 light-years). This is smaller than the value of 8,500 parsecs recommended decades ago by the International Astronomical Union. Also, we find that the Milky Way is spinning at 236 kilometers per second, which is about eight times the speed at which Earth orbits the sun. Based on these parameter values, we find that the sun circles the Milky Way every 212 million years. To put this in perspective, the last time our solar system was in this part of the Milky Way, dinosaurs roamed the planet.

The part of our galaxy interior to our sun has a very thin and nearly flat planar shape. Although this has long been known, the location of the sun relative to this plane has been controversial. Recently astronomers settled on a value of 25 parsecs (82 light-years) above the plane, but our results strongly disagree with this estimate. By fitting a plane through the locations of massive stars for which we have accurate distances, we determine that the sun is only about six parsecs (20 light-years) above that plane. This distance is only 0.07 percent of the sun's distance from the plane's center, meaning it is extremely close to the midplane. We also confirmed previous observations that farther out in the Milky Way the plane starts warping upward on its northern side and downward on its southern side, a bit like a potato chip.

When describing their observations, astronomers divide the Milky Way into quadrants, with our sun at the center. Using that convention, we have traced spiral arms in the first three quadrants. To complete the map in the fourth quadrant, we need observations from the Southern Hemisphere. These are being planned and will be obtained with telescopes across Australia and New Zealand. While awaiting those results, we can extrapolate the known arms into the fourth quadrant by using auxiliary information from observations of atomic hydrogen and molecular carbon monoxide. The architecture revealed by these observations coincides with previously theorized structures named the Norma-Outer, Scutum-Centaurus–Outer-Scutum-Centaurus, Sagittarius-Carina and Perseus arms. We caution, though, that we have only one distance measurement to a star-forming region well beyond the galactic center. The measured location of this region, coupled with its position in galactic longitude-velocity plots of carbon monoxide emission, gives us some confidence in how we connected arms on the far side of the galactic center. We will need more such measurements to be certain of our model, however.

We now have a clearer picture of our cosmic neighborhood. It seems we live in a four-armed spiral galaxy with a bright central bar and a reasonable degree of symmetry. Our sun is located almost exactly in its midplane but far from its center, about two thirds of the way out. In addition to arms that wrap approximately all the way around, the Milky Way has at least one additional arm segment (the Local arm) and probably has numerous spurs. These features make our galaxy appear fairly normal, but it certainly is not typical. About two thirds of spiral galaxies exhibit bars, so in this way the Milky Way is in the majority. Yet its possession of four clearly defined and fairly symmetric spiral arms makes it stand out from most other spiral galaxies, which have fewer, messier arms.

MORE MYSTERIES

ALTHOUGH WE HAVE SOME new answers, we are also left with significant questions. Astronomers are still actively debating how spiral arms arise in the first place. Two competing theories are that gravitational instabilities on the scale of the entire galaxy form long-lasting spiral-wave patterns or that smaller-scale instabilities stretch and amplify over time into arm segments that then link up to form long arms. In the former theory, spiral arms can last for many billions of years, whereas in the latter theory, arms are shorter-lived and new ones emerge many times over a galaxy's lifetime.

It is also difficult to set an age for the Milky Way because it has no clear birth date. Current thinking is that it gradually coalesced over eons as many smaller protogalaxies that had formed earlier in the history of the universe collided and merged. The Milky Way probably would have been recognizable as a large galaxy about five billion years ago, but it might have looked quite different then because major mergers would have been likely to scramble any existing spiral structure.

Improving on our latest image of the Milky Way will require many more observations and will be facilitated by the next generation of radio telescope arrays capable of VLBI. Such arrays are being planned now and include the Square Kilometer Array in Africa and the Next Generation Very Large Array in North America. Both are giant arrays of radio telescopes projected to span their continents, and they could be fully operational by the end of this decade. By greatly increasing the telescope collecting area compared with that of current arrays, they will allow the detection of much fainter radio emissions from stars and hence will see farther across the Milky Way. Ultimately we hope to definitively trace our galaxy's large-scale architecture to confirm or reject the competing theories of how its grand, spiraling structure came to be. SA

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ENDANGERED Key Largo woodrat has suffered from habitat loss, hurricanes, pythons—and cats.

CONSERVATION

CAT *vs.* WOODRAT

How do you protect an endangered species when its biggest threat is beloved by humans?

By Carrie Arnold

IN BRIEF

Worldwide, feral cats kill a significant amount of wildlife every year. But methods to solve the problem are often controversial, and their efficacy is understudied.

In Key Largo, Fla., ongoing research is illuminating the precise interactions between a colony of cared-for feral cats and the endangered woodrat.

A more granular understanding of how free-ranging cats affect vulnerable wildlife could help conservationists and cat advocates collaborate on solutions.

Ralph DeGayner knew he was seeing the work of a serial killer.

Carrie Arnold is a health and environmental reporter based in Virginia. She lives with her husband and (indoor) rescue cat.

All of the victims had been ambushed and mutilated; many had their throats ripped out. Every morning for several weeks DeGayner, a lanky octogenarian, found the bodies buried under leaf litter along Key Largo's route 905, a county road that runs through the Crocodile Lake National Wildlife Refuge. The more disemboweled woodrats DeGayner encountered, the more his disappointment turned to rage.

"It was the cats," he says, his blue eyes flashing in the Florida sun. "That's exactly how they kill. I didn't need more proof than that." Returning to the site of the massacre, even eight years later, filled DeGayner with ire. He turned north, glaring toward the abutting Ocean Reef Club, a gated community home not just to millionaires but also to hundreds of feral cats.

The plight of the endangered Key Largo woodrat became DeGayner's personal crusade late in life. To occupy his time when the conditions were not right for fishing, the retired hot-tub salesman began volunteering at the wildlife refuge, which opened in the late 1990s. He was quickly taken by the cinnamon-colored rodents, which build large, meticulous nests with a precision he found endearing. Woodrats had long eked out an existence under a thin stretch of the lush canopies of Key Largo's semitropical forests, where they shared their neighborhood with crocodiles, snakes and raptors. The population had managed to hang on even as much of its habitat was razed to make room for pineapple plantations, a missile silo, oil derricks and luxury condos. But the cats were a different kind of menace. For one thing, not everyone agreed that cats were a menace at all.

Fifteen years ago, in a last-ditch attempt to save the woodrat from extinction, conservationists at the refuge teamed up with Disney (with its Florida presence and rodent mascot) to begin a breeding program at the Animal Kingdom in Orlando. Over several years wildlife biologists successfully bolstered the woodrats' numbers in captivity. The real test, though, would be surviving back in Key Largo.

DeGayner was sure the woodrats would make it if he could keep the feral cats out of the refuge. He was not alone. Local conservationists had repeatedly asked the Ocean Reef Club, which fed and cared for the cats through a program called ORCAT, to figure out how to keep them contained. But ORCAT demurred: the cats were being scapegoated for a long list of problems, and anyway it would be impos-

PRECEDING PAGES: JOEL SARTORE; THIS PAGE: MICHAEL COVE *North Carolina State University* AND USFWS

FREE-ROAMING cat investigates a woodrat nest in the Crocodile Lake National Wildlife Refuge in Florida.

sible to restrict them all to the 2,500-acre property.

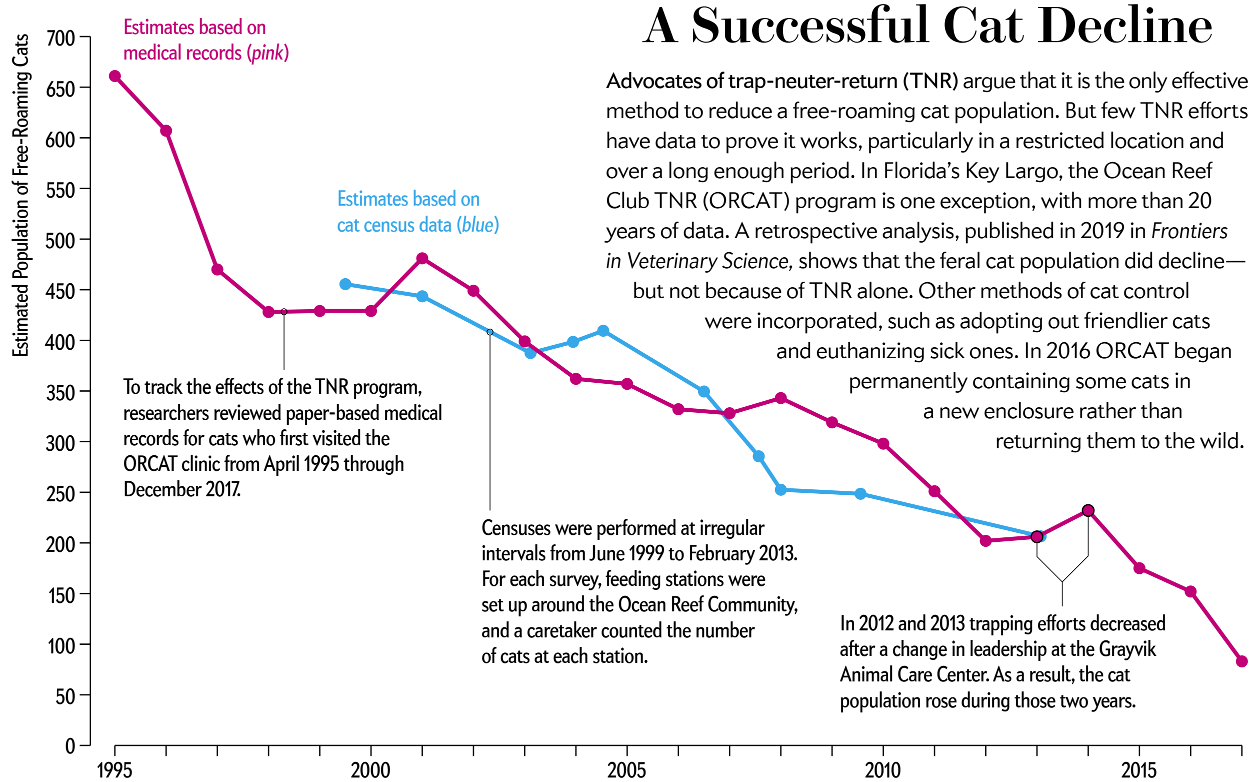
Over several weeks in 2010 and 2011, biologists released 27 tagged woodrats into the refuge. Within weeks cats killed every one of them. "They spent millions of dollars to show that cats eat rats," DeGayner says. The breeding program was scrapped. And the antagonism between the cat advocates and the conservationists intensified.

AN ALTERNATIVE SOLUTION

HUMANS DID NOT DOMESTICATE CATS as actively as they did dogs. As a result, there are far fewer genetic differences between house cats and wildcats than between dogs and wolves. But cats have lived alongside humans for more than 10,000 years. Grain stored by early farmers attracted rodents, and the rodents lured cats, which then stayed for our food scraps (and maybe a scratch or two behind the ears). Wherever humans went, cats followed—and multiplied. A female cat can start reproducing at less than a year old and can have as many as three litters of five or more kittens each year for the rest of her life. It is not surprising, then, that people have been complaining about cat overpopulation for decades.

A Successful Cat Decline

Advocates of trap-neuter-return (TNR) argue that it is the only effective method to reduce a free-roaming cat population. But few TNR efforts have data to prove it works, particularly in a restricted location and over a long enough period. In Florida's Key Largo, the Ocean Reef Club TNR (ORCAT) program is one exception, with more than 20 years of data. A retrospective analysis, published in 2019 in *Frontiers in Veterinary Science,* shows that the feral cat population did decline—but not because of TNR alone. Other methods of cat control were incorporated, such as adopting out friendlier cats and euthanizing sick ones. In 2016 ORCAT began permanently containing some cats in a new enclosure rather than returning them to the wild.



Over the past 10 years the science has made it clear that domestic cats are a conservation nightmare around the world. Because cats are found at population densities 10 to 100 times higher than those of similarly sized predators, their impact is far more profound than that of naturally occurring predators such as raptors, raccoons and snakes. They have been implicated as a major force in the extinction of 14 percent of bird, mammal and reptile species on islands. In 2013 Georgetown University conservation biologist Peter P. Marra and his colleagues at the Smithsonian's Migratory Bird Center and the U.S. Fish and Wildlife Service estimated that feral and outdoor cats kill about 2.4 billion birds every year—and that is on top of the estimated 12.3 billion rodents and other mammals also killed by cats. As free-ranging cats have been increasingly documented killing endangered wildlife, disputes such as the one in Key Largo have popped up around the world. Much less clear, however, is how to tackle the problem.

Historically, "cat control" meant rounding up and killing strays every now and then, often as a reactionary measure when things got out of hand. But given a cat's extraordinary fertility rate, it did not take long for the feline population to get right back to where it started. Over the past few decades governments have tried an arsenal of more deliberate strategies, including poison sausages, sharpshooters, deadly viruses and a toxic gel sprayed on cats' fur. Few of these tactics were practiced consistently over a long-enough period. Nearly all of them have failed, emboldening people who work in animal welfare to insist that simply killing cats is not just cruel but ineffective: today there are anywhere from 70 million to 100 million feral or unowned cats in the U.S. alone.

Instead cat supporters advocate for humanely trapping cats, sterilizing them and returning them to their colonies, or social groups, in the wild—a process known as trap-neuter-return, or TNR. If free-ranging cats are prevented from reproducing, feral cat colonies will naturally decrease in size over time as cats die. In the mid-1980s Julie Levy, who was then a veterinary student at the University of California, Davis, led one of the country's first TNR efforts. Within a few years almost all the campus's feral cats had been trapped and sterilized, and by the time Levy graduated the area around the veterinary school was nearly cat-free. "People were so excited to have an alternative solution," she recalls.

In 1993 word of Levy's California TNR project reached Alan Litman, a prolific inventor and a resident of the Ocean Reef Club. At the time thousands of feral cats roamed the property, which takes up one third of Key Largo. The occasional roundups for euthanasia, which did not sit well with many locals, were not working. Cat feces were everywhere, and

SOURCE: "DECREASE IN POPULATION AND INCREASE IN WELFARE OF COMMUNITY CATS IN A TWENTY-THREE YEAR TRAP-NEUTER-RETURN PROGRAM IN KEY LARGO, FL: THE ORCAT PROGRAM," BY RACHAEL E. KREISLER ET AL., IN *FRONTIERS IN VETERINARY SCIENCE;* FEBRUARY 1, 2019

Graphic by Amanda Montañez

owners filed a never-ending stream of complaints about the noise of cat fights and the smell of territory markings. Litman lobbied Ocean Reef to try TNR, and the club agreed, providing long-term funding to launch ORCAT with money from the homeowners' association and private donations. Litman hired Susan Hershey, a technician at a local veterinary hospital, to head up the program. When she arrived in 1995, Hershey popped open a can of food on the street and encountered "70 or 80 cats, easily," she recalls. "It was an extreme problem."

Hershey spent most of the daylight hours baiting traps with cans of Friskies and waiting for unsuspecting cats to step inside. As the cats learned her routine and began to avoid the traps, Hershey constantly evolved her methods. Many of the cats she trapped were sick and had to be humanely euthanized; others were friendly and could be adopted into homes. Hundreds of cats, however, were healthy enough to be spayed or neutered but too fearful of humans for a life indoors. These cats were returned to their colonies with the top of their left ear removed to indicate that they were fixed. For five years Hershey and a growing team trapped and neutered practically around the clock. Slowly but surely, the number of cats at Ocean Reef began to drop.

THE NEGOTIATOR

NEWS OF ORCAT'S SUCCESS began to spread throughout the animal welfare community. Hershey became something of a TNR celebrity, fielding visitors from around the world who wanted to learn how to replicate the Key Largo program. The area's feral cats also attracted biologist Michael Cove, then a young doctoral student at North Carolina State University, who arrived at the Crocodile Lake National Wildlife Refuge in 2012. Although the number of cats at Ocean Reef had indeed declined, the woodrats were still in serious trouble, and Cove wanted to figure out how to better protect them. Feral cats often wandered into the refuge, lured by the industrious activities of the woodrats. Cove wanted to document the effects of cats on the woodrat population and understand how the cats—among other factors—limited woodrat recovery. To conservationists, the presence of ORCAT was anything but a victory.

Although a handful of studies from Rome to Rio de Janeiro have indeed shown persistent population reductions from TNR, it is not easy to sterilize enough cats to create a steady downward population trend, explains conservation biologist Grant Sizemore of the American Bird Conservancy. Modeling studies have shown that upward of 90 percent of the cats need to be fixed to create a steady population decline, and trapping that many cats is nearly impossible. Domestic cats reproduce so efficiently that even small gaps in cat colony maintenance can lead to a resurgence in numbers—something ORCAT's own data show. Additionally, the presence of cared-for feral cats has been found to encourage people to dump their unwanted cats in the same area—which is often a reason the strategy fails. (It also helps to explain the success of ORCAT, which is located in a gated community on a small island.) "TNR is a Band-Aid solution for a gaping wound," Sizemore says.

TNR supporters acknowledge that the method is imperfect. But Levy and Hershey argue that even with all its flaws, TNR is the only technique that has so far been shown to reduce cat populations over time. Humans have been killing cats for centuries, Levy says, yet millions of feral cats are currently living in the U.S. Marra disputes this logic, arguing that there is a difference between the occasional roundups of problem cats and newer efforts to strategically wipe cats out of an ecosystem. Modeling studies by Auburn University ecologist Christopher Lepczyk and others seem to support Marra's point: under most circumstances, TNR is less effective at reducing cat populations than euthanizing the cats once they are trapped.

Both sides have accused the other of cherry-picking data to support its points. In 2018 Marra and other conservationists wrote an article calling TNR promoters "merchants of doubt," the same term used for those who defend tobacco products and deny climate change for personal gain. But the underlying issue is that there are few data to start with, both on the scope of the problem (feral cats are difficult to count accurately, for instance) and on the best methods to reduce cat numbers in the context of bolstering wildlife. In that sense, the conservation cat fight has rested more on opinions than on evidence-based science. In a May 2019 article entitled "A Moral Panic over Cats" in *Conservation Biology,* ethicists, anthropologists and conservation biologists argued for seeing the gray areas.

Stepping into the morass, Cove knew that expelling cats from the refuge would require buy-in from ORCAT. He needed to show Hershey evidence that her cats were guilty as charged. No one had done fine-grained studies showing precisely how cats affected any species of endangered rodent, so that was where he started. Cove's first results, later published as his Ph.D. dissertation, were damning: woodrat population density was inversely proportional to the number of feral cats on the landscape. If cats were around, woodrats generally were not, and any that were behaved differently than is typical.

On reviewing the results, Hershey bristled at the implication that she was part of the problem. After all, she had spent two decades working tirelessly to reduce cat numbers while no one at Crocodile Lake offered help. "I honestly didn't know what more we could do," she says. Cove switched tactics. He wanted to show that the population decline that comes with TNR is still too slow to save vulnerable species such as the woodrat. As Marra explains, "If you put a cat back in the environment, it's going to keep killing." When Cove analyzed cat fur found in the wildlife refuge, he learned that the cats almost exclusively ate food provided by humans, including commercial pet food and garbage scraps—only a small percentage consumed wildlife. But that did not stop them from hunting and killing woodrats.

Cove's finding was supported by the work of University of Georgia ecologist Sonia Hernandez, who tracked the hunting habits of local cats on Georgia's Jekyll Island in 2014 and 2015. Hernandez placed collar-mounted KittyCams on 31 feral cats that, like ORCAT's, were fed daily. Evidence from the KittyCams showed that 18 of the cats were successful hunters, with an average of 6.15 kills a day. The cats, however, did not eat all of their prey. Cats hunt not because they are cruel or bloodthirsty, Marra explains, but simply because they are cats.

Ultimately Cove appealed to emotions. During his research, he had often set up motion-triggered cameras near woodrat nests to monitor cats in action. Cove captured several instances of cats climbing on the nests, proof that ORCAT's animals were active in the refuge. In 2014 he got his money shot: a photograph of a cat with a limp woodrat in its mouth.

Michael Cove's study was small, but it was the first documented, scientifically rigorous attempt to control a feral cat population in the service of an endangered species. Now other groups are taking a data-centric approach.

A COOPERATIVE EFFORT

COVE'S FOOTAGE helped to break through Hershey's denial. Even if conservationists did not consider her work worthwhile, she had to admit the image was alarming. Many cat lovers have a similar response, explains Brooke Deak, a socioecology Ph.D. student at the University of Adelaide in Australia. She points to a 2013 study showing that Audubon Society members tend to view outdoor cats as invasive killers, whereas TNR practitioners see the same animals as the fluffy friends that share their homes.

Hershey had other incentives to rethink TNR as a panacea. Shortly after the failure of the woodrat-breeding program, officials at Crocodile Lake announced an invasive-species management plan that would, for the first time, empower them to trap and remove any cats found on the refuge. Some would be returned to Ocean Reef, and others would be delivered to animal control, where they could be reunited with owners, adopted, or humanely euthanized. The program was not just aimed at cats: it was also intended to manage invasive Burmese pythons, which had taken over the Everglades and prey on woodrats and cats alike. Reasonable as it might sound, cat lovers' long-standing distrust of conservationists led them to worry that the plan amounted to a green light for indiscriminate killing of cats.

Fearing for the cats' safety, an Ocean Reef resident donated $15,000 so that ORCAT could build a 500-square-foot indoor-outdoor enclosure to protect elderly, sick and otherwise vulnerable ferals. In 2016 the ORCAT team began setting traps not just to sterilize cats at Ocean Reef but also to keep them contained. Critically, Hershey acquiesced to Cove's pleas that any of their cats found in the wildlife refuge be kept permanently in the new enclosure on return rather than being released back onto the property.

Cove, who is now a curator at the North Carolina Museum of Natural Science, dislikes that TNR is still used at Ocean Reef: about 220 cats there roam free. "Feral cats should not be allowed within three miles of any natural area," he says. But Cove grudgingly admits that Hershey's recent efforts did reduce the number of feral cats even if they did not eliminate them. In work published in 2019 in *Biological Conservation,* Cove reported that as cats were permanently removed from Crocodile Lake through a multipronged approach, the woodrats' distribution increased. The percentage of woodrat nest sites with active occupants in the refuge increased from 37 to 54 percent in just two years.

Cove's study was small, but it was the first documented, scientifically rigorous attempt to control a feral cat population in the service of an endangered species. It provides evidence that it is necessary to remove cats permanently but that with community collaboration, it can be accomplished without the wholesale slaughter of cats. Now other groups are taking a data-centric approach. Projects in Washington, D.C., and in Portland, Ore., are seeking to provide an accurate count of outdoor cats, and a collaboration between Portland Audubon and the Feral Cat Coalition of Oregon is tracking the efficacy of cat-control methods on Hayden Island. The exact method of cat control will always be customized to each area, Deak says, but Cove's work in Key Largo provides a blueprint.

HOME IMPROVEMENT

ALTHOUGH REDUCING FERAL CATS' INCURSIONS at Crocodile Lake National Wildlife Refuge was an important first step, the woodrat population is still far from secure. Last November, Cove flew down from North Carolina to start prepping for a new series of studies. With no way to remove all free-roaming cats, regardless of the approach taken, Cove is investigating whether additional methods of human interven-

TWO WOODRATS pose outside the entrance of their nest. They build these structures as protection from predators.

MICHAEL COVE *North Carolina State University* AND USFWS

tion could help protect the beleaguered rodent from cats and other invasive species.

Woodrats build giant nests by dragging thousands of sticks across yards of dense undergrowth. These structures—which can stand up to four feet high and stretch to more than eight feet across—serve as nursery, toilet, pantry and sanctuary. But the racket the woodrats create during construction can act as a homing beacon for nearby cats. In the mid-2000s DeGayner and his brother tried to solve this problem by providing the woodrats with artificial nests. If the brothers could not eliminate the cat threat, they could at least help mitigate some of its impact. They removed the innards of a discarded Jet Ski, repurposing the hull as a ready-made habitat. Woodrats moved in almost immediately, augmenting the structure with sticks over time. The brothers eagerly collected more watercraft.

Human assistance to endangered species is common in conservation. Cove wants to see how these faux châteaus affect woodrats' chances of becoming a cat's dinner. The study could provide valuable information to other conservationists who aim to protect vulnerable animal populations from feral cats.

On a cold November morning Cove and DeGayner cruised the two-lane highway that bisects Crocodile Lake, armed with a list of nest sites to check. First up was nest 427. The multigeneration woodrat home is just a few hundred yards from a busy road, but the site is hidden in a nearly impenetrable wall of green that swallows any traffic sounds. This family of woodrats built its home around the hull of a derelict Sea-Doo that the DeGayner brothers had dragged in more than a decade earlier. The woodrats decorated it with snail shells, Sharpie caps and bungee cords.

When Cove saw that the entrance to nest 427 had been swept clear of leaves and cobwebs—a clear sign that there were woodrats inside—he gave DeGayner a thumbs-up. "This one's good," he said. Over the next several hours the duo repeated this process upward of 20 times, sometimes celebrating signs of life, sometimes lamenting empty hulls. Crouching down in the shade just a few feet from the traffic rushing past on the highway, Cove pointed to a jumbled heap of sticks—a new nest he had not seen before. "It's not much," he said, "but it's there." SA

MORE TO EXPLORE

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EVOLUTION

The TROUBLE *with* TEETH

Our teeth are crowded, crooked and riddled with cavities. It hasn't always been this way

By Peter S. Ungar

I SAT AT AN ORAL SURGEON'S OFFICE WAITING FOR MY DAUGHTER. The scene called to mind an assembly line. Patients went in, one after another, resigned to having their third molars, commonly known as wisdom teeth, taken out. They left with bandages, specially form-fitted with ice packs, wrapped around their heads. Each carried a gift T-shirt, preprinted home care instructions, and prescriptions for antibiotics and pain meds.

Removal of the wisdom teeth is almost a rite of passage for young adults in America today. From my vantage point, however, there is something very wrong with this tradition. I am a dental anthropologist and evolutionary biologist and have spent 30 years studying the teeth of living and fossil humans and countless other species. Our dental issues are not normal. Most other vertebrate creatures do not have the same dental problems that we do. They rarely have crooked teeth or cavities. Our fossil forebears did not have impacted wisdom teeth, and few appear to have had gum disease.

IN BRIEF

Dental problems such as crowding and cavities are common in people today. But other species tend not to have such afflictions, nor did our fossil forebears.

Our teeth have evolved over hundreds of millions of years to be incredibly strong and to align precisely for efficient chewing. They developed these characteristics to function in a specific oral environment.

Our dental disorders largely stem from a shift in the oral environment caused by the introduction of softer, more sugary foods than the ones our ancestors typically ate.

Indeed, the teeth of modern-day humans are a profound contradiction. They are the hardest parts of our body yet are incredibly fragile. Although teeth endure for millions of years in the fossil record, ours cannot seem to last a lifetime in our mouths. Teeth gave our ancestors dominance over the organic world, yet today ours require special daily care to be maintained. The contradiction is new and is limited largely to industrial-age and contemporary populations. It is best explained by a mismatch between today's diets and those for which our teeth and jaws evolved. Paleontologists have long understood that our teeth are deeply rooted in evolutionary history. Now clinical researchers and dental practitioners are also starting to take notice.

Peter S. Ungar is a paleontologist and dental anthropologist at the University of Arkansas. His research focuses on diet and feeding adaptations in living and fossil primates.

ANCIENT ORIGINS

EVOLUTIONARY BIOLOGISTS often marvel at the human eye as a "miracle of design." To me, eyes have nothing on teeth. Our teeth break foods without themselves being broken—up to millions of times over the course of a lifetime—and they do this despite being built from the very same raw materials as the foods they break. Engineers have much to learn from teeth. Their remarkable strength comes from an ingenious structure that gives them the hardness and the toughness to resist the start and spread of cracks. Both properties result from the combination of two components: a hard external cap of enamel made almost entirely of calcium phosphate and an internal layer of dentin, which also has organic fibers that make the tissue flexible.

The real magic happens on the microscopic scale, though. Think of a single strand of dried spaghetti breaking easily when bent. Now imagine thousands of strands bunched together. Enamel structures known as crystallites are like those strands, each one 1,000th the width of a human hair. They bundle together to form rods of enamel called prisms. In turn, prisms are packed together, with tens of thousands per square millimeter, to form the enamel cap. They run parallel to one another from the surface of the tooth to the underlying dentin, wriggling, weaving and twisting as they go—an elegant configuration that confers impressive durability.

This design did not emerge overnight. Nature has been tinkering with teeth for hundreds of millions of years. Recent insights from paleontology, genetics and developmental biology have allowed researchers to reconstruct the evolution of their structure.

The first vertebrates were jawless fishes that appeared more than half a billion years ago, during the Cambrian period. These earliest fishes did not have teeth, but many of their descendants had a scaly tail and head armor made from toothlike plates of calcium phosphate. Each plate had an outer surface of dentin, sometimes covered by a harder, more mineralized cap, and an interior pulp chamber that housed blood vessels and nerves. Some fishes' mouths were rimmed by plates with small nubs or barbs that may have assisted in feeding. Most paleontologists think that these scales were eventually co-opted by evolution to form teeth. In fact, the scales of today's sharks are so similar to teeth that we lump them together in a category of structures called odontodes. Developmental biologists have shown that shark scales and teeth develop the same way from embryonic tissue, and recently molecular evidence confirmed that they are controlled by the same set of genes.

The earliest definitive teeth came later, with the jawed fishes. These were mostly simple pointed structures that could be used to capture and immobilize prey and to scrape, pry, grasp and nip all manner of living things. For example, some acanthodians—extinct spiny fishes related to ancestral sharks—possessed teeth about 430 million years ago in the Silurian period. They had no hypermineralized caps covering their dentin crowns, and they were neither shed nor replaced, but they were teeth nonetheless. Some had lip and cheek scales that graded into teeth the closer they occurred to the mouth, a smoking gun for continuity between the two structures. Even in their earliest forms, teeth must have given their bearers an advantage because they spread quickly through the primeval oceans, and those lineages that had them eventually sidelined those that did not.

Once teeth were in place, many innovations followed, including changes in their shapes, numbers and distributions, in how they were replaced and in how they attached to the jaw. Enamel first appeared by around 415 million years ago, close to the boundary between the Silurian and Devonian periods, in a group called the sarcopterygians. This group includes modern-day tetrapods (amphibians, reptiles and mammals) and the lobe-finned fishes, best known for their paired front and back fins, with bones and muscles resembling those in limbs. Other fishes lack both enamel and the suite of genes that encode the proteins required to make it. Enamel was initially limited to the scales, which suggests that like teeth, enamel originated in skin structures and then made the leap to the mouth.

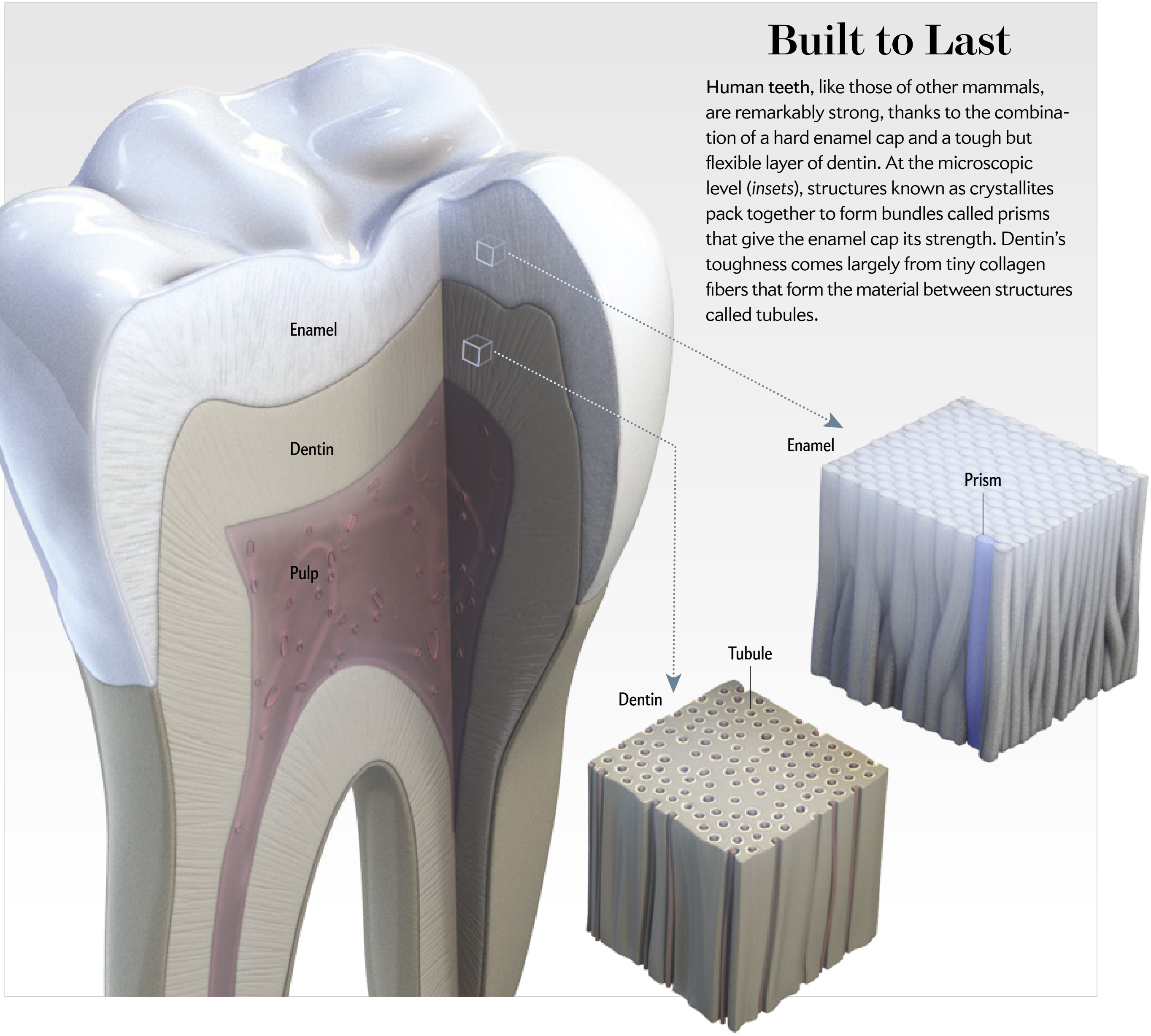
Teeth figured heavily in the origin and early evolution of mammals because of their role in supporting warm-bloodedness (endothermy). Generating one's own body heat has a lot of advantages, such as enabling one to live in cooler climates and places with more variable temperatures; allowing one to sustain higher travel speeds to maintain larger territories; and providing stamina for foraging, predator avoidance and parental care. But endothermy comes with a cost: mammals burn 10 times as much energy at rest as reptiles of similar size do. Selective pressure to fuel the furnace has fallen on our teeth. Other vertebrates capture, contain and kill prey with their teeth. Mammalian teeth must wring more calories out of every bite. To do that, they must chew.

Mammalian teeth guide chewing movements; direct and dissipate chewing forces; and position, hold, fracture and fragment food items. For teeth to function properly during chewing, their opposing surfaces must align to a fraction of a millimeter. The need for such precision explains why, unlike fishes and reptiles, most mammals do not just grow new teeth repeatedly throughout life when old ones wear out or break. Ancestral mammals lost that ability to facilitate chewing.

Enamel prisms are part of the same adaptive package. Most researchers believe they evolved to increase tooth strength to

Built to Last

Human teeth, like those of other mammals, are remarkably strong, thanks to the combination of a hard enamel cap and a tough but flexible layer of dentin. At the microscopic level (*insets*), structures known as crystallites pack together to form bundles called prisms that give the enamel cap its strength. Dentin's toughness comes largely from tiny collagen fibers that form the material between structures called tubules.



the level needed for chewing. Whether the prisms evolved once or several times independently is a matter of some debate, but in any case, the basic mammalian tooth structure—a dentin crown capped by prismatic enamel—was in place in the Triassic period. The myriad forms of mammalian molars, including ours, followed as mere tweaks of the same general plan.

MICROBIAL IMBALANCE

THE EVOLUTIONARY HISTORY of our teeth explains not only why they are so strong but also why they fall short today. The basic idea is that structures evolve to operate within a specific range of environmental conditions, which in the case of our teeth include the chemicals and bacteria in the mouth, as well as strain and abrasion. It follows that changes to the oral environment can catch our teeth off guard. Such is the case with our modern diets, which are unlike any in the history of life on our planet. The resulting mismatch between our biology and our behavior explains the dental caries (cavities), impacted wisdom teeth and other orthodontic problems that afflict us.

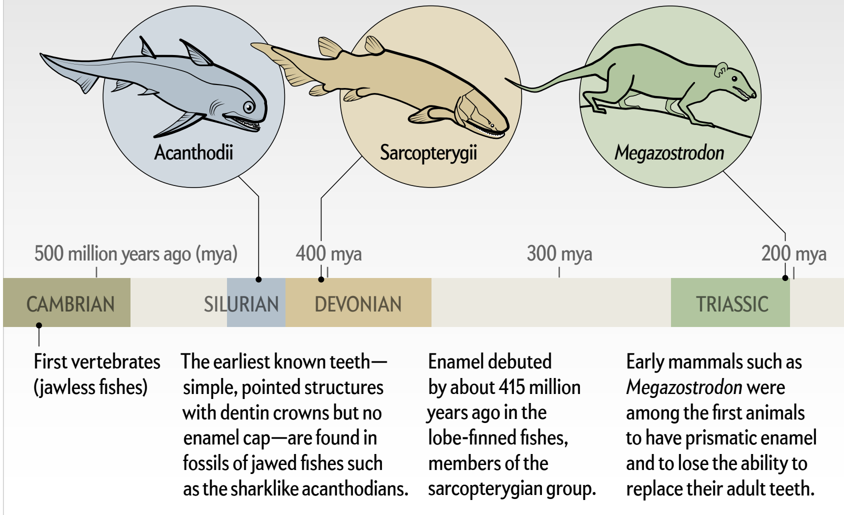
Dental caries is the most common and pervasive chronic disease in the world. It afflicts more than nine in 10 Americans and billions of people across the globe. Yet over the past 30 years I have studied hundreds of thousands of teeth of fossil species and living animals and seen hardly any tooth decay.

To understand why the teeth of modern-day humans are so prone to decay, we need to consider the natural oral environment. The healthy mouth is teeming with life, populated by billions of microbes representing up to 700 different species of bacteria alone. Most are beneficial. They fight disease, help with digestion and regulate various bodily functions. Other bacteria are harmful to teeth, such as mutans streptococci and *Lactobacillus*. They attack enamel with lactic acid produced during their metabolism. But concentrations of these bacteria are usually too low to cause permanent damage. Their numbers are

Illustration by AXS Biomedical Animation Studio

Deep Roots

Our teeth are the product of hundreds of millions of years of evolution. Fossil, genetic and developmental evidence indicates that teeth originated from specialized fish scales. The features that make them so strong evolved piecemeal. The dental problems that plague most people today—from impacted wisdom teeth to cavities—are largely the result of a mismatch between the foods our ancient ancestors evolved to eat and the processed, sugar-laden foods that only became available relatively recently.



kept in check by their commensal cousins, the mitis and sanguinis streptococcal groups. These bacteria produce alkalis (chemicals that raise pH), as well as antimicrobial proteins that inhibit the growth of harmful species. Saliva buffers the teeth against acid attack and bathes them in calcium and phosphate to remineralize their surface. The balance between demineralization and remineralization has held for hundreds of millions of years, and both beneficial and harmful bacteria are found in oral microbiomes across the mammalian order. We evolved to maintain a stable community of microbes, as Kevin Foster of the University of Oxford and his colleagues have put it, to "keep the ecosystem on a leash."

Caries results when the leash breaks. Diets rich in carbohydrates feed acid-producing bacteria, lowering oral pH. Mutans streptococci and other harmful species thrive in the acidic environment they produce, and they begin to swamp beneficial bacteria, further reducing pH. This chain of events leads to what clinical researchers call dysbiosis, a shift in balance wherein a few harmful species outcompete those that normally dominate the oral microbiome. Saliva cannot remineralize enamel fast enough to keep up, and the equilibrium between loss and repair is shot. Sucrose—common sugar—is especially problematic. Harmful bacteria use it to form a thick, sticky plaque that binds them to teeth and to store energy that feeds them between meals, meaning the teeth suffer longer exposure to acid attack.

Bioarchaeologists have long suggested a link between caries and the transition from foraging to farming within the past 10,000 years or so during the Neolithic period because acid-producing bacteria consume fermentable carbohydrates, which abound in wheat, rice and corn. For example, studies of dental remains led by Clark Larsen of the Ohio State University found a more than sixfold increase in the incidence of caries with the adoption and spread of maize agriculture along the prehistoric Georgia coast. The link between tooth decay and agriculture is not that simple, though. Caries rate varies among early farmers over time and space, and the teeth of some hunter-gatherers, such as those with honey-rich diets, are riddled with cavities.

The biggest jump in the caries rate came with the Industrial Revolution, which led to the widespread availability of sucrose and highly processed foods. In recent years researchers have conducted genetic studies of bacteria entombed in tartar on ancient teeth that document the ensuing transition in microbial communities. Processed foods are also softer and cleaner, setting up a perfect storm for caries: less chewing to cut the organic film and fewer dietary abrasives to wear away the nooks and crannies in teeth where plaque bacteria take refuge.

Unfortunately, we cannot regrow enamel like we can skin and bones because of the way our tooth caps form. This limitation was established back when enamel first evolved in the lobe-finned fishes. Ameloblasts, the cells that make enamel, migrate outward from the inside of the cap toward the eventual surface, leaving trails of enamel—prisms—behind. We cannot make more enamel, because the cells that make it are sloughed off and lost when the crown is complete. Dentin is another story. The odontoblast cells that produce it start back-to-back with the ameloblasts and migrate inward, eventually coming to line the pulp chamber. They continue to produce dentin throughout an individual's life and can repair or replace worn or wounded tissue. More serious injury calls for fresh cells that form dentin to wall off the pulp chamber and protect the tooth.

As cavities grow, however, caries can overwhelm these natural defenses, infecting the pulp and in the long run killing the tooth. From an evolutionary perspective, a couple of centuries is a flash in the pan—not nearly enough time for our teeth to adapt to the changes in our oral environment wrought by the introduction of table sugar and processed foods.

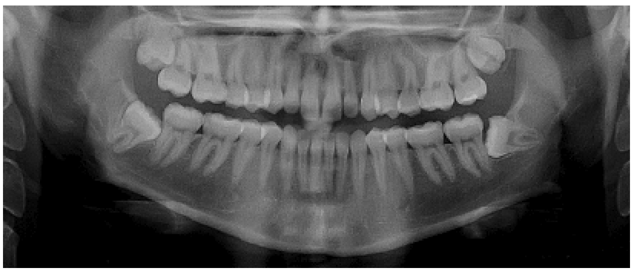
MISSING STRESS

ORTHODONTIC DISORDERS are also at epidemic levels today. Nine in 10 people have teeth that are at least slightly misaligned, or maloccluded, and three quarters of us have wisdom teeth that do not have enough room to emerge properly. Simply put, our teeth do not fit in our jaws. The ultimate cause is, as with caries, an imbalance caused by an oral environment our ancestors' teeth never had to contend with.

Illustration by Jen Christiansen

The famed Australian orthodontist "Tick" Begg recognized this mismatch back in the 1920s. He found that Aboriginal peoples living traditional lifestyles wore their teeth down more than his dental patients of European ancestry did. They also had perfect dental arches—their front teeth were straight, and their wisdom teeth were fully erupted and functioning. Begg reasoned that nature expects wear between adjacent teeth to reduce space requirements in the mouth. He believed that jaw length was "preprogrammed" by evolution to take this into account. So our teeth evolved for tough foods in an abrasive environment, and our soft, clean diet has upset the balance between tooth size and jaw length. Hence the assembly line at the oral surgeon's office. Whether by wear or extraction, tooth mass has to go.

With this logic in mind, Begg developed what has long been the gold standard for straightening teeth. It involves creating space by extracting the front premolars, attaching a wire to brackets on the remaining teeth, and pulling the dental arch into line while closing the gaps. Other orthodontists had used wires to straighten crooked teeth before Begg, but they did not extract the premolars, and as a result the straightened teeth commonly reverted to crookedness. Many dentists initially balked at the idea of pulling healthy teeth to straighten the arch, but Begg's technique worked, lasted a lifetime and had evolution to back it up. Begg went so far as to suggest that children chew gum containing abrasive silicon carbide dust to wear their teeth down and thus avoid the need for orthodontic treatment entirely.



WISDOM TEETH cannot emerge properly when the jaw is too short, as occurs when children are raised on foods that are easier to chew than the ones we evolved to eat.

Begg was right about the mismatch between teeth and jaws, but he got the details wrong. According to anthropologist Rob Corruccini of Southern Illinois University, the key change was not to the abrasive environment but to the stress environment, meaning the mechanical stresses jaws experience during eating. And the teeth were not too big—the jaw was too small.

Remarkably, Charles Darwin made the connection between stress and jaw size in his 1871 book *The Descent of Man*. But Corruccini was among the first to offer definitive evidence. He had just started teaching at Southern Illinois when a student from nearby rural Kentucky told him that in his community seniors were raised on hard-to-chew foods, whereas their children and grandchildren had more refined, processed diets. Follow-up study showed that older residents had better bites, despite almost no professional dental care, than younger ones did. Corruccini explained the difference in terms of dietary consistency. Thus, the dental differences were not genetic but environmental. Corruccini went on to find many other examples, including the Pima of Arizona before and after they had access to store-bought foods and rural peoples near Chandigarh, India, who had diets of coarse millet and tough vegetables as compared with urban dwellers, who ate soft bread and mashed lentils.

Corruccini reasoned that tooth size is preprogrammed to fit a jaw subjected during growth to levels of mechanical stress in line with a natural childhood diet. Subsequently, when the jaw does not get the needed stimulation during development, the teeth become crowded at the front end and impacted in the rear. He confirmed this hypothesis with experimental work on monkeys evincing that those fed softer diets had smaller jaws and impacted teeth.

DARWINIAN DENTISTRY

AN EVOLUTIONARY PERSPECTIVE reveals our dental disorders as a consequence of an ecological shift. This new vantage point is starting to help researchers and clinicians tackle the root causes of dental disease. Sealants shield our crowns, and fluoride strengthens and remineralizes enamel; however, these measures do nothing to change the conditions in the mouth that bring about decay. Antiseptic mouthwashes kill the bacteria that cause cavities, but they also kill beneficial strains that have evolved to keep harmful bacteria in check. Inspired by recent innovations in microbiome therapies, researchers are beginning to focus on remodeling the dental plaque community. Oral probiotics, targeted antimicrobials and microbiota transplants are on the horizon.

We can also keep the natural oral environment in mind when we think about treating orthodontic disorders. Dentists and orthodontists are realizing that highly processed, softened foods can change the mechanical strains on the face and jaws. Chewing stresses stimulate normal growth of the jaw and the middle of the face in children. Subsisting on such foods leaves these parts of the body chronically underdeveloped. This condition has implications beyond dental crowding: some experts have suggested that resulting constriction of the airway is responsible for sleep apnea, in which breathing repeatedly stops and starts.

No one wants toddlers to choke when they eat, but perhaps there are better options for weaning our youngsters than mashed peas. Over the past few years a whole new industry has developed that focuses on growing the jaws to open the airway and fit the teeth as nature originally intended. Effective treatments range from removable palatal expanders and other growth-guidance appliances to surgery. But perhaps if we fed our children foods requiring vigorous chewing from an earlier age, like our ancient ancestors did, we could spare many of them the need for such interventions. SA

MORE TO EXPLORE

Evolution's Bite: A Story of Teeth, Diet and Human Origins. Peter S. Ungar. Princeton University Press, 2017.

FROM OUR ARCHIVES

The Real Paleo Diet. Peter S. Ungar; July 2018.

scientificamerican.com/magazine/sa

C-DENTAL X-RAY, INC.

e

TULLBERGIA, smaller than a sesame seed, uses its two fleshy antennae and six legs to navigate between crushing Antarctic glaciers and toxic soils.

Photographs by Igor Siwanowicz

BIOLOGY

xtreme survivor

A tiny, six-legged animal has persevered through more than 30 ice ages in the harshest badlands of Antarctica. Scientists are just now figuring out how

By Douglas Fox

IAN HOGG AND BYRON ADAMS PEERED OUT THE WINDOWS OF THEIR helicopter as it glided over the rocky slopes of the Transantarctic Mountains, dry peaks that rise above vast ice sheets just 600 kilometers from the South Pole. Their eyes flitted across the ledges and cliffs below. It was a sunny day in January 2018, and they were searching for landmarks that matched those described in some brief notes left by a deceased entomologist who, back in 1964, had discovered an enigmatic creature in this desolate landscape. No one had seen it since.

Douglas Fox writes about extreme polar science, climate and biology from California. He wrote our 2018 article "The Brain, Reimagined."

IN BRIEF

Scientists have found a tiny animal, *Tullbergia,* living under rocks in Antarctica's inland mountain peaks, where nothing should survive.

Tullbergia seems to have persisted in the same place for millions of years, somehow avoiding deadly ice sheets and toxic salts.

Gene sequences from *Tullbergia* and other Antarctic critters may explain their survival and might rewrite the history of ice across the continent.

The Transantarctic Mountains stretch more than 3,000 kilometers across the continent, from the shoreline in the north toward the interior in the south, splitting the continent in two. The mountain chain, 100 to 200 kilometers wide, acts as a dam, holding back the vast East Antarctic ice sheet, a dome that rises 3,000 meters above sea level. Glaciers fed by that ice sheet ooze through gaps between the mountain peaks and slowly empty into lower-lying West Antarctica. Dry winds screaming off the eastern plateau keep the peaks themselves largely free of ice.

In winter, temperatures in the southern Transantarctics plunge below –40 degrees Celsius. Some of the hard, thin soils on these peaks haven't tasted appreciable amounts of water for tens to hundreds of thousands of years, allowing them to accumulate caustic salts, much like the surface of Mars. Yet despite the harsh environment, a handful of tiny animals call these mountains home. Hogg and Adams had been collecting samples since 2006, trying to learn which species live where. The species that had been discovered in 1964, however—an insectlike animal called *Tullbergia mediantarctica*—had so far eluded them.

The location they were scanning, Mount Speed, was a low ridge in the southern Transantarctics, 700 kilometers inland from the sea. Here Shackleton Glacier pours from east to west through a gap in the mountains roughly 10 kilometers wide. Hogg, a biologist at Polar Knowledge Canada, spotted a cliff resembling one described in the entomologist's notes. The pilot landed above it, and the passengers stepped out onto a barren rock slope strewn with chunks of yellowish granite. They began to methodically peek under one rock at a time. Within minutes they found their pale beasts—dozens of white, six-legged animals smaller than sesame seeds.

The critters stepped slowly and purposefully among the sand grains, navigating with antennae that were soft and fleshy, like two outstretched fingers. The animals are extremely susceptible to dehydration, however, and within a minute of being exposed they began to shrivel and die in the dry air. Over the next few days Hogg and Adams found *Tullbergia* under rocks on four different slopes along the lower end of Shackleton Glacier. Sometimes the oasis they inhabited was smaller than a basketball court.

1

Tullbergia is one species in a larger group of springtails—primitive, wingless relatives of insects. Few people have heard of springtails, although the soil in your backyard probably harbors millions of them. These minuscule animals are found around the world—and a few species inhabit the sparse patches of ice-free ground that dot Antarctica's interior, where there is little to eat but the occasional bacterium or microscopic fungus.

How *Tullbergia* and other springtails got to these remote mountains, and how they survived dozens of ice ages, is a mystery that scientists are eager to solve. Since the 2018 expedition Hogg and Adams, a biologist at Brigham Young University, have been performing genetic studies on the rediscovered *Tullbergia,* as well as on another species of springtail they found on the same expedition. The studies, which they discussed with me and which will be published later this year, will shed new and surprising light on the history of these species, which in turn may rewrite the story of how massive ice

BYRON ADAMS (1 and 2)

2

RESEARCHERS scoop up soil samples (*1*) containing *Tullbergia* on the scree slopes of Mount Speed (*2*), along Shackleton Glacier in Antarctica.

sheets waxed and waned across the continent as ice ages came and went across millions of years. Species such as *Tullbergia* are also stretching our ideas about the limits of biology, reinforcing the notion that even the cruelest environments on Earth can often sustain complex animal life.

ICE AGE IMMIGRANTS

ANTARCTICA IS KNOWN for its penguins and seals, but these animals live only on its coastline, fed by a rich food web of phytoplankton, fish and krill. Those iconic species cannot survive in the continent's interior, an area larger than the U.S. and Mexico combined, about 98 percent of which is blanketed in glacial ice sheets.

But starting around 1900, scientists began to find that ice-free patches of ground, kilometers in from the coast, were inhabited by animals of a different kind: tiny springtails, mites, worms and wingless flies called midges. These creatures required water and often inhabited small patches of lichens or moss on north-facing slopes, where 24-hour summer sunlight melted snow and dampened the soil. Scientists gradually found them in colder and drier places, farther inland.

In 1964 entomologist Keith Wise flew to Shackleton Glacier to see if he could find animals in one of the most secluded inland places on the continent. On December 13 he skied several kilometers up the glacier from camp until he arrived at the bottom of the Mount Speed ridge. Snowmelt trickled down a cliff, wetting the soil at its base. There Wise found two species of springtails: gray *Antarctophorus subpolaris,* which he had seen before in other places, and ghostly white *Tullbergia,* new to science.

In the decades after Wise's discovery, scientists tried to piece together a rough history of the landscape where *Tullbergia* was found. Seafloor sediments revealed that Antarctica had experienced 38 ice ages in the past five million years. During those freezes its glaciers thickened, rising inland and cloaking many of the mountain slopes that are exposed today. Temperatures were 5 degrees C to 10 degrees C colder than at present. Most researchers assumed the rising ice sheets "more or less wiped everything out," says Steven Chown, a polar ecologist at Monash University in Melbourne, Australia.

Scientists reasoned that once an ice age ended, the glaciers thinned, slumping downhill and exposing more of the peaks, allowing species arriving from Patagonia, New Zealand or Australia on ocean currents or on the muddy feet of seabirds to settle anew. These immigrants would replace species that had been exterminated by the advancing glaciers. When the next ice age arrived, the newcomers would also vanish, to be replaced by another wave of immigrants after the ice retreated again. Most experts assumed that the species currently in Antarctica could not have been there for more than about 20,000 years.

Then, in 2005, came a game changer. Two different teams published genetic studies that contradicted this widespread view. Peter Convey, an ecologist at the British Antarctic Survey, teamed up with Giuliana Allegrucci of the University of Rome to compare the gene sequences of midges living in Antarctica and in Patagonia, the southern tip of South America. Based on differences in DNA sequences and basic assumptions about how quickly DNA sequences undergo random change, they estimated how long ago these species had parted ways evolutionarily. Convey admits that he expected to see a separation "in the tens of thousands of years." But his calculations suggested that they had not mingled for 68 million years. "That was actually quite amazing," Convey says. It meant that the Antarctic midges were not immigrants at all: instead they were descendants of the continent's original inhabitants.

Tullbergia may have scraped by in a narrow band of habitable soil just a few meters wide.

ISOLATED FOR FIVE MILLION YEARS

SIXTY-EIGHT MILLION YEARS ago Antarctica was covered in lush forests, populated with dinosaurs and early mammals. It was still attached to South America, forming the last vestige of the supercontinent Gondwana, from which Africa and Australia had already separated. Only after breaking away from South America, roughly 35 million years ago, did Antarctica plunge into a deep freeze that eliminated nearly every living thing.

A second study in 2005 put the origin of some Antarctic springtails far earlier than past ice ages. Hogg and his former Ph.D. student Mark Stevens, who had worked together at the University of Waikato in New Zealand, used gene sequences to estimate when several Antarctic springtail species had diverged from species in Australia, New Zealand and Patagonia. Their results showed a separation of at least 10 million to 20 million years.

These and similar findings left many scientists at a loss to explain how tiny creatures could have persisted through so many ice ages. Some speculated that the animals might have survived in various small, isolated valleys called the McMurdo Dry Valleys in the northern section of the Transantarctic Mountains, 850 kilometers north of where Hogg and Adams had found *Tullbergia*. The valleys have been strangely ice-free for the past 12 million years. Others hypothesized that during the ice ages, animals might have sheltered in geothermal hotspots near a handful of volcanoes that dot the continent's coastline. And maybe after surviving each ice age in those coastal areas, they somehow traveled far inland to mountains like the ones by Shackleton Glacier.

But these ideas did not hold up to the evidence that had been collected. *Tullbergia* and the other animals "aren't found in other parts of Antarctica," Adams explains. "You don't find them near the volcanoes; you don't find them on the coasts"—undercutting the idea that they inhabited those faraway places in the past.

Between 2006 and 2017 Hogg visited more than a dozen locations along the Transantarctic Mountains to collect live specimens. He and Adams, who joined some of the trips, found five species of springtails, all of them previously known. But they did not lay eyes on *Tullbergia* until they scoured Mount Speed in 2018.

Once Hogg brought the *Tullbergia* samples back to his laboratory, his team began to sequence genes from them. Ph.D. student Gemma Collins sequenced a short snippet of DNA from each creature, from a gene called cytochrome C oxidase. She spent months comparing the sequences of more than 1,100 animals found at different points along the Transantarctics (some of them collected years earlier). The comparisons would show which animals, if any, shared a common history. They would reveal whether different populations in diverse locations had been isolated from one another, perhaps by expanded ice sheets, or if they had been able to move to new territory when ice was very low.

In the warmest periods between ice ages, the West Antarctic ice sheet would have thinned and retreated. And the Ross Ice Shelf, which borders most of the central and southern mountains and floats on the sea, probably disappeared. Both events would have allowed open ocean to advance inland along the mountain chain, though not as high up on the mountains as the ice sheets had risen. Hogg speculated that during these warm stretches tiny animals could probably move around and interbreed with other previously isolated populations of the same species because broader swaths of land were ice-free. Springtails could have dispersed by floating on water. "They get into new habitat," Hogg says, and then they manage to persist for 50,000 or 100,000 years as the ice builds upslope again.

But the results for *Tullbergia* and *Antarctophorus* suggested that even in warm times, the movement of these animals was more restricted than people thought. Two populations of *Antarctophorus* collected from exposed ridges on opposite sides of Shackleton Glacier appeared not to have interbred for five million years—

despite the fact that they lived just 10 kilometers apart, the width of the gap that the glacier flows through. “It’s quite surprising,” Hogg says. “Five million years is a long time.” It appeared that the species had not traveled at all.

Geologic evidence shows that during an especially warm period three million to five million years ago, the West Antarctic Ice Sheet collapsed multiple times. Conceivably, this would have allowed springtails to float along the mountain chain as the ocean intruded. Springtails could have crossed the 10-kilometer gap and bred with genetically different springtails there. But the *Antarctophorus* populations had not. The genetic results in Hogg’s lab also showed that groups of *Antarctophorus* from Shackleton Glacier had not interbred with another population, 160 kilometers farther north along the mountains, for at least eight million years. These results suggested that even when the West Antarctic ice sheet collapsed, enough ice still remained in the Transantarctic Mountains to prevent the animals from moving around.

The analysis of *Tullbergia* collected around Shackleton Glacier stunned the researchers even more: the gene sequences from all four sites were virtually identical. “It’s like they’re all clones,” Adams says. That could mean that all the animals are descended from a couple of individuals and that these descendants have never bred with any outside populations. “That is something that we’re all trying to wrestle [with] to explain,” Adams says.

TOXIC QUANDARY

HOW COULD *TULLBERGIA* have persisted for millions of years, pinned down by ice during at least 30 ice ages, without moving more than a few kilometers or breeding with other populations? This question is all the more puzzling because for much of that time, these animals were trapped in a narrow zone between deadly ice and deadly salt.

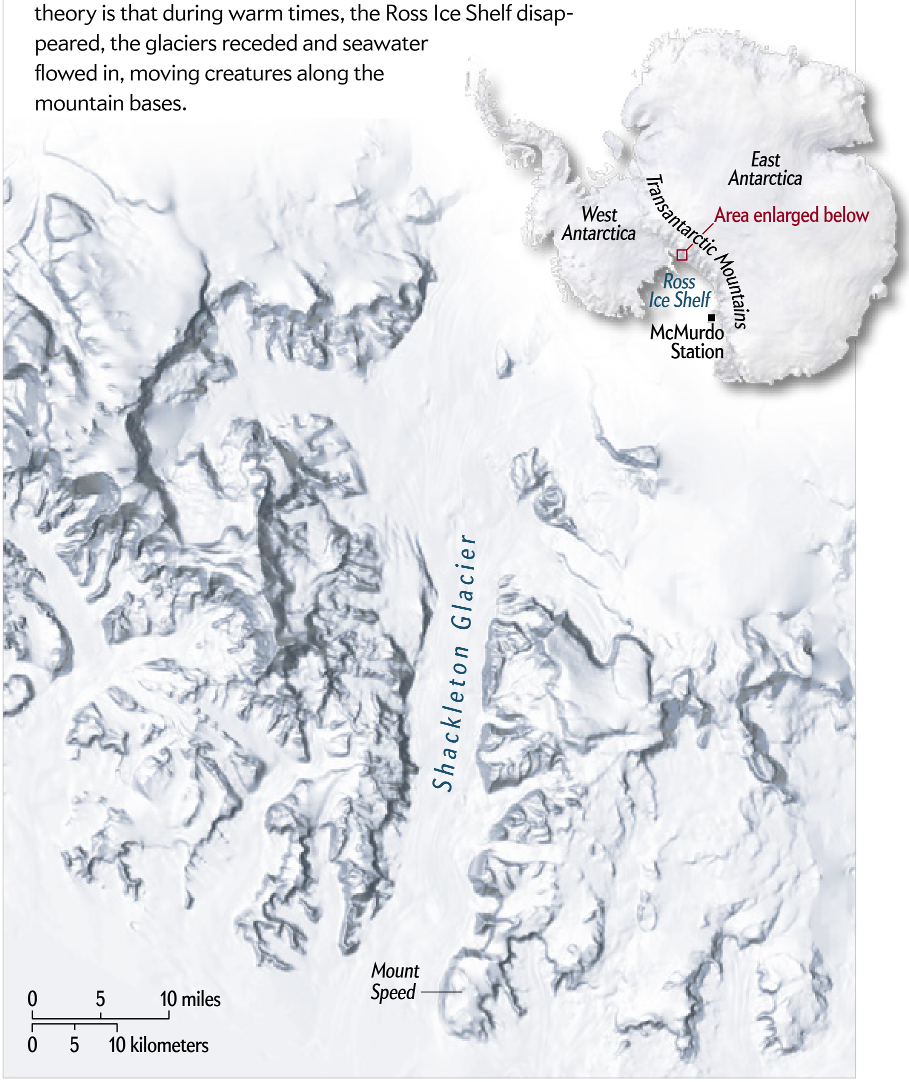
When Hogg and Adams were helicoptering up and down Shackleton Glacier back in 2018, they often saw a faint line running across the sides of the mountains: A couple of hundred meters above the surface of the ice the rock changed color, from lighter below the line to darker above it. These “trimlines” show how high the ice rose during the last ice age—the result of subtle differences in the way that minerals oxidize when they are exposed to air rather than covered.

It is easy to imagine that as the glaciers thickened, the animals would have migrated farther up the mountainside, to stay above the ice. But there is a major problem with that explanation: the upper reaches of the mountains are loaded with toxic chemicals. Turn over a rock above the trimline at Shackleton or any other Transantarctic mountain, and the soil underneath is often crusted in white salts. “It’s not a good salt. It’s not Himalayan rock salt,” Adams quips. “Put your tongue on this stuff, and it will light you up.”

The salt is high in nitrate, toxic to many living things. Nitrate constantly rains down on Earth as ultraviolet radiation reacts with atmospheric gases. In most

Home amid the Ice

The Transantarctic Mountains separate the vast East and West Antarctic Ice Sheets, yet certain glaciers such as Shackleton ooze from east to west through gaps between peaks. Researchers found the surprising *Tullbergia* critter on the glacier-facing slope of Mount Speed (*bottom*). How it got there is a mystery. One theory is that during warm times, the Ross Ice Shelf disappeared, the glaciers receded and seawater flowed in, moving creatures along the mountain bases.



Map by Mapping Specialists

WHITE AND BRISTLY when alive, *Tullbergia* quickly dries out and dies when exposed to air. On this individual's remains—stained with dye and greatly enlarged—the hard exoskeleton appears red; the softer, cuticlelike membrane looks green. Two eyeholes are visible at the base of the antennae (*top image*).

parts of the world, it does not accumulate in soils, because rain washes it away. But in dry places, like the Transantarctic Mountains, it can build up over millennia, until it reaches toxic levels. These high places also accumulate perchlorate, an oxidizing chemical used in disinfectants and rocket propellants—and famous, as discovered by the Phoenix Mars Lander, for making the surface of that planet an unpleasant place.

The salts create a catch-22 for small animals such as springtails trying to escape advancing glaciers: remaining in place means they will become buried underneath ice, but creeping uphill leads to places that are "just nasty, toxic," Adams says. "Really crappy habitat."

Sure enough, Hogg and Adams only found springtails living below the trimline. These places, however, would have been covered by 100 meters or more of ice at the last glacial maximum, and it would have been impossible for complex life-forms such as *Tullbergia* to survive in ice for tens of thousands of years. So where did the animals go?

HISTORY REWRITTEN

THE SURVIVAL of any animal depends on water, and water seems to point to an explanation for *Tullbergia*'s unlikely endurance.

Seven hundred kilometers northwest of Shackleton Glacier the Transantarctic Mountains emerge from the interior of the continent and begin to run along the coastline. This is where the isolated McMurdo Dry Valleys are. Despite the dryness, several of the valleys hold ice-covered lakes, fed by summer meltwater. The lakes are only a few meters deep, yet high up on a few of the valley walls are bathtub rings—ancient shorelines of sand and gravel. They suggest that some of these valleys had once held hundreds of meters of water, fed by streams tumbling down the mountains. This idea is incomplete, however, because the valleys are open on their seaward ends, with nothing to hold in such deep water.

Scientists surmise that sometime during a previous ice age, the West Antarctic Ice Sheet had advanced hundreds of kilometers farther north than it currently sits, approaching the mountains and damming the mouths of the valleys at the sea, allowing big lakes to form. One of them, Glacial Lake Washburn, was at least 300 meters deep.

During the 1990s Brenda Hall, a geologist at the University of Maine, dug into the ancient sediments high up on the Lake Washburn valley wall and collected freeze-dried tatters of algal mats that had grown there. Using radiocarbon dating, she estimated that the algae—and hence the lake—had existed 23,000 to 13,000 years ago, at roughly the pinnacle of the last ice age. This finding led to a curious contention, Hall says: during the ice age, the thinking went, "the glaciers were probably melting more than they do now."

Scientists have strained to explain how that could happen because the climate was colder. One theory is that the surrounding oceans were more widely covered in ice than they are today—leading to less evaporation and therefore fewer clouds, less snowfall and more sunlight warming the dark rocks of the mountains. This, in turn, would cause more melt high up. This increased melt could have happened along the entire length of the mountains, including where *Tullbergia* was found.

Closely related is a strange phenomenon that scientists now call the solid-state greenhouse effect. Most sunlight that strikes a glacier is reflected by its snowy exterior. But in the Transantarctic Mountains, where hard, dry winds slowly evaporate snow and ice, glaciers often have deep, relatively transparent ice exposed on the surface. Sunlight can penetrate a meter into this ice, warming and melting it from within. Andrew Fountain, a glaciologist at Portland State University, has found that this can occur at air temperatures down to –10 degrees C.

Hall has witnessed this phenomenon high in the southern mountains, as far as 200 kilometers south of Shackleton Glacier. "I've seen on sunny, clear days," she says, "these films of water creeping down the front of the ice cliff."

To Hogg and Adams, these mechanisms offer important clues into how *Tullbergia* and *Antarctophorus,* as well as small worms, mites and other animals, might have survived dozens of ice ages along the edges of glaciers such as Shackleton. Adams calls them "Goldilocks habitats"—north-facing (sun-facing) hollows with just the right configuration of dark rocks and transparent ice. Along the edge of that ice would be a narrow habitable band, maybe just a few meters wide, where slight, occasional meltwater could flush the soil of salts and also help critters rehydrate, "at least every so many years," Adams says. As an ice age moved in, gradually pushing ice farther up the slopes, *Tullbergia* could have slowly moved upslope as well, maybe just a meter a year, if it was lucky enough to encounter Goldilocks habitats along the way.

These explanations sound plausible but are unfinished. Hogg and Adams, neither of whom has been back to Shackleton Glacier, need to connect the genetics to a clearer time line of how Antarctica's ice has waxed and waned. They also need to see if the pattern holds for other species. They and their students are now trying to sequence DNA from the same cytochrome gene in a species of mite and a species of nematode worm they found at Shackleton Glacier and at other locations around the southern Transantarctic Mountains. They hope that the genetic sequences will help explain how long these other animals have lived here, how they moved around in the past and how they stayed alive.

What is already apparent is that some species survived by the thinnest of margins. During glacial retreats, they could have established new outposts on nearby mountains. But with each new ice age, most of the populations died off. *Tullbergia* bears the scars of that brutal history in its DNA. The fact that every individual from around Shackleton Glacier carries virtually identical gene sequences suggests that at some point in the past, as few as two of the animals managed to survive. Every representative alive today is descended from those progenitors, which may have been lucky enough to be blown by a windstorm onto a patch of Goldilocks ground the size of a basketball court. *Tullbergia* "came extremely close to extinction," Adams says.

Of course, entire communities of plants and animals have disappeared from Antarctica, part of the waves of extinctions that have occurred across Earth's history. Would a warmer, wetter Antarctica help *Tullbergia* rebound? Adams was back in the McMurdo Dry Valleys in January. Lake levels are rising, dry soils are getting moister and numbers of small animals such as certain nematode worms that live in the ground are increasing. At the same time, animals that have survived the really cold, dry, harsh soils "are decreasing in abundance, and their range across the landscape is contracting," Adams says. Perhaps newcomers are crowding out the old hangers-on.

The question is whether *Tullbergia* will suffer a similar fate. "Based on what they've done in the past, my guess would be that they'd do quite well," Adams says. "Just so long as they don't have to compete with invasive species." SA

MORE TO EXPLORE

Nematodes in a Polar Desert Reveal the Relative Role of Biotic Interactions in the Coexistence of Soil Animals. Tancredi Caruso et al. in *Communications Biology,* Vol. 2, Article 63; February 2019.

Spatial and Temporal Scales Matter When Assessing the Species and Genetic Diversity of Springtails (Collembola) in Antarctica. Gemma E. Collins et al. in *Frontiers in Ecology and Evolution,* Vol. 7, Article 76; March 2019.

FROM OUR ARCHIVES

Life at Hell's Gate. Douglas Fox; July 2015.

scientificamerican.com/magazine/sa

NICOBAR ISLANDERS celebrate an ancestor, who passed away decades earlier, with a canoe race. In their view, no one really dies. Instead they transit to the spirit world and protect the community.

ANTHROPOLOGY

The Aid Tsunami

How disaster relief ravaged an indigenous community

By Ajay Saini and Simron J. Singh

Illustrations by Greg Manchess

Ajay Saini is an assistant professor at the Indian Institute of Technology Delhi. He works with remote indigenous communities.

Simron J. Singh is an associate professor at the University of Waterloo in Ontario. He studies sustainable resource use on small island states or jurisdictions threatened by climate change.

IT WAS A NOVEMBER MIDNIGHT, YEAR 2000, ON NANCOWRY, ONE OF THE NICOBAR Islands in the Bay of Bengal. One of us (Singh) waited in the pitch-black darkness, listening to the roar of waves crashing on the shore some 20 meters away, the stars brilliant in the sky above. Soon villagers appeared carrying dried-leaf torches. Chacho, a shaman, had died in July, and tonight was the culmination of the Tanoing festival commemorating her death. All day family and friends had ritually expressed their grief by sacrificing pigs they had raised and smashing beautiful objects they had spent hours or days crafting. (To the Nicobarese, something that took time and effort to create represents wealth, and its destruction signifies detachment from the material world.) They had decorated Chacho's home elaborately and feasted on pandanus (a starchy fruit), pork and other delicacies. Now they arrived in procession, led by Chacho's brother Yehad, a *minluana* (spirit healer) named Tinfus and a few other elders, followed by dozens of men, women and children, all in a celebratory mood.

Yehad and his companions carried Chacho's possessions—her tools, baskets and other things that she had treasured. Some they hung on a nearby tree; the remainder they placed on a bamboo platform at the head of the grave. Then the elders festooned the grave, wrapping meters of colorful cloth around the pole that marked the site until it resembled a standing mummy. Everyone was steadily getting tipsy from the toddy (the sap tapped from coconut palms) being passed around in coconut shells, and teenagers were flirting. A few beautifully dressed girls offered the guests tobacco and betel leaves from decorated baskets.

After the elders had finished the rites, the crowd returned to Chacho's home, laughing and joking. Tinfus installed a delicate winged figure representing her spirit, which he had carved and painted, inside the house. The mourners began singing and swaying, entering an ecstatic collective trance as they consumed more and more toddy. The joyous mood continued for most of the next day: the shaman had transitioned to the spirit world, where she would live on and protect the community.

In the Nicobarese worldview, death is the continuation of life in another form. All their ceremonies involve the veneration and celebration of ancestral and natural spirits channeled through carved and painted statues. These objects are regarded as living beings who guard the home, the village and the community. No one ever really dies. If any society has the cultural and psychological resources to cope with the staggering trauma of sudden mass death from a natural disaster, it is the indigenous peoples of these remote islands.

EARLY IN THE MORNING on December 26, 2004, the Indian continental plate slid under the Burma microplate at a depth of 30 kilometers off the western coast of northern Sumatra. The resulting magnitude 9.1 earthquake triggered a tsunami—the deadliest in recorded history. The Nicobar archipelago, comprising 22 islands with a combined landmass of only 1,841 square kilometers, lay along the fault line and very close to the earthquake's epicenter. Waves more than 15 meters high hit several times, washing clean over the smaller islands and taking with them

IN BRIEF

The devastating tsunami of December 2004 prompted a massive relief and rehabilitation effort, with nongovernmental organizations raising and governments committing unprecedented resources.

Culturally inappropriate aid inundated the indigenous peoples of the Nicobar Islands, who previously enjoyed a self-sufficient economy. The assistance ruptured community ties and fostered consumerism.

Fifteen years later the Nicobarese have acquired a taste for consumer goods that they lack the means to satisfy. They are plagued by lifestyle diseases such as diabetes and suffer from depression and alcoholism.

entire villages. Tens of square kilometers of land sank under the water because of rupture and submergence; the beautiful island of Trinket broke into three pieces. Official numbers put the human toll on the Nicobars at 3,449 missing or dead, but estimates from independent researchers were as high as 10,000. (The population was 42,068 according to the 2001 census, with about 26,000 being ethnic Nicobarese.) Some 125,000 domestic animals were killed, and more than 6,000 hectares of coconut plantations, 40,000 hectares of coral reefs and almost three quarters of the houses were destroyed.

Tradition saved a few people. The chief of the village of Munak on Kamorta Island remembered ancestors' warnings about the aftermath of a colossal earthquake and urged the villagers to flee from the beach. Fortunately for them, the island has an elevated hinterland; no one from Munak died. And incredibly, many from Chowra Island were able to swim back after having been swept away by the giant waves.

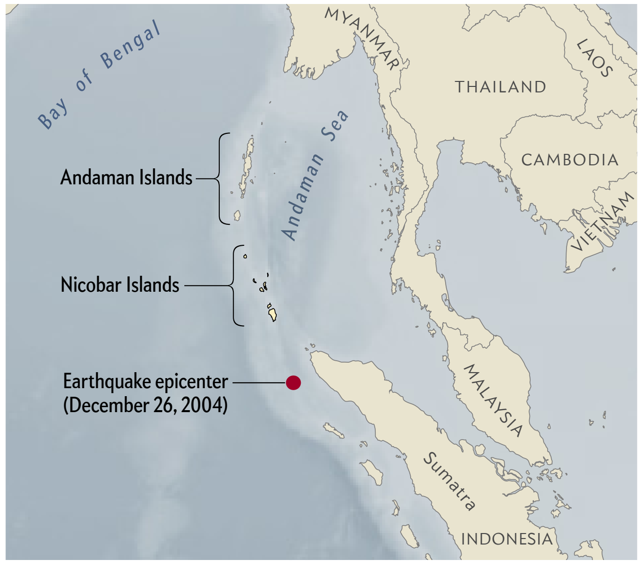
The magnitude of the catastrophe led to a massive humanitarian response. More than $14 billion was mobilized, 39 percent of which came from voluntary private donations, to help tsunami victims around the Bay of Bengal and elsewhere. The Indian government—which had inherited the Nicobar Islands from the British Empire in 1947—launched a rescue-and-relief operation, and aid agencies arrived in force. Over the ensuing months and years these benefactors inundated an essentially isolated society with packaged foods, a wide range of electronic and consumer goods, and enormous cash handouts.

It might seem that such a generous effort would have left the Nicobarese far better off than before the tsunami. But the culturally insensitive aid undermined what was historically a resilient society with centuries-old institutions for independent and democratic decision-making. It ended up bringing a formerly close-knit community to the point of disintegration, with many of its members beset by alcoholism, diabetes and other formerly alien ailments. Now, 15 years later, the desperate plight of the islanders raises questions about the effectiveness of humanitarian aid that is driven by the priorities of donors rather than of recipients.

Every year the world experiences approximately 350 natural disasters, which harm millions of people. Over the past three decades nation-states and nongovernmental organizations (NGOs) have aimed to reduce the impact of these tragedies through prevention, mitigation and preparedness. Unfortunately, however, governments and other actors often regard indigenous cultures "as being inferior, primitive, irrelevant, something to be eradicated or transformed," according to an assessment by the United Nations Department of Economic and Social Affairs. These communities become especially vulnerable during disasters, with economically and politically dominant sections of modern society imposing ideologically motivated changes on them, forever alienating them from their culture and territory.

WE ARE TWO ANTHROPOLOGISTS whose studies of the Nicobarese, conducted independently, span two decades and have given us deep insight into the society and culture before and after the tsunami. Singh conducted his fieldwork between 1999 and 2009, whereas Saini has been studying the indigenous peoples since 2010.

The Nicobarese migrated to the archipelago from the Malay



NICOBAR ISLANDS lie on a major fault line that slipped on December 26, 2004, generating a devastating tsunami. It killed thousands of indigenous Nicobarese and ravaged their villages.

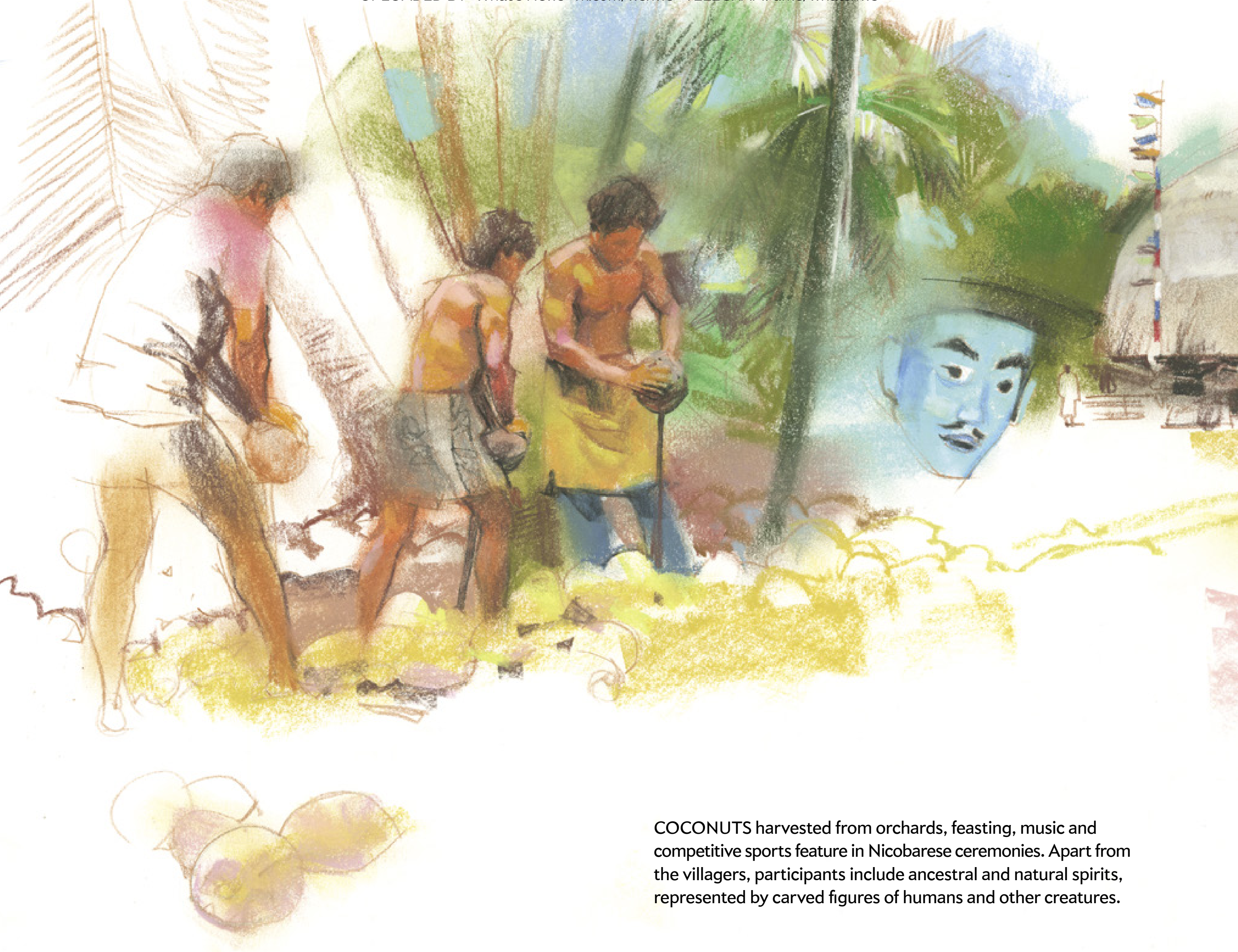
Peninsula thousands of years ago and speak an Austro-Asiatic language. Before the tsunami they subsisted by hunting, foraging, raising pigs, and fishing in the rich coral reefs surrounding the islands. Some extended families, called *tuhets* or *kamuanses,* grew crops such as tubers, oranges, sugarcane, lemons, bananas, yams, papaya, jackfruit and, especially, coconuts, many of which they traded with outsiders. The entire family, made up of three or more generations, tended the orchards together, singing, joking and enjoying toddy; work and leisure were integrated. Social capital—how much help one could summon from friends and neighbors in times of need—varied and was considered a significant form of wealth. But social codes ensured that no one suffered from want.

For centuries ships sailing between India and China anchored at the Nicobars to replenish food and other supplies during their long voyages. In 1756 Danish settlers colonized the archipelago, eventually giving way to the Austrians, the British, the Japanese (during World War II), the British again and then the Indians. None of these occupations left a significant mark on the indigenous culture. In 1956 India introduced legislation limiting entry to the islands to administrators, military personnel and select businessmen and settlers. The Nicobarese began drying coconut flesh into copra, which they bartered with private traders or local cooperatives for rice, sugar, kerosene, cloth and other goods not produced on the islands. Cash rarely changed hands.

But when Singh reached the archipelago three weeks after the 2004 catastrophe, nothing was as it had been in the past. The coastline was unrecognizable, with the sea washing over the remains of many villages. Smashed corals, downed trees and other debris impeded access by boat, and SUVs got stuck in swamps, requiring arduous treks.

More jarring, however, was what had happened to the people. The Indian armed forces had evacuated almost 29,000 survivors—roughly 20,000 of whom were Nicobarese, including everyone from six of the smaller islands, such as Trinket, Chowra and Bom-

Map by Dolly Holmes



COCONUTS harvested from orchards, feasting, music and competitive sports feature in Nicobarese ceremonies. Apart from the villagers, participants include ancestral and natural spirits, represented by carved figures of humans and other creatures.

poka. The local administration, based in the region's capital, Port Blair on South Andaman Island, had accommodated them in 118 relief camps in the higher hinterlands of the remaining islands. Crammed into tents rigged out of blue tarpaulin, they had received clean water and food but little else. Many were still in shock.

It was imperative that the people of Bompoka return right away to construct shelters, tend to the orchards and plant vegetable gardens to ensure future food security, said Kefus, the island's chief. He and other elders feared—presciently—that prolonged separation from their islands could mean the extinction of their roots and their identity. "We may die, but we have to go back," declared Jonathan, the chief of Chowra. Several chiefs asked government officials for boats and tools. The administrators advised, however, that a major aid effort was being planned by the Indian government in New Delhi (which directly controls the archipelago), which the refugees would forgo if they left. That promise left many of the camp dwellers confused, unsure of whether to rely on their own resources and traditions or trust the officials. Most decided to wait and see.

In the following weeks and months relief materials started to arrive, often poorly matched with the needs and the culture of their recipients. By the middle of 2005 the Nicobarese were living in shelters that the administration had constructed out of tin sheets. The government was providing them with rations and medicines; NGOs supplied other relief materials, including processed foods and consumer goods hitherto unknown to the indigenes. Many were unusable. Camp residents received wool blankets (unfit for a hot and humid climate), saris (worn by Indian women but alien to the Nicobarese) and a range of electronics (where the electric supply was either fitful or nonexistent).

The Indian government's approach to dispersing the aid compounded the problems. Officials consulted with the aid recipients on several issues but preferred to work with inexperienced and impressionable youths who could speak Hindi or English. These so-called tsunami captains could not effectively represent the community and ended up becoming the yes-men of the administrators. The authority of elders, who were previously the decision makers, weakened, engendering conflicts between generations and consolidating power in the hands of the administration.

With the assistance of the tsunami captains, the government deposited large compensations for tsunami damage into newly opened bank accounts. Without exception, nuclear families headed by men got the money, undermining the joint family system and the status of women, who had previously played an im-

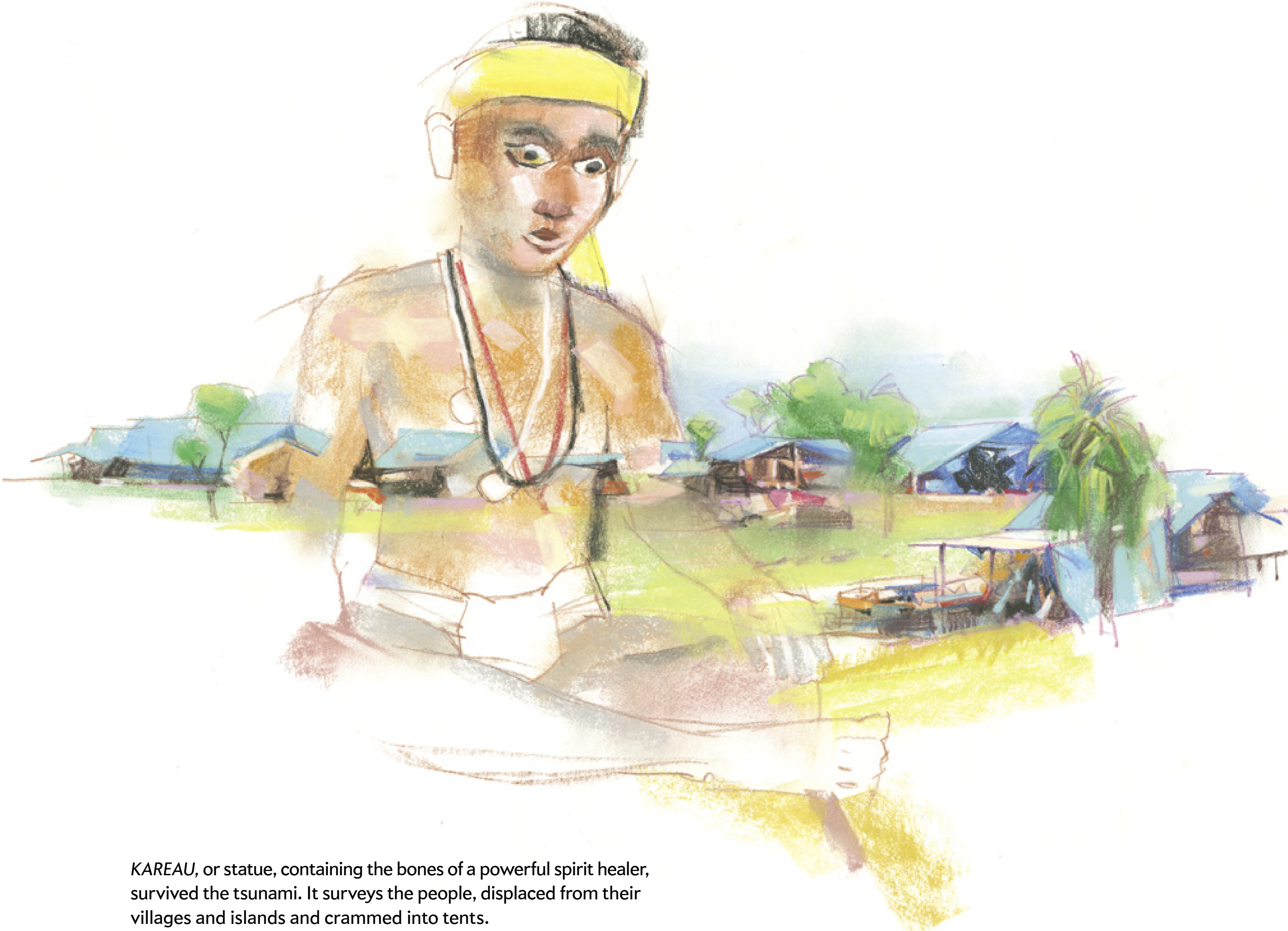
portant role in making key economic decisions. Their heads turned by unfamiliar power, several of the captains favored their own families when it came to identifying aid recipients, which provoked disputes among them.

All the while the Nicobarese languished in the sweltering, rattling tin cubicles; Mohoh of Kondul Island said he felt like a "caged bird." The cramped shelters offered no space to plant vegetables or raise pigs. The forests were full of fallen timber, but there were no axes to chop it with so they could construct houses. The creeks of the evacuated islands were replete with fish and crab, and the sowing season was around the corner, but most of the Nicobarese were stuck in the camps, dependent on relief rations. Some felt they were being turned into beggars. "We can manage on our own," said Hillary, captain of Tapong, a village on Nancowry Island. "We don't need biscuits and chips. We need to make our homes and plant our gardens. Give us tools if you wish to help us."

Mild protests erupted across the islands. The Nicobarese needed the space to grieve and to rebuild their lives in culturally prescribed ways. "Leave us alone or we are sure to die," said John Paul, a leader from Katchal Island. These pleas fell on deaf ears. Many elders, such as Paul Joora, chief of Great and Little Nicobar, foresaw that "one day this aid will break the Nicobarese's heart." But because of conflict with younger leaders and confusing signals from the administration, the elders could not prevail. Additionally, Nicobarese culture, being based on achieving consensus, makes it difficult for the people to express disagreement; they could not emphatically protest whatever was imposed on them.

A few of the Nicobarese refused to give in. While in camps on neighboring Teressa, the people of Chowra, who had exceptionally strong traditions, built canoes with tools they had salvaged from the more intact villages. The canoes enabled them to repeatedly visit Chowra to clean debris, plant orchards and repair houses. Eighteen months after their evacuation, they returned home for good, with more than 100 small canoes and 10 festive canoes, used in celebrations, which they had spent their time in exile building.

BY THE TIME THE GOVERNMENT finished building permanent shelters for the Nicobarese refugees, in 2011, their society had been irrevocably changed. During their years in the relief camps the indigenes had come in close contact with Indian settlers, who looked down on them as "primitives" who were seminude and ate raw fish. Over time many of the young people internalized these views and came to be ashamed of their culture. The



KAREAU, or statue, containing the bones of a powerful spirit healer, survived the tsunami. It surveys the people, displaced from their villages and islands and crammed into tents.

cash from the government enabled them to buy things that gave them the look and lifestyles of outsiders: televisions, motorbikes, mobile phones. The yardstick of wealth became the possession of modern commodities. Settlers and traders fleeced the gullible Nicobarese, rapidly emptying their bank accounts.

With money, free rations and enforced idleness for years on end, many of the Nicobarese gradually lost their motivation to work. Their diets shifted toward spicy Indian dishes and fast foods. Their prolonged inactivity and dependence led to depression, and many found solace in alcohol much stronger than fermented coconut sap. Though prohibited by the 1956 protection act, sales of Indian-made foreign liquor (IMFL) such as whiskey and rum, supplied by settlers and traders, shot up.

The government launched some livelihood-regeneration programs to engage the idle Nicobarese, but most were ill conceived. For instance, when officials introduced community plantations, they did not understand that land ownership in the Nicobars was vested with the lineages, which distributed usage rights among their constituent nuclear families. Whoever planted a tree owned it, but the land remained with the *tuhet* or *kamuanse*. Severe conflicts arose if anyone attempted to plant a tree on land that had not been granted by the lineage.

When the 7,001 permanent shelters were finally completed, they triggered yet another set of crises. Before the tsunami a typical Nicobarese village lay near the coast within a bay, often sheltered behind mangroves. Outrigger canoes provided easy access to other villages or to nearby islands. The huts were raised on stilts for protection from poisonous reptiles and from flooding during monsoon storms; pigs and chickens lived in the shade below. Designed for the tropics, the houses were extremely comfortable. The entrance usually faced the sea, the roof was thatched, and walls and floors were made from split bamboo that allowed breezes to move freely in and out.

But the administration constructed the permanent houses, called tsunami shelters, at higher altitudes that were far from the coast. Building contractors brought in shiploads of imported materials—prefabricated structures, steel columns, clapboards, concrete blocks, iron pillars and galvanized iron sheets—as well as hundreds of laborers from elsewhere. Many of them encroached on Nicobarese land and ended up staying permanently.

When their roofs leaked or their walls fell, the Nicobarese could no longer repair their own homes. They had to beg the authorities for help. Worse, while designing and allocating these homes, the government split the extended families into several nuclear households, undermining the very basis of Nicobarese society. In the past, the lineages had supported all within them and also helped related families in times of need or during the organization of large ceremonies. With their fragmentation, the strong social support system that the community had enjoyed collapsed, leaving its members vulnerable at a critical juncture.

For some the consequences were even more devastating. The authorities declared some islands uninhabitable and constructed houses for their former residents on other islands. The cleavage from their ancestral lands, with which they had deep spiritual and emotional bonds, caused these people tremendous suffering. "We miss our villages, but they will also be missing us," Paul Joora grieved. The homeland, inhabited by ancestral spirits, was a living being, and the severing of ties with it was more painful than the loss of a family member.

In addition, over the years prolonged stress, sedentary lifestyles and a taste for processed foods had taken a toll. Previously unknown ailments such as hypertension appeared. The islands lack modern medical facilities, and most of the traditional healers—with their extensive knowledge of plant-based medicines—had perished during the tsunami. The Nicobarese began to die of heart attacks, diabetes, injuries, respiratory diseases, pneumonia, malaria and other diseases. Alcoholism became a scourge as well.

After allocating the last tsunami shelters in 2011, the administration abruptly stopped providing aid. As the cash ran out, addicts could no longer buy IMFL and began to consume *junglee,* an illicit and toxic mix of ethyl alcohol, urea, battery acid and other chemicals that mainland laborers had introduced to the Nicobarese during the reconstruction phase. "*Junglee* will kill more Nicobarese than the tsunami had," predicted Ayesha Majid, who chairs the Nancowry tribal council.

Many of the indigenes believe that their perpetual sadness is the root cause of disease and death among them. "We may seem alive, but deep inside we all are dead people," despaired Chupon, an elder of Nancowry. Tinfus, the spirit healer who had participated in Chacho's joyous funeral ceremony, echoed the sentiment. "The Nicobar is dying," he said to Saini in 2014. In a soft, shaky voice, Tinfus explained how the *kareau,* or ancestral spirits, had always protected the Nicobarese from evil spirits. But of late, his people had lost faith in their traditional wisdom and trod a path of self-destruction. He prophesied that tsunami aid would end up ruining generations of Nicobarese. His speech was long and punctuated by thoughtful pauses; suddenly, in the middle of a sentence, he broke down in tears. In September 2018 Tinfus, one of the last *minluanas,* passed away at the age of 80. His death marked the end of an era in the Nicobar Islands.

SINCE THE TSUNAMI the Nicobarese community has lost its social cohesion, spiritual traditions, rules of sustainable resource use, and other immaterial attributes that once ensured its resilience. Their material consumption (as measured by weight) has increased sixfold, and their consumption of fossil fuels has increased 20-fold. In the absence of continued aid or well-paying jobs, they can only tread a path of hopelessness about meeting their expanded wants with their limited means. With the compensation money exhausted and few livelihood options in the Nicobars, many of the islanders are migrating to Port Blair, the capital, to seek work. There they live precariously, facing exploitation and racism from mainstream Indians. Christopher, secretary of Teressa's tribal council, told Saini in 2018 that the mainlanders abused them verbally and physically. "It hurts," he said. "But what can we do?"

We believe that the fallout of misguided assistance in the Nicobars could have been averted. This close-knit community with a rich traditional knowledge base needed no outside experts to determine how to deal with its post-tsunami predicament. In the words of Rasheed Yusoof, spokesperson for Nancowry's tribal council, the Nicobarese needed only "listening ears" to get what little they needed from outsiders. With NGOs and government officials convinced that they knew best, however, the initial determination of the Nicobarese to rebuild their futures dissipated in a stream of inappropriate aid, ultimately leaving them a sedentary, depressed and disoriented people.

In 2015 a U.N. conference formalized guidelines for preventing, mitigating and preparing for disasters while also resolving to "Build Back Better" (BBB)—that is, to leave the victims better off than before the disaster. Yet case studies from places as diverse as Haiti, Nepal and the Philippines show that practitioners of the BBB approach have repeatedly failed to account for the specific needs and preferences of those they seek to help. "The promise to not re-create or exacerbate predisaster vulnerabilities has generally been unfulfilled," concluded researchers Glenn Fernandez and Iftekhar Ahmed in a 2019 review of literature on BBB. Seen against this backdrop, the lessons from the fallout of aid in the Nicobars become even more relevant.

Rather than adopting a one-size-fits-all attitude to disaster relief and rehabilitation, recovery efforts should rely on context-sensitive measures that recognize cultural diversity, learn from traditional knowledge, ensure the active participation of affected peoples, build resilience and reduce vulnerabilities. Instead of trying to erase differences, those who administer aid need to protect and celebrate cultural diversity where it still survives and to foster the principles that guide human and planetary well-being.

Fifteen years after the tsunami, many of the Nicobarese regret having trusted the promises of their rescuers. Some are now going home. "We have no future here," declared Portifer, who lived in Trinket but now resides on adjacent Kamorta Island, in December 2019. "Many of us are planning to go back." Trinket was only 36 square kilometers to begin with and was reduced to 29 by the earthquake and tsunami. To an outsider, life on the fragmented island may seem precarious, with man-eating crocodiles roaming the coast, but seven Nicobarese families have already returned, choosing the perils of the ocean over those of modern civilization. SA

MORE TO EXPLORE

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Disciplining the Other: The Politics of Post-tsunami Humanitarian Government in Southern Nicobar. Ajay Saini in *Contributions to Indian Sociology,* Vol. 52, No. 3, pages 308–335; October 2018.

The Sustainability of Humanitarian Aid: The Nicobar Islands as a Case of "Complex Disaster." Simron Jit Singh et al. in *The Asian Tsunami and Post-Disaster Aid.* Edited by Sunita Reddy. Springer, Singapore, 2018.

FROM OUR ARCHIVES

The Andaman Islanders. Sita Venkateswar; May 1999.

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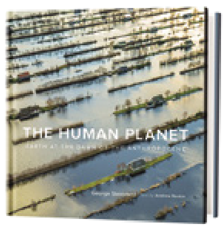
RECOMMENDED

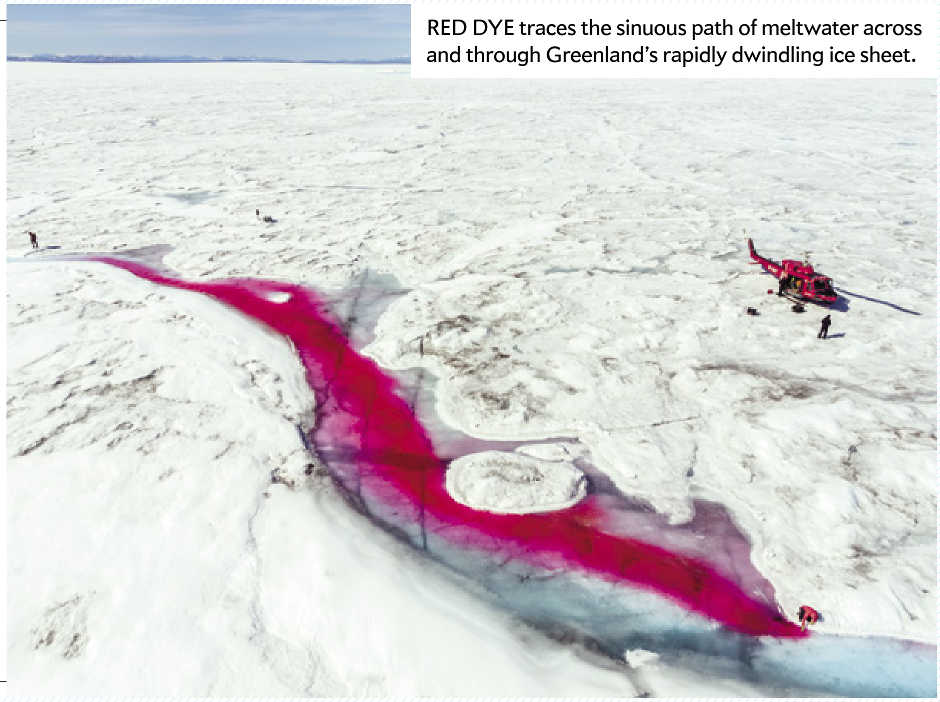
By Andrea Gawrylewski

The Human Planet:

Earth at the Dawn of the Anthropocene

Photography by George Steinmetz, text by Andrew Revkin. Abrams Books, 2020 ($50)



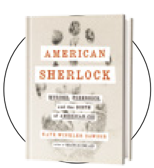


RED DYE traces the sinuous path of meltwater across and through Greenland's rapidly dwindling ice sheet.

This stunning book offers a bird's-eye view of a changing Earth—each image taken by Steinmetz on a paraglider or by a camera attached to a drone. But it is not just another coffee-table book of photographs. Veteran journalist Revkin, who has devoted his career to covering a warming world, makes the strong case throughout that it is no longer enough to passively observe how the climate is transforming Earth. We must ask ourselves what kind of future we wish to create. Nearly every locale covered—from the islets of the Maldives to the southern tip of Antarctica—is subject to the effects of human action or will be soon. As Revkin writes, "Our species has, in an instant of planetary time, become a potent planet-scale player."

American Sherlock: Murder, Forensics, and the Birth of American CSI

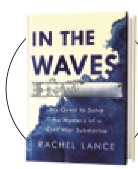
by Kate Winkler Dawson. G. P. Putnam's Sons, 2020 ($27)



Edward Oscar Heinrich is "the most famous criminalist you've likely never heard of." Through a hybrid of biography, true crime and science history, journalist Dawson introduces the riveting narrative of how largely self-taught scientist Heinrich helped to pioneer and refine many areas of forensic science over a 40-year career spent working more than 2,000 cases. Dawson—who was granted exclusive access to Heinrich's vast forensic archives—uses several of the headline-grabbing cases he investigated as the lens to illuminate the scientist's contributions to the U.S. court system, ranging from ballistics evidence to forensic entomology. That legacy is a mixed one, though, as Dawson point outs, with some of the disciplines he championed, such as blood-spatter patterns, having since been debunked. *—Andrea Thompson*

In the Waves: My Quest to Solve the Mystery of a Civil War Submarine

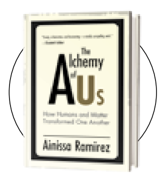
by Rachel Lance. Dutton, 2020 ($28)



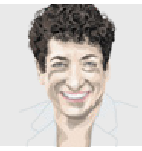
Most would refuse to climb into a 40-foot-long metal tube—of dubious quality—with a 135-pound black powder charge attached to it. But the small crew of the Confederate submersible craft, the *HL Hunley,* did exactly that. Unfortunately for them, the sub sank in 1864 during battle, killing all onboard. The ship's remains were raised in 2000 from the bottom of the Charleston, S.C., harbor, and researcher Lance chronicles her subsequent investigation into what precisely sunk the craft. She builds a model of the boat, tests the explosive force of the charge it carried, re-creates the blast effects on the craft's hull, and considers whether the crew's fate was asphyxiation or, perhaps, death by gunfire. In the end, the answer to the 156-year-old cold case was uncovered far away from the scene of the sinking: a farm pond in North Carolina. *—Michael Mrak*

The Alchemy of Us: How Humans and Matter Transformed One Another

by Ainissa Ramirez. MIT Press, 2020 ($27.95)



Humans have reshaped the world with inventions such as railroads and transistors. But these innovations have altered our behavior in turn. Materials scientist Ramirez details the battle between retired reverend Hannibal Goodwin and entrepreneur George Eastman of the Eastman Kodak Company over the patent for lightweight, flexible photographic film. She also exposes a sinister side of the story, explaining how Kodak's engineers created film that made darker faces appear flat, almost like inkblots, because they fine-tuned the product's sensitivity to lighter skin tones. And barrier breakers such as Polaroid employees Caroline Hunter and Ken Williams fought tirelessly, starting in 1970, to pressure Kodak to divest from apartheid-era South Africa. New technologies may lead to a brighter future, but as Ramirez writes, "their use is not always for the greater good." *—Sophie Bushwick*



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

Who's Rational about Risk?

White men and scientists tend to dismiss it most easily

By Naomi Oreskes

Scientists often complain that people are irrational in their opposition to technologies such as nuclear power and genetically modified (GM) crops. From a statistical perspective, these are very safe, and so (it is argued) people's fear can be explained only by emotion, undergirded by ignorance. Electricity from nuclear power has led to far fewer direct deaths than has coal-fired power, yet many people are afraid of it, and hardly anyone is afraid of coal plants. Similar arguments can be made about GM crops, which studies have shown are generally safe for most people to eat.

Scientific illiteracy may be part of the problem. Most of us are afraid of things we don't understand, and studies have shown that scientists tend to be more accepting of potentially risky technologies than laypeople. This suggests that when people know a lot about such technologies, they are usually reassured.

But there's more to the issue than meets the eye. It is true that many of us fear the unknown, but it is also true that we can be cavalier about routine risks. Part of the explanation is complacency: we tend not to fear the familiar, and thus familiarity can lead us to underestimate risk. The bipartisan commission that reviewed the Deepwater Horizon blowout and oil spill concluded that complacency—among executives, among engineers and among government officials responsible for oversight—was a major cause of that disaster. So the fact that experts are unworried about a threat is not necessarily reassuring.

Scientists also make a mistake when they assume that public concerns are wholly or even mostly about safety. Pope Francis, for example, rejects genetic modification of organisms in part because he views it as an inappropriate interference in God's domain; this is a theological position that cannot be refuted by scientific data. Some people object to GM crops such as Roundup Ready corn and soy because they facilitate the increased use of pesticides. Others have a problem with the social impacts that switching to GM organisms can have on traditional farming communities or with the political implications of leaving a large share of the food supply in the hands of a few corporations.

Geoengineering to lessen the impacts of climate change is another example. Some concerns about geoengineering—not just among laypeople but among scientists as well—have more to do with regulation and oversight than with safety. Who will decide whether this is a good way to deal with climate change? If we undertake the project of setting the global temperature by controlling how much sunlight reaches Earth's surface, who will be included in that "we," and by what process will the "right" global temperature be chosen?

Such considerations may help explain the results of a classic study of perceptions of health risks from a polluted environment, which showed that white women, as well as nonwhite men and women, were substantially more worried about these risks than white men. Because scientists are for the most part less worried about risks than laypeople, we might conclude that the insouciant white men are right and the others unnecessarily troubled.

Of course, the majority of scientists are white men, so it's not entirely surprising that their views track with those of the demographic group to which they belong. And there is a more important point here: risks are not equally distributed. Women and people of color are more likely to be the victims when things go wrong (think the Marshall Islands or Flint, Mich.), so it makes sense that they tend to be more worried. Moreover, women and people of color have historically been excluded from important decision-making processes, not just in science and technology but in general. When you're excluded from a decision-making process, it is not irrational for you to view that process as unfair or to be skeptical about what it yields.

Can we say whether men or women are more rational about risk? Can we say which group's view is closer to an accurate assessment? Well, here's one relevant datum: women are more likely than men to wear seat belts. SA

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Illustration by Carlo Giambarresi

Steve Mirsky has been writing the Anti Gravity column since a typical tectonic plate was about 36 inches from its current location. He also hosts the *Scientific American* podcast Science Talk.

Titan-ick

How not to spend a lot of time

By Steve Mirsky

In June 2018 the journal *Science* published research showing that chlorophyll-containing blue-green algae, also known as cyanobacteria, that were grown in extremely red light could carry on some photosynthesis despite the light's low energy.

Soon after, the magazine *Cosmos* ran with that finding to produce a nice article entitled "Pushing the Limit: Could Cyanobacteria Terraform Mars?" The subhead read: "The discovery that blue-green algae can photosynthesize in extremely low light has implications for astrobiology."

Then, on January 19, 2020, Senator Rand Paul of Kentucky cited the article in a tweet that also said, "Despite climate alarmist predictions, humans will likely survive for hundreds of millions of years into the future. In the meantime, we should begin creating atmospheres on suitable moons or planets." He then tweeted, "With so many billionaires about, why not a private prize of \$10 million for the scientist who genetically creates an O_2 producing organism that will thrive in the frigid, methane lakes of Titan?"

These notions struck me as, well, wacky. I knew that species don't last for hundreds of millions of years. And making an organism to terraform Saturn's moon Titan, if even possible, would undoubtedly cost more than some billionaire's chump change.

So I contacted Emory University paleontologist and geologist Anthony J. Martin. He noted that another species of humans, *Homo neanderthalensis,* "only lasted [approximately] 350,000 years before going extinct." Our species, *Homo sapiens,* has tens of thousands of years to go before we even catch up to the Neandertals.

I then wrote to University of Edinburgh evolutionary biologist Steve Brusatte. "If we make it another 10 million years, we'll be a record setter," Brusatte wrote back. "I can't think of any species that has approached that type of longevity. Ten million years ago there wasn't even a human lineage—it would still be another few million years before our ancestors split from the chimps." (Podcasts with Martin and Brusatte about books they've written are at ScientificAmerican.com.)

On to tweet two. A guest blog on our Web site in 2016 did in fact claim that Titan might be the second-best place in the solar system (in some ways better than the moon or Mars) for humans to live—a loooooog time from now.

Curious about the idea of oxygenating Titan with an engineered microorganism to be created on the cheap, I wrote to a planetary scientist. That person, who requested anonymity, replied, "I appreciate that Senator Paul is not a planetary scientist nor—apparently—an economist, but it's clear he could thrive as a humorist. I am not sure that a longer lecture on the density of Titan's atmosphere or the hazards of adding free oxygen to a methane mix will help in this case." The scientist also mentioned the challenge of "finding a photosynthetic bacterium that produces oxygen at 94 kelvins [–290 degrees Fahrenheit]."

Then I heard from Donald Canfield, a geoscientist at the University of Southern Denmark and author of the book *Oxygen: A Four-Billion-Year History.* "As far as we know," Canfield wrote, "all life requires water, so if we are looking for life to thrive in something else, we are pushing the boundaries way beyond how we understand life to function. Such a discovery would be foundational but way beyond what we know about life now. Prize money would be incidental to the Nobel Prize that would follow."

Did I mention that Earth's sulfidic seas in the mid- to late-Proterozoic eon are referred to as the Canfield Ocean, in honor of his research? Anyway, Canfield continued, "I think it might be wiser to offer a prize to someone who could produce a photosynthetic organism that could produce copious amounts of hydrogen for energy, or plastics, or some other useful hydrocarbon as a substantial part of their metabolism."

Because if we're going to spitball ideas about designer microbes that can help humanity, they might as well be good ones. SA

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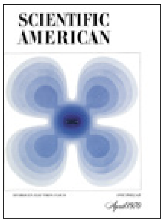
Illustration by Matt Collins

50, 100 & 150 YEARS AGO

INNOVATION AND DISCOVERY AS CHRONICLED IN *SCIENTIFIC AMERICAN*

Compiled by Daniel C. Schlenoff

APRIL



1970

1920


1870

1970 Once a Leader

"In his recent message to Congress on the environment President Nixon listed 37 steps 'we can take now and that can move us dramatically forward toward what has become an urgent common goal of all Americans: the rescue of our natural habitat as a place both habitable [by] and hospitable to man.' The steps are designed to achieve progress in four major areas: control of water pollution, control of air pollution, management of solid wastes and provision of more recreational areas and open space. One of the administrative actions was to create a three-man Council on Environmental Quality to 'be the keeper of our environmental conscience, and a goal to our ingenuity.'"

Liquid-Crystal Displays

"In recent years liquid crystals have stimulated the imagination of engineers. These substances are currently being used to create a new family of devices for the display of symbols such as numbers and letters. They may also make it possible to devise a window that can be made cloudy or transparent at the flick of a switch and a television set no thicker than a picture frame. Someday liquid crystals may become the picture-producing element in the most ubiquitous display device of all: the television receiver. —George H. Heilmeier"

1920 Making Panes of Glass

"Our image shows a typical scene in a factory for the making of ordinary window glass—a branch of manufacture that is today of more than ordinary interest in the non-Teutonic countries of Europe, by virtue of the efforts being made to foster home production and thereby break the German monopoly which existed before the [First World War]. It is perhaps not generally known that the formation of the thin sheets of glass called for by the glazer follows the rather roundabout formula of blowing the glass into cylinders, to be later slit and flattened out into sheets; but this is the fact."

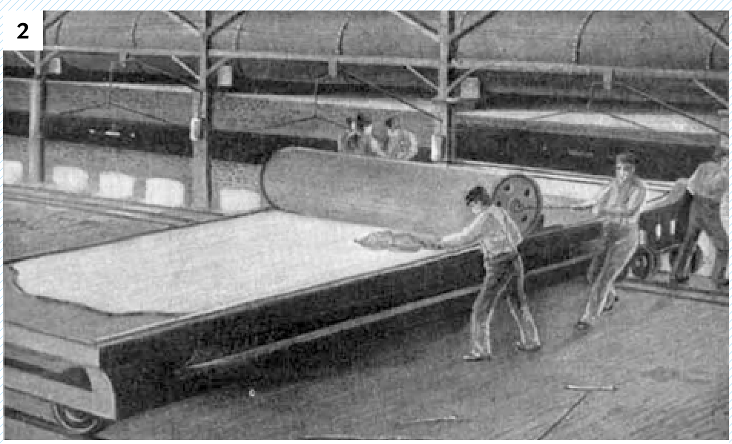
1

1920: Blowing cylinders of glass to make windowpanes was old-fashioned but still the best method.

1870 A Species' Demise

"The Great Auk, once very abundant on both shores of the North Atlantic, is now believed to be entirely extinct, none having been seen or heard of alive since 1844, when two were taken near Iceland. The death of a species is a more remarkable event than the end of an imperial dynasty. In the words of Darwin, 'No fact in the long history of the world is so startling as the wide and repeated extermination of its inhabitants.' How the Great Auk departed this life, by which of the great causes of extinction now slowly but incessantly at work in the organic world—the upheaval or subsidence of strata, the encroachments of other animals, and climatal revolutions—we cannot say."

EPIC TALES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1901: Early mass production of large sheet-glass windows from cast glass.

CELEBRATING 175 YEARS

Glass: A Window on Modernity

Windowpanes have been made from blown glass cylinders since the early Middle Ages. Cast sheet glass, poured into molds, flattened (as in our drawing from 1901) and polished, was well suited for mass production but expensive to make. In 1902 Irving W. Colburn "built and destroyed machine after machine and … produced the first commercially successful apparatus for drawing sheet glass." In the 1950s Alastair Pilkington introduced "float glass" (whereby hot glass is floated on molten tin); today it accounts for 90 percent of flat glass used worldwide. At the forefront of modernity, the glass on your smartphone screen is probably Corning's fusion-drawn Gorilla Glass: it separates environments but provides a … window … between them. *—D.S.*

SCIENTIFIC AMERICAN, VOL. CXXII, NO. 15: APRIL 10, 1920 (1); SCIENTIFIC AMERICAN, VOL. LXXXIV, NO. 20: MAY 18, 1901 (2)

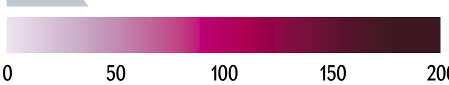
Text and graphs by Amanda Montañez | Maps by Mapping Specialists

Survival of the Youngest

Deaths of young children are decreasing, yet progress varies significantly within countries

Actions taken in response to goals set by the United Nations have reduced the deaths of children younger than five from 93 per 1,000 live births in 1990 to 39 in 2018. Low- and middle-income countries, which generally have higher under-5 mortality rates (U5MR) than their richer counterparts, have achieved some of the largest decreases. A recent paper in *Nature* suggests there is more to the story, however. Researchers who studied local U5MR rates in districts, counties, states and provinces within 99 low- and middle-income nations from 2000 to 2017 found great variability within many countries—especially those with particularly high or low rates overall. In some cases, though, subnational gaps have narrowed substantially. One important insight: in some countries, the ratio of infant (younger than one) deaths to under-5 deaths has risen, suggesting that preventing fatalities among the youngest children may be tougher to attain.

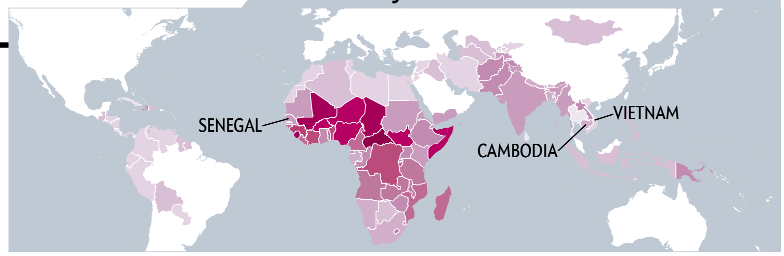
KEY



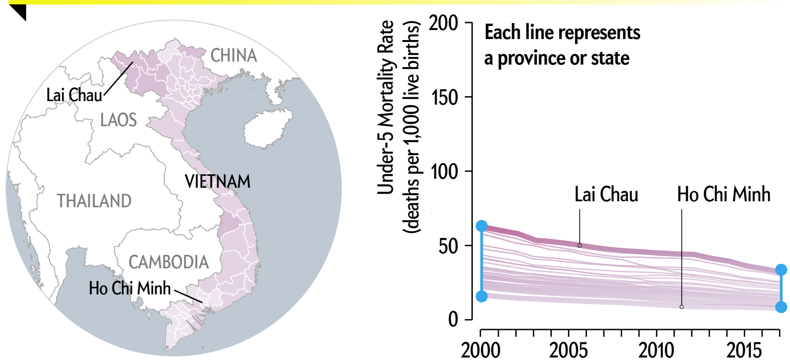
Under-5 Mortality Rate (deaths per 1,000 live births)

Maps show 2017 estimates of U5MR.
Line graphs show annual estimates from 2000 to 2017.

Child Mortality in 99 Low- and Middle-Income Countries

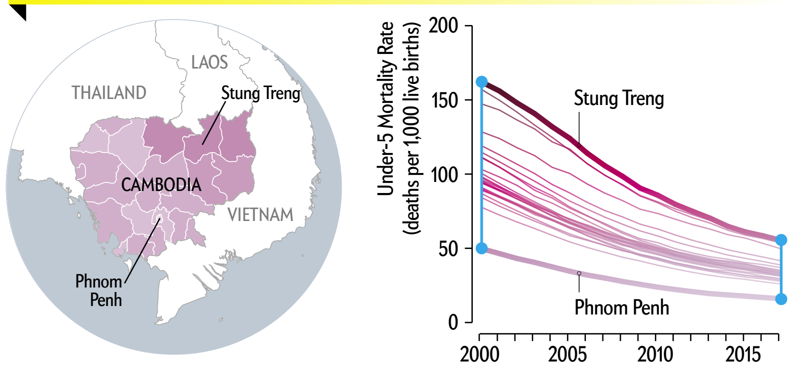


INEQUALITY WITHIN A NATION



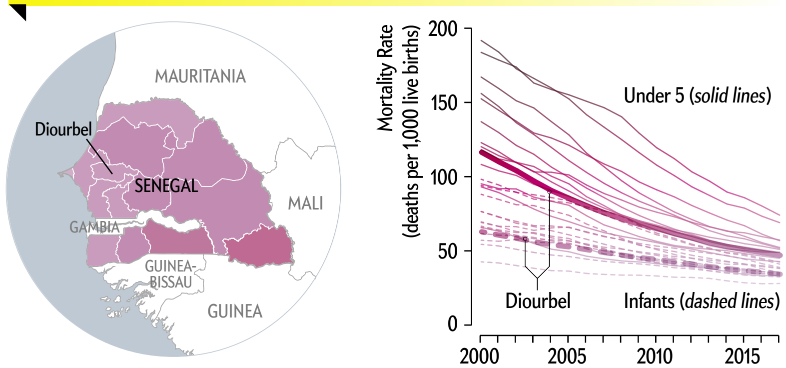
Vietnam's U5MR is relatively low. But at the subnational level, inequality among regions has prevented the gap between the highest and lowest rates from closing substantially. From 2000 to 2017 the U5MR in the province of Lai Chau remained about four times higher than that of Ho Chi Minh.

CLOSING THE GAP



The U5MR in Cambodia is higher than that of neighboring Vietnam, but within Cambodia the regional variation has been significantly reduced. The gap between the highest and lowest U5MR in the country shrank nearly threefold between 2000 and 2017.

INFANTS STILL AT RISK



Although the mortality rate of infants (younger than one) has fallen, it has done so more slowly than that of children aged one to five, making it a larger percentage of the U5MR. This is notable in Diourbel, Senegal, where the ratio of infant deaths to under-5 deaths rose from 54 percent in 2000 to 73 percent in 2017.

SOURCE: "MAPPING 123 MILLION NEONATAL, INFANT AND CHILD DEATHS BETWEEN 2000 AND 2017," BY ROY BURSTEIN ET AL., IN *NATURE*, VOL. 574; OCTOBER 17, 2019