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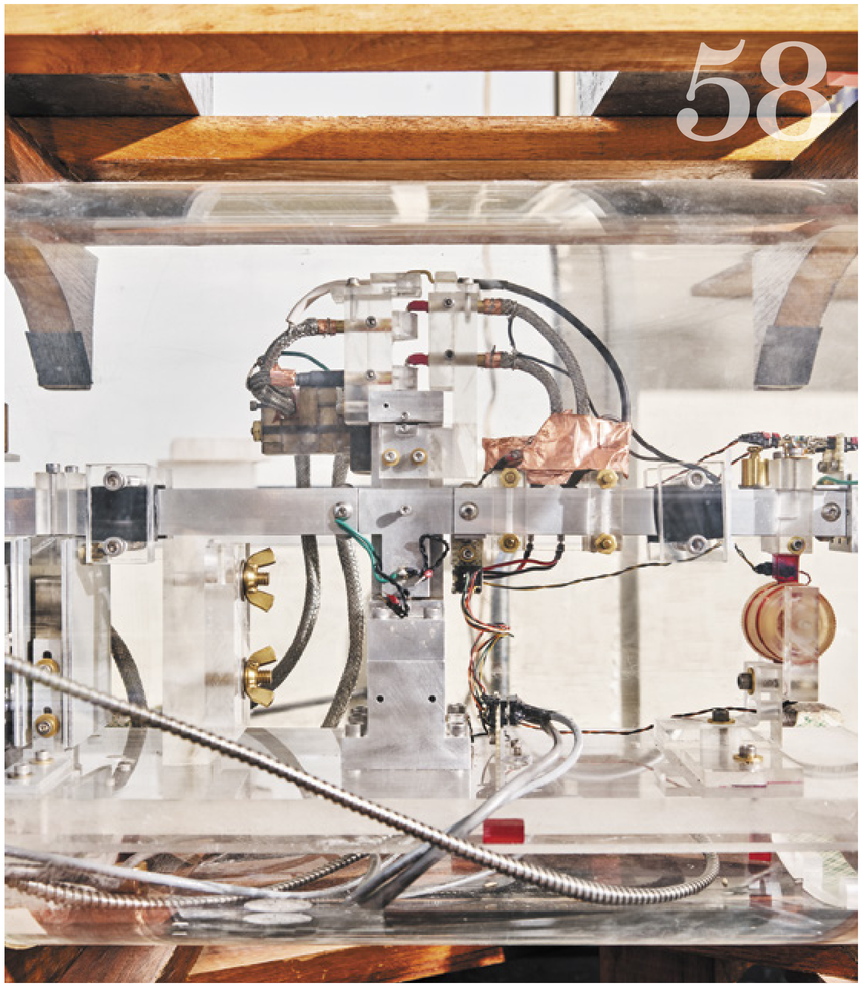

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Sea ice breaks apart on June 6, 2019, in the Amundsen Gulf, far into the Arctic Ocean above Canada's Northwest Territories. The thawing seas have inspired Arctic states and other countries to vie for seafloor rights to oil and natural gas deposits, shipping lanes and even military positioning in the high north. Photograph by NASA Earth Observing System Data and Information System (https://worldview.earthdata.nasa.gov)

Photograph by Spencer Lowell

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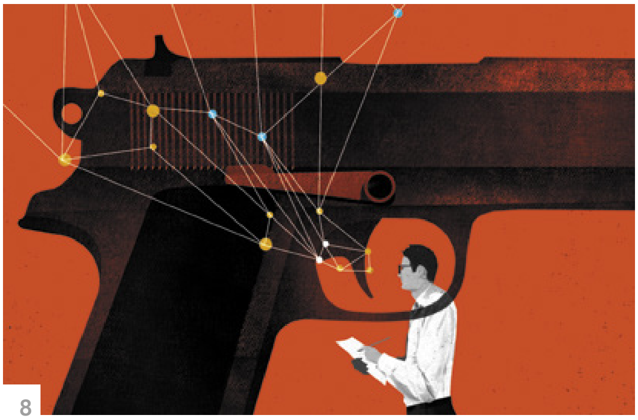
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ON THE WEB

Water, Water Everywhere

The closer scientists look at Mars, the more evidence they find that this freeze-dried world once harbored aqueous abundance. But just how much water exists on the Red Planet today?
Go to www.ScientificAmerican.com/aug2019/water-on-mars

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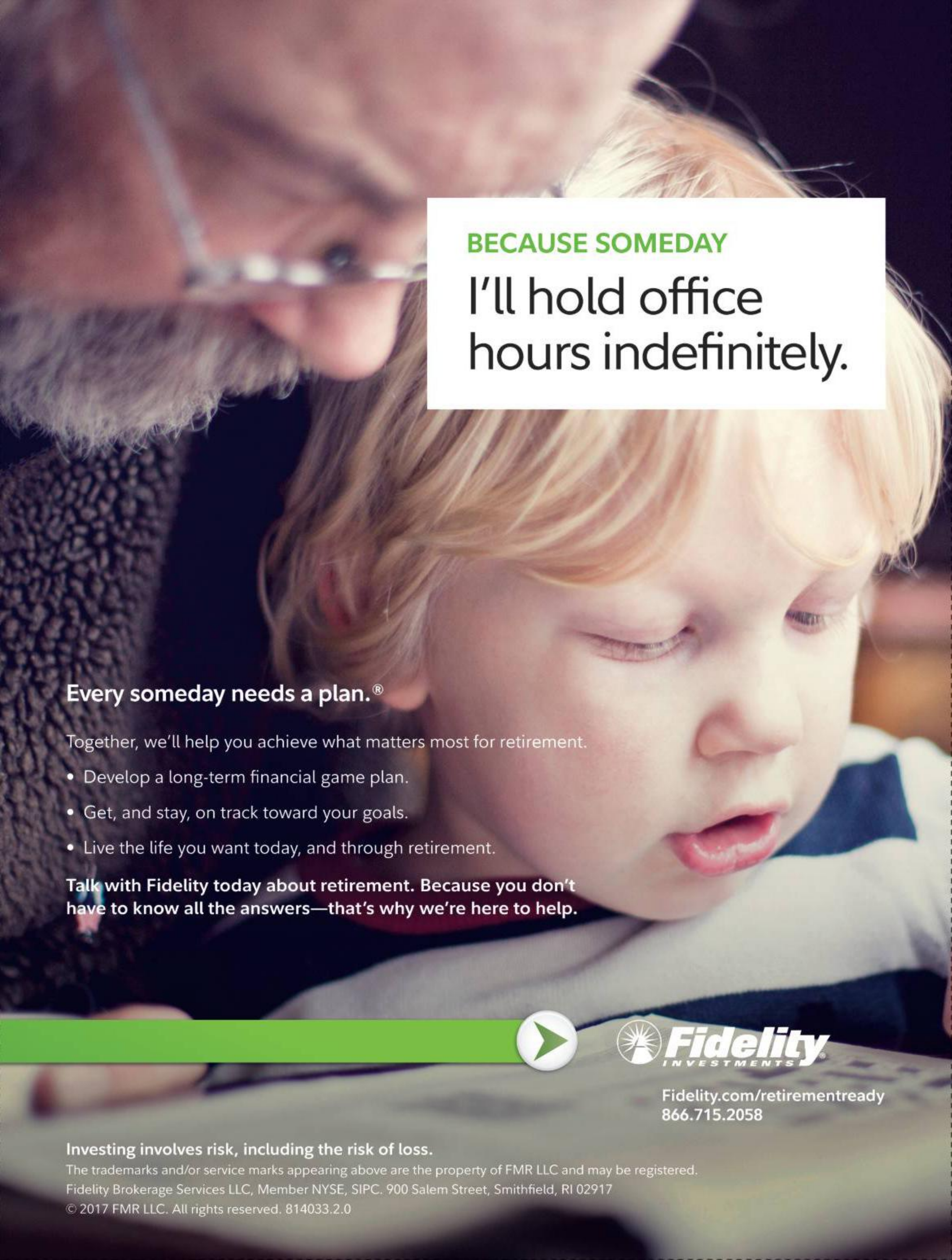
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Mariette DiChristina is editor in chief of *Scientific American.* Follow her on Twitter @mdichristina

What's Next for the Arctic?

In 1894 John William Strutt, Lord Rayleigh—who later went on to garner the 1904 Nobel Prize in Physics—penned an appreciation in *Scientific American* about the work of John Tyndall, an Irish physics professor, mathematician, geologist, atmospheric scientist, public lecturer and mountaineer.

"The most important work," Strutt wrote, "that we owe to Tyndall in connection with heat is the investigation of the absorption by gaseous bodies of invisible radiation." Tyndall's work showed the power of gases such as water vapor and "carbonic acid"—today known as carbon dioxide—to absorb heat and later speculated on such gases' effect on climate. Strutt himself repeated some of the experiments. As he wrote in his 1894 article: "When we replace the air by a stream of coal gas, the galvanometer indicates an augmentation of heat, so that we have before us a demonstration that coal gas when heated does radiate more than equally hot air, from which we conclude that it would exercise more absorption than air."

Today it is not a stretch to say that the way carbon dioxide and other so-called greenhouse gases are affecting climate is *the* story of our shared human experience globally. We at *Scientific American* look at various impacts nearly daily online and in every print issue. In this edition, we present a special report and cover story, "Future of the Arctic," starting on page 26.

Coordinated by senior editor Mark Fischetti, the package looks at the geopolitical consequences of a fast-melting region: how different countries are vying for control ("Divide or Conquer," by Fischetti), how rapid environmental alterations are transforming life at the putative top of the world ("A New Reality," by Fischetti), and what to do about rising political tensions ("Is Confrontation Inevitable?" by political scientist and scientific group leader Kathrin Stephen).

Not all change is so far-reaching, of course. On a more prosaic note, I'll soon become dean of the College of Communication at Boston University, my alma mater. I love *Scientific American* and am hugely grateful for the privilege of my 18 years here, with the past decade as its editor in chief (and first woman in the role since its founding in 1845). At the same time, I feel passionate about supporting young minds to help shape a better future for us all. In other words, I'll be pursuing essentially the same mission of learning and sharing that knowledge—but from a different vantage point. I'll remain a contributor to *Scientific American*. More next month. SA

Illustration by Nick Higgins


SMALLER.
FASTER.
STRONGER.
Meet the all new SimpliSafe.
It's smaller, faster, stronger than ever.
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And blanket it with protection.
More than easy to use—downright delightful.
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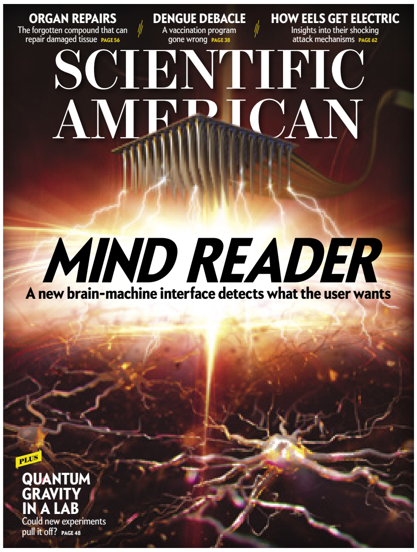

April 2019

THE BODY ELECTRIC

I enjoyed reading "Shock and Awe," Kenneth C. Catania's article on the electric eel. I'm curious about what was done to determine how the eel is protected from shocking itself. My guess is that the nervous system is somehow insulated or shielded.

BRUCE ROGERS *via e-mail*

CATANIA REPLIES: Rogers is in good company: lots of people are curious about why these eels don't shock themselves—including me. No one seems to know the details, but I think Rogers is on the right track. It seems inevitable there are paths of very low resistance, along with areas of electrical insulation, within the animals (we do know the latter exists around their electrocytes—the biological batteries). But I can say this much: the eels are just barely protecting themselves. Sometimes an eel that has curled itself to amplify the electrical effect on its prey ends up activating its own fins with each high-voltage volley. So the experience is at least mildly shocking, even to the eel.

HISTORY OF HIV TREATMENT

In "Outsmarting a Virus with Math," Steven Strogatz writes about the mathematics of HIV replication in humans (excerpted from his book *Infinite Powers*). He rightly praises immunologist Alan Perelson's calculus skills in dissecting clinical data from antiviral drug trials. But Martin Nowak and Sebastian Bonhoeffer, both then at the University of Oxford, working with virologist George Shaw and others, published analyses and conclusions in the same 1995 issue of *Nature* that were essentially identical to those in the report by Perelson and his colleague David Ho. Their contributions should not be overlooked.

Strogatz's statement that calculus "led to triple-combination therapy [for HIV]" also does not truly reflect the events of the time. The various mathematical calculations did not drive the development of multidrug combination therapy, although they did eventually guide how the drugs might best be used. The key factor in effectively suppressing HIV replication in vivo was the clinical development of protease inhibitors in the decade preceding the two 1995 papers.

The complex series of events that took place in the early 1990s, along with the contributions made by many people, have been thoroughly summarized in review articles. Yet contemporaneous coverage by the media has skewed public perceptions of what happened in the critical period when HIV infection transitioned from being almost always fatal to becoming a manageable, chronic disease. Strogatz's article reinforces the oversimplification of these important historical events.

JOHN P. MOORE *Weill Cornell Medicine and a member of* Scientific American*'s Board of Advisers*

"Inspiration for the Cavendish experiment came from Charles Mason and Jeremiah Dixon's work to settle the boundary between Pennsylvania and Maryland."

MARK ARNOLD *VIA E-MAIL*

MASON-DIXON GRAVITAS

"Quantum Gravity in the Lab," by Tim Folger, mentions the late 18th-century experiment in which British scientist Henry Cavendish measured the mass of the earth.

Inspiration for that experiment came from Charles Mason and Jeremiah Dixon's work to settle the boundary between Pennsylvania and Maryland. Cavendish found that the plumb bobs they were using for the survey were affected by the Allegheny Mountains.

MARK ARNOLD *via e-mail*

Folger states that one of the significant problems in doing quantum gravity experiments is "the need for large superpositions that last for seconds at a time and stay close enough together so that gravity can entangle them." Achieving that scenario, such as with one proposed experiment involving micron-wide diamond spheres, is difficult in a laboratory because the earth's gravity is enormous as compared with micron-sized objects. And if you let objects fall in a vacuum, as in the proposed diamond sphere experiment, the required length of the shaft grows as the square of the duration.

It seems like such experiments could be carried out in an almost zero-*g* environment such as the International Space Station or even in a small test satellite. Then the duration could easily run to a day or more, and the experiment could be done multiple times.

ROBERT H. BEEMAN *Coral Springs, Fla.*

Why does gravity have to exist at the quantum level?

BILL YANCEY *St. Augustine, Fla.*

FOLGER REPLIES: I had considered opening my article with an anecdote similar to Arnold's: In the early 1770s British scientist Nevil Maskelyne trekked to Schiehallion, a mountain in Scotland. Maskelyne wanted to see if the mountain's mass would deflect a plum bob and then use the result to estimate the earth's density. The result, as calculated from Maskelyne's data by mathematician Charles Hutton, was less than 20 percent off today's accepted value. Maskelyne's work shows how ingenious Cavendish was: he didn't need to use a mountain as a test mass—only the heavy spheres in his shed.

Regarding Beeman's suggestion: Physicists have proposed a space mission to test quantum superpositions, called MAQRO. But it hasn't been funded yet.

In answer to Yancey: If gravity doesn't exist at the quantum level, then why does

it exist at our level? Where gravity comes from—what its fundamental nature is—is what physicists are trying to find out.

TALKING ABOUT REGENERATION

In "A Shot at Regeneration," Kevin Strange and Viravuth Yin discuss the compound MSI-1436, which removes limits to the body's ability to regenerate cells by blocking the enzyme protein tyrosine phosphatase 1B (PTP1B). The article speaks of research being directed toward muscular dystrophy. I am wondering if application research on MSI-1436 would be appropriate for arthritis or crippling spinal cord injuries.

Chris Schofield *via e-mail*

STRANGE REPLIES: PTP1B is expressed in virtually all tissue and cell types, where it functions to inhibit receptor tyrosine kinase (RTK) signaling. RTKs activate multiple cellular processes that must work together in a coordinated manner for regeneration to occur. By inhibiting PTP1B, MSI-1436 thus enhances the activity of diverse, RTK-regulated cellular pathways required for tissue regeneration. Given this arrangement, we suspect MSI-1436 may have various disease indications whereby stimulating tissue repair and regeneration would be therapeutically valuable. But a great deal of very careful science must be carried out before we know for certain. Our work to date has been focused on heart and skeletal muscle injury.

BIPARTISAN CLIMATE ACTION

"Feverish Planet," by Tanya Lewis [Advances, March 2019], covers the direct health effects of global warming. Remedies are only briefly touched on: phasing out coal and carbon-based fuels in vehicles. But how do we do this?

For the U.S., there is a simple answer: pass the Energy Innovation and Carbon Dividend Act, which is already in the House of Representatives, with bipartisan support. The act taxes carbon emissions and returns the funds to every U.S. resident. Climate scientists and economists have endorsed this concept. And the "cash back" will appeal to voters and therefore to members of Congress.

Charles M. Bagley, Jr. *Seattle*

LETTERS TO THE EDITOR

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Gun Research Needs More Firepower

A new bill promises millions of dollars for lifesaving studies, and scientists should use it wisely

By the Editors

When bullets fired from a passing car sliced through the St. Louis night one Sunday in June, they hit two children, killing three-year-old Kenndei Powell and seriously wounding another little girl, age six. Police in the Missouri city were not immediately able to identify or find the shooter, and Powell joined the grim ranks of the 36,000 people killed by guns every year in the U.S., on average. An additional 100,000 are injured.

That adds up to 136,000 Americans harmed or killed annually by gun violence. Worse, the death side of this sad ledger is growing, according to the Centers for Disease Control and Prevention, in an upward trend that began in 2015. While mass shootings in Sutherland Springs, Tex., or Parkland, Fla., dominate headlines, people such as the St. Louis children, cut down singly or by twos or threes, make up the bulk of the victims. Guns are a clear and present danger in this country, where there are about 393 million civilian-owned firearms—more than enough to put one in the hands of every man, woman and child and amounting to the highest rate of gun ownership in the world by far.

The tremendous toll makes gun violence a huge public health problem. Yet unlike other pressing health threats, Americans have few ideas about the most effective prevention strategies because there has been almost no large-scale research on the issue.

All that could change this year. In an appropriations bill this spring, the U.S. House of Representatives included $50 million to be used for such studies by the CDC and the National Institutes of Health—the first time in decades that this kind of support has been given. If the U.S. Senate concurs and the bill becomes law, researchers need to jump at this opportunity.

Congress created the research gap in the first place, so it is right for Congress to fix it. In 1996, after a series of studies linked gun ownership to increased violence and crime and prompted an antiresearch campaign from the National Rifle Association of America (NRA), legislators inserted language into the CDC's budget bill that said no money could be used to "promote gun control." Congress also zeroed out the agency's budget for firearms research. The message was clear, and federally supported science in this area ground to a halt.

Since then, dozens of small-scale studies have been carried out—research comparing the effects of licensing laws in one county or state to laws in another, for instance. But none has had the power of large investigations that look at the effects of various kinds of interventions across the entire country and that involve tens of thousands of people. This is the kind of science that showed us the safety and health advantages of using seat belts, quitting smoking and reducing air pollution.

Experts have identified many areas where our firearms ignorance is killing us, gaps that scientists should now move to fill. For one, we cannot answer basic questions about people who commit gun violence—the percentage of them who legally possessed the guns they used, for example, or how those firearms were acquired. Studies of possession and acquisition patterns would give us a sober assessment of whether existing permitting, licensing or background-check laws are actually being used to disarm dangerous people—including those who intend to harm themselves through suicide.

We also need information on the best ways to stop underground gun markets, where weapons are often sold to people who cannot obtain them from a licensed gun shop. The way to get a solid answer is through research that traces guns in a large number of cities with regulations of varying strictness. There is also a crying need to evaluate violence-prevention policies and programs based on data about individuals who participate in large randomized controlled trials—the scientific gold standard for determining causes and effects.

None of this research infringes on Second Amendment rights to firearm ownership. It does, however, promote other, unalienable rights set out in our Declaration of Independence—"Life, Liberty and the pursuit of Happiness"—and helps to stop them from being taken away at gunpoint. SA

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Illustration by Brian Stauffer

Rob Jackson chairs Stanford University's Earth system science department and the Global Carbon Project.

Pep Canadell is a staff scientist at CSIRO in Australia and executive director of the Global Carbon Project.

A Crazy-Sounding Climate Fix

We should convert methane, a more powerful greenhouse gas, into CO_2

By Rob Jackson and Pep Canadell

Carbon dioxide in the atmosphere blew past 415 parts per million this past May. The last time levels were this high, two or three million years ago, the oceans rose tens of meters, something likely to happen again as Earth's ice melts over the next 1,000 years.

To replace bad news with action, we need hope—a vision for restoring the atmosphere. Think about the Endangered Species Act: it does not stop at saving plants and animals from extinction; it helps them recover. When we see gray whales breaching on their way to Alaska every spring, grizzly bears ambling across a Yellowstone meadow, bald eagles and peregrine falcons riding updrafts, we are celebrating a planet restored. Our goal for the atmosphere should be the same.

As leaders of the Global Carbon Project, we have spent our careers working to reduce greenhouse gas pollution. Today we are making what may at first seem like a counterintuitive proposal: we want to increase carbon dioxide emissions temporarily to cleanse the atmosphere of a much more powerful greenhouse gas.

Stick with us here.

We are *not* saying increasing CO_2 is a good thing in and of itself. The gas that concerns us is methane, which leaks from wells and pipelines; bubbles up when organic matter rots in landfills and rice paddies; emerges from the digestive systems of cattle and from the manure piles they leave behind; and more. The good news about methane is that it remains in the atmosphere for a far shorter time than CO_2 does. The bad news is that methane is vastly more efficient at trapping heat—more than *80 times* more, in the first 20 years after its release—which makes it, pound for pound, a bigger problem than carbon.

We want to remove methane from the air and then use porous materials called zeolites to turn it into carbon dioxide. Zeolites can trap copper, iron and other metals that can act as catalysts to replace methane's four hydrogen atoms with two oxygens. Because a methane molecule holds more energy than carbon dioxide, the reaction typically runs to completion if you can jump-start it. Furthermore, by releasing the carbon dioxide back into the air instead of capturing it, you make the process less expensive and lengthen the life of the zeolites.

Researchers around the world are already studying zeolites and other materials to convert methane to methanol, a valuable feedstock for the chemical industry. Making methanol is a halfway point in our reaction, tacking one oxygen atom onto each methane molecule. No one seems to have considered finishing the job by making carbon dioxide in the same way because carbon dioxide is not valuable like methanol. We should consider it now.

Another surprise about our proposal is that you could restore the atmosphere by removing "only" three billion metric tons of methane. Doing so would generate a few months' worth of industrial carbon dioxide emissions but eliminate up to one sixth of overall warming. That is a good trade by any measure.

What we propose will not be easy to accomplish. Methane is uncommon: whereas the atmosphere currently holds more than 400 molecules of carbon dioxide for every million molecules of air, methane accounts for only two or so out of a million. That makes pulling it from the atmosphere harder than keeping it from entering in the first place. We will need other things to work as well. To give companies, governments and individuals financial incentives to do this, there has to be a price on carbon or a policy mandate to pay for removing methane. We also need research on the large arrays needed to capture methane from air. And of course, we need to fix methane leaks and limit emissions from other human sources. But we cannot eliminate those emissions entirely, so we would have to continue removing methane from the atmosphere indefinitely.

Restoration of all the gases in the atmosphere to preindustrial levels may seem unlikely today, but we believe it will occur eventually. Such a goal provides a positive framework for change at a time when climate action is sorely needed. Stabilizing global warming at 1.5 or two degrees Celsius is not enough. We need the planet to recover. SA

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Illustration by Francesco Ciccolella

ADVANCES

Even fearsome great white sharks may steer clear of an area when orcas are close by.

RODRIGO FRISCIONE *Getty Images*

INSIDE

- Rivers, interrupted: how humans restrict water flow
- Babies know what friendly laughter sounds like
- UV lights keep birds at bay
- A faster method for imaging the brain

ANIMAL BEHAVIOR

Scaredy-Sharks

Even great whites may have something to fear

Salvador Jorgensen has spent more than 15 years studying great white sharks near California's coast. The senior research scientist from the Monterey Bay Aquarium and his team have attached tracking tags to 165 of the toothy predators, which routinely visit islands west of San Francisco and prey on elephant seals. But something odd happened one autumn: "In 2009, 17 of those tagged white sharks were simultaneously swimming around the Farallon Islands, when they abruptly departed. Not just one or two but all 17, in a matter of hours," Jorgensen recalls. "Normally the sharks hang around for weeks or months at a time." So why did they flee? Great white sharks are perhaps the most widely feared predators in the ocean, but it turns out they may have something to fear, too: orcas, also known as killer whales.

Jorgensen and his colleagues drew this conclusion in a recent study that combined their shark-tagging data with a nearly three-decade survey of wildlife abundance

around Southeast Farallon Island. Great whites have been seen abandoning this prime feeding area when killer whales come too close for comfort—even if the mammals are simply passing through for a few hours. And the sharks do not just disappear for a day or two—they stay away for the entire season. Researchers recorded a fourfold to sevenfold reduction in the number of elephant seals killed by great white sharks during years in which they were scared away. The findings were described in a study published in April in *Scientific Reports.*

Sharks have existed for at least 450 million years, whereas cetaceans (whales and dolphins) evolved just 50 million years ago. "For sharks to have survived and thrived in our ocean for so long, they have their bag of tricks," Jorgensen says. "One of those tricks is knowing when to fold." What was particularly surprising to him is that it can take almost a full year before the sharks feel comfortable returning. Some orcas specialize in eating salmon and other fish; others prefer pinnipeds (a group that includes seals and walruses), and a third type feasts on sharks. At least one orca has been observed killing and eating an adult white shark at the Farallon Islands, back in 1997. It is not clear whether the sharks avoid orcas out of fear of getting eaten or because they compete over the same seal prey. Either way, this extreme caution may simply be a prudent survival strategy for the sharks.

An orca (killer whale) feeding on herring.

GERARD SOURY *Getty Images*

"[Sharks] have their bag of tricks. One of those tricks is knowing when to fold."

—Salvador Jorgensen *Senior research scientist, Monterey Bay Aquarium*

The eastern Pacific great whites do have other hunting grounds. "There's a lot more feeding habitat for white sharks because the [pinniped] rookeries are expanding," thanks to intensive conservation efforts, says ecologist Chris Lowe of California State University, Long Beach, who was not involved with the new study. The sharks' willingness to give up good feeding opportunities at the Farallon Islands suggests that going elsewhere is preferable to sticking around and facing the risk—however slight—of becoming an orca's next meal.

Scientists are not sure how the sharks detect the orcas. The waters around the Farallon Islands are murky, and great whites have been seen escaping the area even when their adversaries were far beyond sight or hearing range. Jorgensen says the most likely explanation is that the sharks "were able to smell something in the water that alerted them." They could be sniffing out the orcas themselves or some chemical cue given off by another stressed-out shark after a run-in, he says. This idea has some support: Jorgensen and his colleagues monitored the movements of a group of great white sharks that were hundreds of kilometers away from the Farallon Islands when orcas arrived. Sometime after the orcas came and left, these sharks showed up. "But they just poked [around] and left almost immediately," he says. Perhaps they somehow sensed that the orcas were—or had recently been—in the area.

Ecologists often use the phrase "landscape of fear" to describe the way predators influence the movements and behaviors of their prey, resulting in a cascade of impacts on the ecosystem. For example, in one recent experiment, island-dwelling raccoons that heard dogs barking spent less time foraging on beaches and around tide pools. That led to increases in fish, worm and crab communities. And that in turn led to decreases in snails—easy prey for a growing crab population.

How the sharks' avoidance of orcas might likewise be affecting marine ecosystems remains a mystery. "We know very little about how these apex predators might interact with each other in the wild ocean," Jorgensen says. That is in part because white sharks, orcas and elephant seals are all still recovering from a century of mistreatment by humans. "The assumption is [these interactions] have been there historically—it's just that all these animals were basically eliminated from the ecosystem for more than 100 years," Lowe says. "There's no reason to believe that orcas weren't [hunting] both seals and sharks 300 or 400 years ago, before people really started exploiting those animals."

—Jason G. Goldman

IN THE NEWS

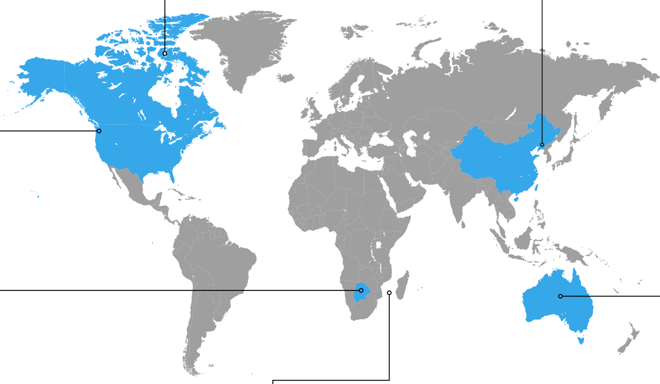
Quick Hits

By Tanya Lewis

CANADA
Billion-year-old fungi have been found in the Canadian Arctic with the use of radioactive dating techniques. Previously the oldest known fungus fossils dated back to fewer than 500 million years ago.

CHINA
Scientists unearthed a fossil in 2017, in the northeastern province of Liaoning, of a bat-winged dinosaur that lived 163 million years ago. The size of a small bird, *Ambopteryx longibrachium* had membranous wings very different from those of other feathered dinosaurs.

U.S.
Washington became the first state to allow human bodies to be composted. The process, which turns a body into soil over several weeks, is seen by some as a greener alternative to cremation or burial.



AUSTRALIA
In what some experts view as a setback for climate change action, Australians voted to retain Prime Minister Scott Morrison and his right-wing Liberal-National coalition. The opposition Labor party had pledged, if elected, to cut greenhouse gas emissions by 45 percent of 2005 levels by 2030.

BOTSWANA
The country's government lifted a five-year-old ban on hunting elephants for sport, after a committee found a "negative impact of the hunting suspension on livelihoods."

INDIAN OCEAN
Seafloor mapping revealed the largest underwater eruption ever observed, at a submarine volcano between continental Africa and Madagascar. Starting last year, it created a mound towering 800 meters above the seabed in just six months, researchers say.

For more details, visit
www.ScientificAmerican.com/aug2019/advances

HYDROLOGY

Damming Evidence

Human infrastructure restricts many of the world's longest rivers

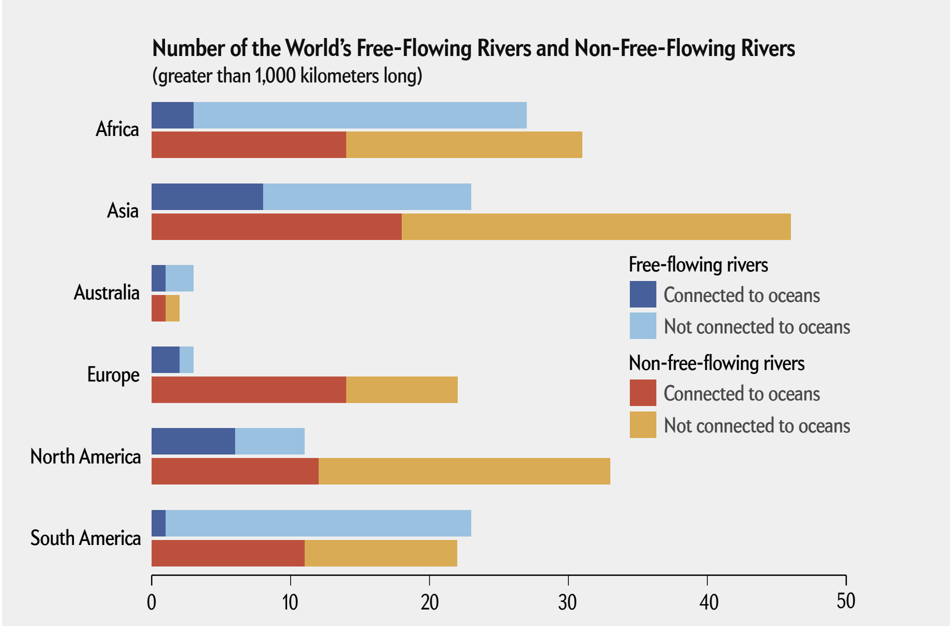
Rivers are terrestrial arteries for the nutrients, sediment and freshwater that sustain healthy, diverse ecosystems. Their influence extends in multiple dimensions—not only along their length but belowground to aquifers and periodically into nearby floodplains.

They also provide vital services for people by fertilizing agricultural land and feeding key fisheries and by acting as transportation corridors. But in efforts to ease ship passage, protect communities from flooding, and siphon off water for drinking and irrigation, humans have increasingly constrained and fractured these crucial waterways. "We try to tame rivers as much as possible," says Günther Grill, a hydrologist at McGill University.

In new research published in May in *Nature,* Grill and his colleagues analyzed the impediments to 12 million total kilometers of rivers around the world. The team developed an index that evaluates six aspects of connectivity—from physical fragmentation (by dams, for example) to flow regulation (by dams or levees) to water consumption—along a river's various dimensions. Rivers whose indices meet a certain threshold for being largely able to follow their natural patterns were considered free-flowing.

The researchers found that among rivers longer than 1,000 kilometers (which tend to be some of those most important to human activities), only 37 percent are unimpeded along their entire lengths (*graphic*). Most of these big unhindered rivers are in areas with a minimal human presence, including the Amazon and Congo basins and the Arctic. Conversely, most rivers shorter than 100 kilometers appeared to flow freely—but the data on them are less comprehensive, and some barriers might have been missed. Only 23 percent of the subset of the longest rivers that connect to the ocean are uninterrupted. For the rest, human infrastructure is starving estuaries and deltas (such as the Mississippi Delta) of key nutrients. The world's estimated 2.8 million dams are the main culprit, controlling water flow and trapping sediment.

The new research could be used to bet-



Graphics by Melissa Thomas Baum, Buckyball Design

SOURCE: "MAPPING THE WORLD'S FREE-FLOWING RIVERS," BY G. GRILL ET AL., IN *NATURE,* VOL. 569; MAY 9, 2019

DEVELOPMENTAL PSYCHOLOGY

Friendly Laughter

Five-month-olds can tell chuckles of friends and strangers apart

Most people can share a laugh with a total stranger. But there are subtle—and detectable—differences in our guffaws with friends.

Greg Bryant, a cognitive scientist at the University of California, Los Angeles, and his colleagues previously found that adults from 24 societies around the world can distinguish simultaneous "co-laughter" between friends from that between strangers. The findings suggested that this ability may be universally used to help read social interactions. So the researchers wondered: Can babies distinguish such laughter, too?

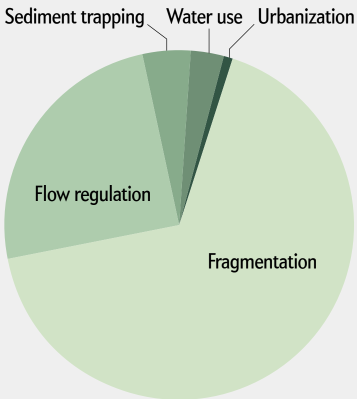
Bryant and his fellow researcher Athena Vouloumanos, a developmental psychologist at New York University, played recordings of co-laughter between pairs of either friends or strangers to 24 five-month-old infants in New York City. The babies listened longer to the laughs shared between buddies—suggesting they could tell the two types apart, according to a study published in March in *Scientific Reports.*

AARTI KALYANI *Getty Images*

The researchers then showed the babies short videos of two people acting either like friends or strangers and paired those with the audio recordings. The babies stared for longer at clips paired with a mismatched recording—for example, if they saw friends interacting but heard strangers laughing.

"There's something about co-laughter that is giving information to even a five-month-old about the social relationship between the individuals," Bryant says. Exactly what components of laughter the infants are detecting remains to be seen, but prior work by Bryant's team provides hints. Laughs between friends tend to include greater fluctuations in pitch and intensity, for example.

Causes of Lost River Connectivity

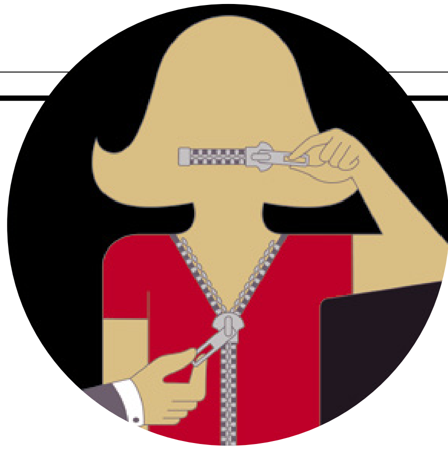


The main causes of river interruption (lost connectivity) are fragmentation by impediments such as dams; changes to the strength and timing of water flow by, for example, dams or levees; and sediment trapping behind structures such as dams.

ter understand how proposed dams, levees and other such projects might impact river connectivity, as well as where to remove these fixtures to best restore natural flow. It could also help inform our approach to rivers as the climate changes, says Anne Jefferson, a hydrologist at Kent State University, who was not involved in the work. Existing infrastructure, she says, "has essentially been built to a past climate that we are not in anymore and are increasingly moving away from." —*Andrea Thompson*

Such characteristics also distinguish spontaneous laughs from fake ones. Many scientists think unprompted laughter most likely evolved from play vocalizations, which are also produced by nonhuman primates, rodents and other mammals. Fake laughter probably emerged later in humans, along with the ability to produce a wide range of speech sounds. The researchers suggest that we may be sensitive to spontaneous laughter during development because of its long evolutionary history.

"It's really cool to see how early infants are distinguishing between different forms of laughter," says Adrienne Wood, a psychologist at the University of Virginia, who was not involved in the study. "Almost every waking moment is a social interaction for [babies], so it makes sense that they are becoming very attuned to their social worlds." —*Diana Kwon*



GENDER EQUALITY

The Price of Speaking Up

Women still face retaliation for reporting workplace sexual harassment

Despite the gains of the #MeToo movement, women still hesitate to file work-related sexual harassment complaints for fear of repercussions. Now a study suggests people may indeed penalize female employees for self-reporting such experiences.

Chloe Grace Hart, a doctoral candidate in sociology at Stanford University, ran an experiment five times between late 2017 and early 2018, each time involving about 200 people who identified as male, female or another gender. Hart asked participants to imagine they were the manager of a company considering a fictional female sales associate, named Sarah, for promotion. Each participant was assigned to one of five groups. Four groups received an employee file that contained information about harassment—either sexual or nonsexual—that Sarah had experienced from a male co-worker. Each incident was either self-reported or reported by a colleague. A fifth group received the same file without any record of harassment.

Hart then asked the participants to rate how inclined they were to recommend Sarah for promotion on a scale from 1 ("extremely unlikely") to 7 ("extremely likely"). Hart found that on average participants were 0.37 points less likely to recommend Sarah for promotion if she self-reported her sexual harassment than if her colleague reported it. They were also 0.16 points less likely to recommend her than if she self-reported nonsexual harassment. Finally, the participants were 0.11 points less likely to recommend her than if her employment file made no mention of any harassment. The study was published online in May in *Gender & Society.*

It serves as a reminder that barriers to reporting sexual harassment "have not gone away," says Nancy Hauserman, professor emeritus of management and entrepreneurship at the University of Iowa, who was not involved in the study. "I think it is important to keep sexual harassment in the scholarly gaze."

The findings are bolstered by a 2018 report that analyzed 46,210 Title VII sexual harassment discrimination charges filed with the U.S. Equal Employment Opportunity Commission and state Fair Employment Practices Agencies. The report found that 65 percent of women who filed such charges between 2012 and 2016 said they lost their jobs after making their complaints.

But Hart's research did find a silver lining. The participants in her most recent study group were significantly more likely to promote Sarah when she self-reported sexual harassment as compared with those in the earliest group—which may be linked to the momentum of the #MeToo movement, Hart says. "I don't think that the study indicates that the problem is solved," she says. "But if nothing else, it indicates that we are able to shift our social perceptions of people in a position of experiencing sexual harassment." *—Agata Boxe*

ECOLOGY TECH

Flight Lights

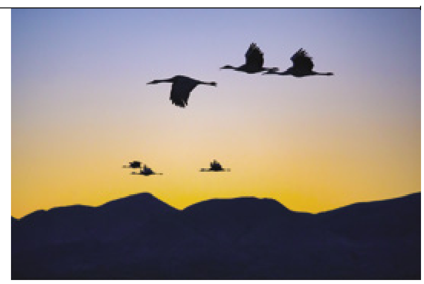
Ultraviolet illumination helps birds avoid power lines

Human activities are killing wildlife at unprecedented rates, with causes ranging from environmental pollution to the built environment. For some bird species, nighttime collisions with power lines are driving substantial population declines. But now scientists have come up with a clever way to make the cables easier for birds to spot, without being unsightly to humans.

Industry and U.S. Fish & Wildlife Service guidelines recommend that utility companies mark their power lines with plastic attachments to increase visibility, but birds are still dying. Biologists reported that 300 Sandhill cranes perished in one month in 2009 from collisions with marked lines at the Rowe Sanctuary in Nebraska, where the cranes stop over during their annual spring migration. "We need forward-thinking methods to protect not only large birds that are inherently at greater risk from power lines but also millions of smaller migratory birds," says Anne Lacy of the International Crane Foundation.

Half of all avian species can see ultraviolet light. So James Dwyer, a wildlife biologist at utility consulting firm EDM International in Fort Collins, Colo., had the idea of using near-visible UV light to illuminate power lines. EDM's engineering team and the Dawson Public Power District developed such light systems and installed them on a tower supporting a power line at Rowe Sanctuary. Over a 38-night period, crane collisions decreased by 98 percent when the lights were on, the researchers reported in a study published online in May in *Ornithological Applications*.

Richard Loughery, director of environmental activities at the Edison Electric Institute, who was not involved in the project, says the new UV system adds an important tool for use in hotspots where endangered bird species nest and feed.

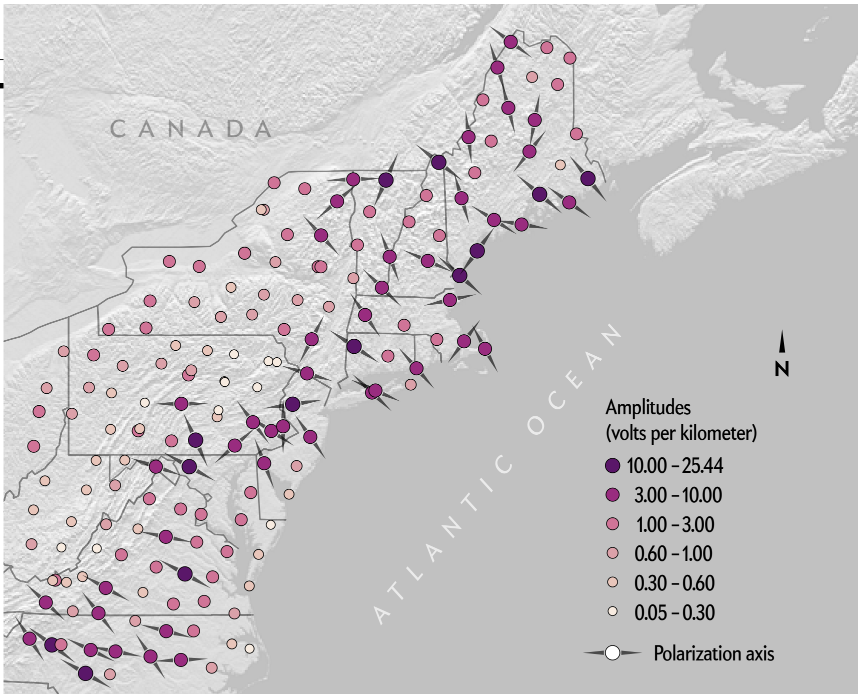


RANDY GREEN *Alamy*

The researchers did not observe any negative impacts on other species: insects did not swarm toward the lights, nor did bats or nighthawks do so in pursuit of a meal. And Dwyer says birds are unlikely to confuse such near-ground UV illumination with natural cues such as starlight.

"I don't want utilities to build lines wherever they want because there's a new tool," says biologist Robert Harms of the U.S. Fish & Wildlife Service, who was not involved in the work. But for existing lines, he says, the UV system could be "absolutely amazing." *—Rachel Berkowitz*

Illustration by Thomas Fuchs



Magnetic storms induce high geoelectric fields in the underlying rock. The fields' amplitude and direction (polarization axis) can help inform utility companies about where power grid interference and damage might occur.

GEOPHYSICS

Stormy Space Weather

New map reveals the risk of blackouts from geomagnetic storms

A massive geomagnetic storm stunned Quebec in 1989, triggering blackouts across the province. The storm—a disturbance in Earth's magnetic field caused by a blast of charged particles from the sun—created electric currents that raced through underground power lines and overloaded the grid. Now new research suggests the composition of rock in specific regions could influence the risks from such "superstorms," which occur about once a century.

Geomagnetic storms induce a local electric field in the ground, producing current. Geophysicist Jeffrey Love of the U.S. Geological Survey and his colleagues used sensors throughout the U.S. Northeast to determine the maximum electric field such a storm could create. By combining these measurements with storm data, they produced a map identifying areas with a higher chance of blackouts (*graphic*). The results were published in March in *Space Weather.*

They found that the type of rock in an area influences the strength and direction of the electric field a geomagnetic storm can create. If the rock is a good conductor, the resulting current flows easily through the ground. But if the rock is resistive, the current may travel through power lines instead, possibly threatening the grid.

Fields greater than one volt per kilometer can interfere with a grid's operation, and much stronger fields can cause blackouts. The team found that the most hazardous area is in Virginia, where fields can be as strong as 25.44 volts per kilometer during intense magnetic storms. Major cities, including New York, Boston and Washington, D.C., can also experience relatively powerful fields. These areas have metamorphic rock (which has been changed by intense heat or pressure) and igneous rock (lava that has cooled and solidified); both are electrically resistive. Other areas, such as the northwestern Appalachians, have a lot of conductive sedimentary rock, which should have lower geoelectric hazards.

The team says the findings could help communities prepare for future storms, and similar studies are planned elsewhere. "There's a lot of work going on in our industry, with help from the scientific community in various parts of the world," says David Boteler, a research scientist at Natural Resources Canada, who was not involved in the study. He says power grids are already being designed to handle the next "100-year storm." *—Jonathan O'Callaghan*

SOURCE: "EXTREME-VALUE GEOELECTRIC AMPLITUDE AND POLARIZATION ACROSS THE NORTHEAST UNITED STATES," BY JEFFREY J. LOVE ET AL., IN *SPACE WEATHER,* VOL. 17, NO. 3; MARCH 2019

Graphic by Pitch Interactive

HEALTH TECH

Save Your Breath

Device that automates breathing bags could save lives

Automated bag valve mask device

When someone has serious trouble breathing, care providers often use a mask with an attached bag—which has to be manually squeezed—to pump air into the lungs until a patient can be put on an automatic ventilator.

In many highly developed regions, this "manual bag valve mask" is usually just a short-term, stopgap measure. But in places with limited medical staff and few—if any—ventilators, "it's up to you to keep your family members alive" by squeezing the bag for much longer periods, says Rohith Malya, director of emergency medicine at Thailand's Kwai River Christian Hospital. The facility treats many refugees from the Rohingya crisis in Myanmar (formerly Burma), just across the nearby border, Malya says. He sees people with pneumonia and other treatable illnesses die because family members are too exhausted to continue "bagging." But now he has partnered with a design team of Rice University undergraduates to create a device that automatically compresses the bag.

The team hopes the $117 machine, called the AutoBVM (short for *automated bag valve mask*), could be used in disaster settings and emergency transport until a ventilator becomes available or even as an alternative to one. The AutoBVM—which plugs into a standard wall outlet—consists of two triangular plastic "pushers" attached to a geared frame and powered by a motor. Creating a battery-powered version is a priority for future work, says Carolina De Santiago, a bioengineer on the Rice team.

A prototype of the AutoBVM ran for up to 11 hours in laboratory tests before overheating, on settings typically used for adult patients, De Santiago says. It has not yet been tested in people. Malya plans to work with a team of graduate students to create another version with a different motor that could increase its operating time. He also hopes to improve the device's seals and filtration system to make it suitable for disaster situations and hot, dusty field environments. He plans to test it in patients at Kwai River Christian Hospital next year.

Many people worldwide lack adequate access to ventilators, which can cost as much as $100,000, says Abdullah Saleh, who directs the University of Alberta's Office of Global Surgery and was not involved in the work. Bag valve masks are "ubiquitous across even remote and low-resource areas," he notes. "Automating a way to deliver air through them could address a real need." —*Rachel Crowell*

JEFF FITLOW *Rice University*

NEUROSCIENCE TECH

Magnetic Vibes

Faster imaging method makes brain scans more responsive

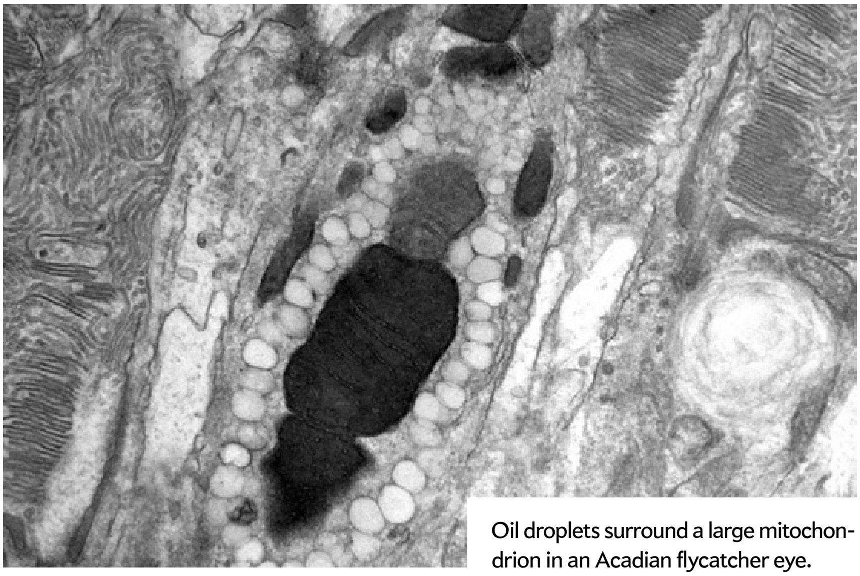
The invention of functional magnetic resonance imaging (fMRI) nearly 30 years ago revolutionized neuroscience by letting researchers visualize brain activity associated with behavior. The technology is spatially precise, but its main limitation is speed; fMRI measures blood oxygen level changes, which take about six seconds—a snail's pace as compared with brain signals themselves. Other methods, such as electroencephalography (EEG), are fast but imprecise and cannot detect deeper brain signals.

Now physicists Samuel Patz of Harvard Medical School and Ralph Sinkus of King's College London and their colleagues have adapted existing tissue-imaging technology to overcome fMRI's speed limitation and tested it in mouse brains. Known as functional MR elastography (fMRE), it involves sending vibrations through tissue and using magnetic resonance to measure their speed. They move faster through stiffer material, producing "elastograms," or maps of tissue rigidity, that may correspond to brain activity. This is the first time fMRE has been used to measure such activity, the researchers say.

In a study published in April in *Science Advances,* Patz, Sinkus and their colleagues applied mild shocks to mice's hind limbs to induce signals in the brain, turning the stimulation on and off at various rates. Comparing fMRE scans taken during on and off periods allowed them to produce images showing which areas changed in stiffness as a result of the stimulation. The researchers think certain brain cells soften when an associated neuron fires, meaning stiffness changes would correspond to neural activity. By varying the stimulation switching rate, they demonstrated that fMRE can detect brain signals at least every 100 milliseconds.

The team is currently testing the method in humans. "We've got very nice data now showing that it works," Patz says. If everything pans out, the technique could represent an important advance in brain imaging. "We'd be in a much better position to conduct 'effective connectivity' analyses, where you try to figure out how information flows in brain circuits," says neuroscientist Jonathan Roiser of University College London, who was not involved in the work.

Patz's colleague Alexandra Golby, a neurosurgeon, hopes to use fMRE to identify critical areas to avoid during brain surgeries. In about 30 percent of patients with tumors, the mass blocks the changes in blood oxygenation that fMRI measures, Patz says—"so [Golby] wanted a method that works differently." The technique might ultimately help researchers understand and diagnose brain disorders involving circuit dysfunctions, such as schizophrenia. "It could reveal a lot of information that might be valuable for disease diagnosis [and] progression," Patz says. —*Simon Makin*



Oil droplets surround a large mitochondrion in an Acadian flycatcher eye.

FROM "A NOVEL CELLULAR STRUCTURE IN THE PHOTORECEPTORS OF INSECTIVOROUS BIRDS," BY LUKE P. TYRRELL ET AL. PREPRINT POSTED AT BIORXIV ON FEBRUARY 15, 2019

EVOLUTION

Eye of the Flycatcher

Structures in the birds' retinas may be key to their motion-tracking abilities

Rather than chasing their prey in flight like many other birds, Acadian flycatchers prefer to ambush insects from a perch. Researchers recently discovered an odd structure in the birds' eyes that may help them track a moving insect while sitting still themselves.

Visual ecologist Luke P. Tyrrell of the State University of New York Plattsburgh and his colleagues found that the photoreceptors, or light-sensitive cells, at the center of the flycatcher's retina contain extra-large mitochondria. These components (which produce energy for cells) are each surrounded by hundreds of oil droplets, forming an elongated blob. Scientists have previously observed large mitochondria in the eyes of zebra fish and tree shrews, and many birds' photoreceptors contain oil droplets for modifying light. But biologists had never before observed an optical arrangement like the flycatcher's.

The structure "comes as a bit of a shock," says Joseph Corbo, a visual scientist at Washington University in St. Louis, who was not involved in the study. "It's just out of the blue. There's nothing in any species, bird or otherwise, that has this distinctive sort of rocket-ship shape."

Some other birds' photoreceptors contain oil droplets—but usually just a single large one, Tyrrell notes. In the flycatcher's case, "there are hundreds or thousands of them, and they're super tiny and packed around these mitochondria, which is also very abnormal," he says. "Almost like packing peanuts." Tyrrell posted the study on the preprint server bioRxiv in February and has since submitted it to peer-reviewed journals.

The oil droplets filter out shorter wavelengths of light, allowing only longer ones (oranges and reds) to pass through. The researchers think these wavelengths might prompt certain enzymes in the mitochondria to produce more energy for the retinal cell, as researchers have previously demonstrated with mice, Tyrrell says. "That energy could be used for the cell to fire more times per second," he explains. "It's like a higher frame rate on a camera." He says this might allow the flycatcher to track fast-moving prey more effectively.

Corbo urges caution in speculating about the structure's energy-boosting role, noting that if such a specialized adaptation exists for that reason, it would likely be more widespread among bird species. He is not sure what function it might have beyond filtering and funneling the different wavelengths of light for some other purpose. "I would guess this is [just] a kind of fancy, modified oil droplet," he says. Tyrrell is now investigating whether birds closely related to Acadian flycatchers have similar structures. *—Jim Daley*

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.*

If You Give a Baby a Peanut

Feeding infants allergenic foods may be the key to preventing allergies

By Claudia Wallis

Few things are more subject to change and passing fancies than dietary advice. And that can be true even when the advice comes from trusted health authorities. A dozen years ago the standard recommendation to new parents worried about their child developing an allergy to peanuts, eggs or other common dietary allergens was to avoid those items like the plague until the child was two or three years old. But in 2008 the American Academy of Pediatrics (AAP) dropped that guidance, after studies showed it did not help. And in its latest report, issued in April, the AAP completed the reversal—at least where peanuts are concerned. It recommended that high-risk children (those with severe eczema or an allergy to eggs) be systematically fed "infant-safe" peanut products as early as four to six months of age to prevent this common and sometimes life-threatening allergy. Children with mild or moderate eczema should receive them at around six months.

These are not whimsical changes. They match advice from a federal panel of experts and reflect the results of large randomized studies—with the inevitable cute acronyms. One called LEAP (Learning Early About Peanut Allergy), published in 2015, found that feeding peanut products to high-risk infants between four and 11 months old led to an 81 percent lower rate of peanut allergy at age five, compared with similar babies who were not given that early exposure. Another trial, known as EAT (Enquiring About Tolerance), published in 2016, found that after parents carefully followed a protocol to begin feeding peanut protein, eggs and four other allergenic foods to healthy, breastfed infants between three and six months of age, the babies had a 67 percent lower prevalence of food allergies at age three than did a control group. The results were strongest for peanuts, where the allergy rate fell to zero, compared with 2.5 percent in the control group. Egg allergies also fell, but the AAP is waiting for more data on eggs, says Scott Sicherer, a professor of pediatrics, allergy and immunology at the Icahn School of Medicine at Mount Sinai and an author of the April report. "We don't want to tell people to do something where there isn't really good evidence."

How food allergies develop and why they have become so commonplace remain dynamic areas of research. Both the allergies and eczema (a major risk factor) have been on the rise. A 2010 study by Sicherer and his colleagues found that the prevalence of childhood allergies more than tripled between 1997 and 2008, jumping from 0.6 to 2.1 percent.

A leading theory about how these allergies develop and the role of eczema has been proposed by Gideon Lack, a professor of pediatric allergy at King's College London and senior author of both LEAP and EAT. The "dual allergen exposure hypothesis" holds that we become tolerant to foods by introducing them orally to the gut immune system. In contrast, if a child's first exposure is through food molecules that enter through eczema-damaged skin, those molecules can instigate an allergic response. Research with mice strongly supports this idea, whereas in humans the evidence is more circumstantial. Lack points out that peanut allergy is more prevalent in countries where peanuts or peanut butter is popular and widespread in the environment, mustard seed allergy is common in mustard-loving France and buckwheat allergy occurs in soba-loving Japan. "Parents are eating these foods, then touching or kissing their babies," Lack suggests, "and the molecules penetrate through the skin."

A modern emphasis on hygiene may also contribute, Lack notes: "We bathe infants and shower young children all the time, very often once a day or more, which you could argue breaks down the skin barrier." Researchers are examining whether applying barrier creams such as CeraVe can help stave off food allergies.

Eight foods account for 90 percent of food allergies: cow's milk, eggs, fish, shellfish, tree nuts, peanuts, wheat and soybeans. Some scientists believe this is so because these foods contain proteins that are unusually stable to digestion, heating and changes in pH and are therefore more likely to cause an immune response.

Early dietary exposure is now the confirmed preventive strategy for peanuts and, pending more research, perhaps the other foods, although this is more easily said than done. In EAT, parents had to get their babies to swallow at least four grams per week of each of the allergenic edibles, and many found it to be challenging. As Lack observes, "It's just not part of our culture to feed solids to very young babies." SA

Illustration by Celia Krampien

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.

The Big Slowdown

Major technological shifts are fewer and farther between than they once were

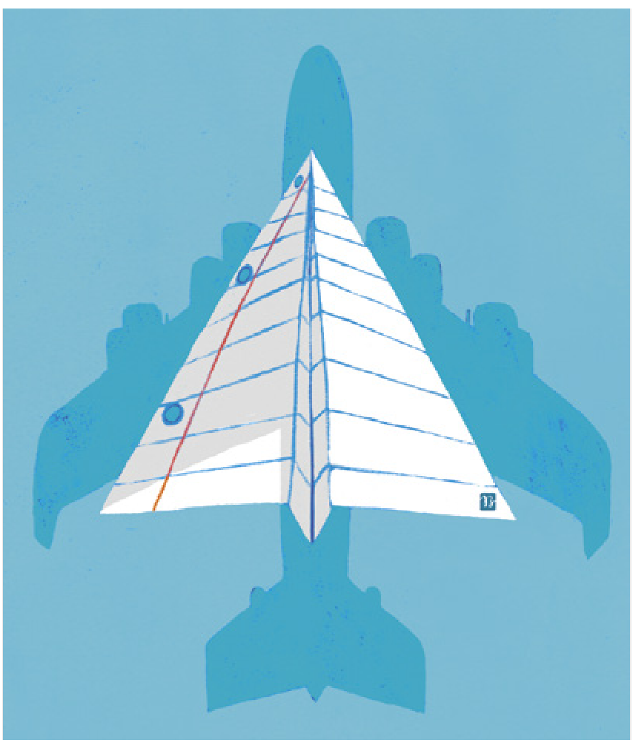
By Wade Roush

On June 22, 1927, Charles Lindbergh flew into Dayton, Ohio, for dinner at Orville Wright's house. It had been just a month since the young aviator's first ever solo nonstop crossing of the Atlantic, and he felt he ought to pay his respects to the celebrated pioneer of flight.

Forty-two years later, on July 16, 1969, *Apollo 11* astronaut Neil Armstrong was allowed to bring a personal guest to the Kennedy Space Center to witness the launch of NASA's towering Saturn V rocket. Armstrong invited his hero, Charles Lindbergh.

That's how fast technology advanced in the 20th century. One man, Lindbergh, could be the living link between the pilot of the first powered flight and the commander of the first mission to another world.

In our century, for better or worse, progress isn't what it used to be. Northwestern University economist Robert Gordon argues that by 1970, all the key technologies of modern life were in place: sanitation, electricity, mechanized agriculture, highways, air travel, telecommunications, and the like. After that, innovation and economic growth simply couldn't keep going at the breakneck pace set over the preceding 100 years—a period Gordon calls "the special century."



Since 1970 the only notable outlier has been the exponential increase in computing power, which has trickled down to consumers in the form of the Internet and our ever present mobile devices. But in most other ways, Gordon argues, the lives of people in developed nations look and feel the same in 2019 as they did in 1979 or 1989.

This is good in one small way, though bad in most of the ways that count. Rapid and incessant change can be disorienting, and when things evolve at a more measured pace, people and institutions do have more time to breathe and adapt. But speaking as a Gen Xer, deceleration isn't what I was taught to expect. And in many areas of technology, the forward movement today feels tragically slow, even nonexistent.

Consider consumer robotics. There's enormous potential for robots to help us with housework, education, entertainment and medical care. But home robotics companies seem to keep folding: social robot maker Jibo closed in March after raising almost $73 million in venture capital, and in April robot toy maker Anki shut down after raising at least $182 million. The only commercially successful home robot, iRobot's Roomba vacuum cleaner, hit the market in 2002.

Or consider access to space. In 2007 the XPRIZE Foundation offered $30 million in prizes, funded by Google, to commercial teams that would compete to land a robotic rover on the moon. When it became obvious that no team would be able to meet the original deadline, the foundation extended the contest four times and finally pulled the plug in 2018. Although five teams had built rovers, all had trouble raising enough money to buy launch contracts. Companies such as Seattle-based Spaceflight Industries are pioneering low-cost ride sharing into space for very small satellites, but the cost per kilogram for getting large satellites and probes into orbit is still, pardon the pun, sky-high. (Israel-based SpaceIL got its Beresheet craft into lunar orbit in April, well after the competition's cancellation, but it crashed after an error during descent.)

Our century's one signature technology achievement is the iPhone. And at this point, we've had smartphones in our pockets long enough to begin to appreciate their dangers. Meanwhile the list of potentially world-changing technologies that get lots of press ink but remain stubbornly in the prototype phase is very long. Self-driving cars, flying cars, augmented-reality glasses, gene therapy, nuclear fusion. Need I continue?

Granted, these are all hard problems. But historically, solving the really big problems—rural electrification, for example—has required sustained, large-scale investments, often with private markets and taxpayers splitting the burden. In this century, we urgently need to undo some of the consequences of the last great boom by developing affordable zero- and negative-emissions technologies. That's another hard problem—and to solve it, we'll need to recapture some of what made the "special century" so special. SA

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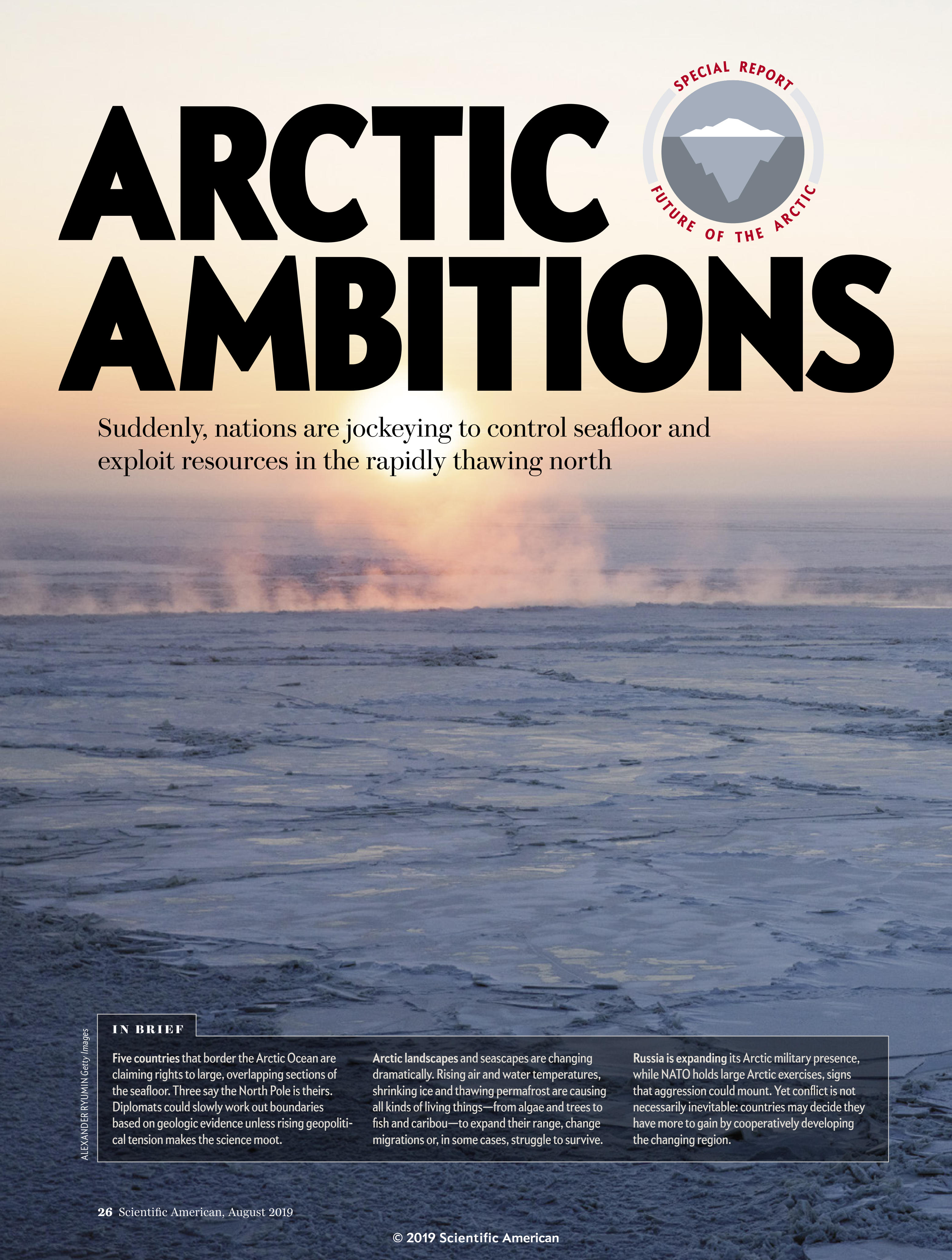
Illustration by Jay Bendt



SPECIAL REPORT
FUTURE OF THE ARCTIC

ARCTIC AMBITIONS

Suddenly, nations are jockeying to control seafloor and exploit resources in the rapidly thawing north

ALEXANDER RYUMIN *Getty Images*

IN BRIEF

Five countries that border the Arctic Ocean are claiming rights to large, overlapping sections of the seafloor. Three say the North Pole is theirs. Diplomats could slowly work out boundaries based on geologic evidence unless rising geopolitical tension makes the science moot.

Arctic landscapes and seascapes are changing dramatically. Rising air and water temperatures, shrinking ice and thawing permafrost are causing all kinds of living things—from algae and trees to fish and caribou—to expand their range, change migrations or, in some cases, struggle to survive.

Russia is expanding its Arctic military presence, while NATO holds large Arctic exercises, signs that aggression could mount. Yet conflict is not necessarily inevitable: countries may decide they have more to gain by cooperatively developing the changing region.

DOUBLE TIME: The Russian icebreaker *50 Let Pobedy* clears a navigation lane. It is also used to carry tourists to newly thawing destinations. Both activities are on the rise as nations hasten Arctic development.


BERING
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NORWEGIAN

SPECIAL REPORT
FUTURE OF THE ARCTIC

DIVIDE OR CONQUER

Five nations are asserting rights to vast, overlapping portions of the Arctic Ocean seafloor

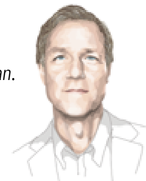
By Mark Fischetti

Illustration by Peter Horvath

ON AUGUST 2, 2007, THREE RUSSIAN EXPLORERS CRAMMED INSIDE a submersible underneath thick sea ice at the North Pole descended 4,300 meters to the dark seafloor below. They extended a robot arm from the pod and planted a titanium national flag in the sediment there. After surfacing to the supporting nuclear-powered icebreaker, expedition leader and parliament member Artur Chilingarov told an onboard reporter for the Russian news agency Itar-Tass, "If 100 or 1,000 years from now someone goes down to where we were, they will see the Russian flag." President Vladimir Putin phoned the ship, expressing his congratulations.

Canadian geophysicist David Mosher wasn't impressed when he heard the news at his Bedford Institute of Oceanography office in Nova Scotia. He glanced at a small cylinder of dried, dense mud about the size of a bratwurst lying on a plastic tray on his bookshelf. It was a short piece of a 13-meter-long sediment core extracted from the same North Pole seabed—in 1991, when Mosher was a Ph.D.

Mark Fischetti is a senior editor at *Scientific American.* He covers all aspects of sustainability.



PRECEDING PAGES: GETTY IMAGES *(ice)*; THIS PAGE: KIRILL KUDRYAVTSEV *Getty Images*

student at Dalhousie University in Halifax. He had ventured there with 40 international scientists on two research icebreakers from Germany and Sweden. The scientists sent a piston corer to the seafloor, drilled down and extracted the sample from the heavy sediment.

"We didn't plant a flag," Mosher quips. "We made the hole for the Russians to plant one."

Setting the flag was a political stunt done mostly to boost the morale of Russians, who were suffering through a deep recession. But the bald declaration for the North Pole made clear to the other four Arctic coastal states that the time had come to formally claim any portion of the Arctic Ocean seabed they felt they had rights to.

One of those countries was on top of it; a year earlier Norway had submitted geologic data and maps outlining three patches of seabed to the international Commission on the Limits of the Continental Shelf (CLCS), which reviews such claims and determines whether science has been applied properly. The Kingdom of Denmark, which includes Greenland, took several more years to amass a huge amount of data and submitted a pile of files in 2014, asserting it had rights to a large section of the Arctic Ocean seafloor covering 900,000 square kilometers. Russia handed in its paperwork in 2015, charting 1.3 million square kilometers—twice the size of Texas—which overlapped more than half of Denmark's outline.

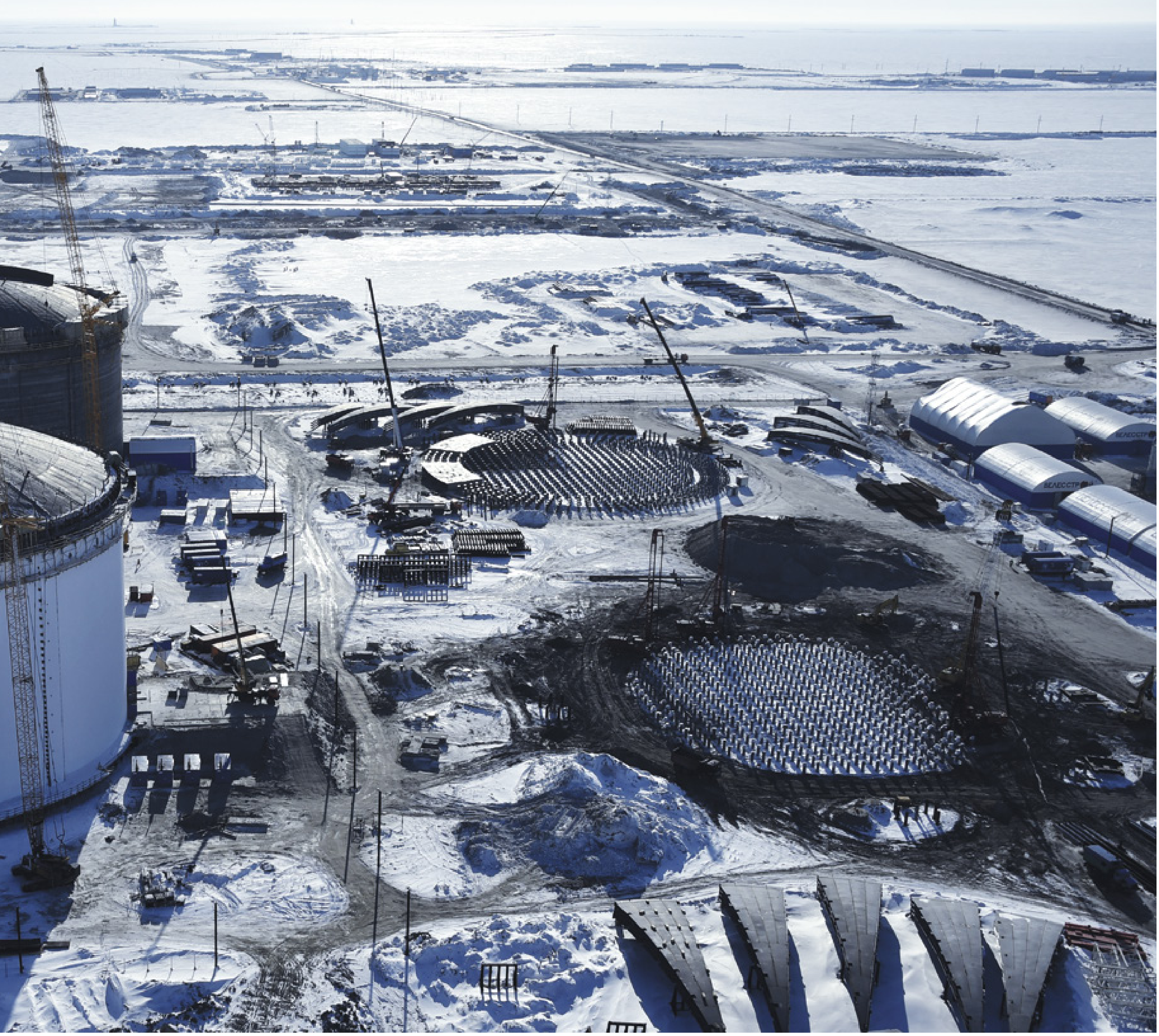
This May a Canadian team led by Mosher, who is now a geophysics professor at the University of New Hampshire, submitted 2,100 pages of text, coordinates and measurements from multibeam sonars, gravitometers and core samples to the CLCS, stating that 1.1 million square kilometers of the seabed are part of Canada. The expanse greatly overlaps the Russian and Danish claims. The U.S., the fifth state with an Arctic coastline (along Alaska), will not present its pitch until at least 2022, but its plot is expected to overlie Canada's.

For most of modern history, countries viewed the Arctic Ocean as a largely useless slab of ice. But then it started to melt, exposing opportunities. A 2008 study by the U.S. Geological Survey concluded that thick sediment in the Arctic could hold 30 percent of the world's yet to be discovered natural gas and 13 percent of its oil. Valuable iron and rare earth minerals could be waiting, too. Retreating sea ice meant shipping lanes could be opened and exploited. Seeing a bountiful future, each of the five countries became eager to secure as much territory as possible. "You never know what will happen," says Flemming Getreuer Christiansen, deputy director of the Geological Survey of Denmark and Greenland.

The CLCS could take years to work through the submissions. It moves slowly, in part because it has more than 80 cases for seafloor worldwide, from Nicaragua to Ghana to Vietnam. It is not expected to finish evaluating Denmark's or Russia's tender for several years. The Canadian review will conclude years after that. The commission does not adjudicate overlapping claims either, so once all the reviews are done countries will have to start diplomatic proceedings, putting their CLCS determinations on the table and negotiating boundary lines, another step that could take a long time.

The mapping and submission process has been civil, even cooperative, firmly grounded in geology. But the glacial pace of the process is problematic. While the scientists methodically work through the various countries' claims, Putin is expanding military bases across Russia's long Arctic shoreline. His speeches and actions have made it clear that he thinks his nation should direct the polar region. Meanwhile NATO countries are reinforcing northern militaries, wary that Russia could take over seabed the way it annexed Crimea in 2014. China is sending ships up north to signal that it, too, wants a role.

The U.S. has historically paid little attention to the region, but now it is throwing its weight around. In May, Secretary of State Mike Pompeo arrived at an Arctic Council meeting in Finland and declared that Russia was acting aggressively and Chi-



STORAGE TANKS to hold liquefied natural gas are built at the Yamal LNG complex, funded in part by China and France, at the expanding Sabetta port on Russia's Arctic coast. Nations bordering the Arctic Ocean are increasingly eager to explore for gas and oil under the seafloor, and nations farther away are eyeing potentially lucrative investment opportunities.

na had to be watched closely. For the first time in 23 years, the meeting ended without the participants signing a declaration of cooperation. All the posturing could make boundary negotiations contentious, with opposing sides disregarding the science instead of compromising over it. Even worse, headstrong leaders might simply run out of patience with the CLCS's review and take what they think is theirs.

LOMONOSOV IS MINE

FOR CENTURIES nation-states saw the oceans as wild. In the 1600s they began to assert rights over the first three miles (4.8 kilometers) of seawater, based on the longest distance of a cannon shot. That practice held until the 20th century, when countries started to unilaterally claim rights out to various distances, threatening the long-standing concept of freedom of the high seas. To settle matters, in 1982 more than 160 countries agreed to the United Nations Convention on the Law of the Sea (UNCLOS). It established that a nation bordering any of the earth's oceans has an exclusive economic zone, or EEZ, reaching from its shoreline 200 nautical miles (370.4 kilometers) out to sea. It has all rights to resources in and under the water. Areas beyond that line are international waters—free to all, belonging to none.

The convention left a door open. Article 76 says a state can establish sovereign rights to exploit seabed beyond 200 nautical miles if it can present detailed geologic evidence proving that its continental shelf—the gently sloping seafloor that stretches from shore far out into the ocean before dropping into the deep sea—extends beyond the 200-nautical-mile line. Here a nation would have exclusive rights to resources on and under the seabed but not in the water column above it (fishing and

MELTING ICE CAPS in regions such as Svalbard (*shown*) and Greenland are exposing shorelines that can be developed, while receding sea ice exposes seafloor and shipping lanes that can be exploited throughout more of the year.

MICHAEL NOLAN *Getty Images*

navigation would remain open). Arctic countries did not focus much on the provision, until sea ice began to retreat.

Article 76 presents rules a state must follow to delineate the outer edge of a proposed extended continental shelf. It describes two formulas to draw the lines as far out as geologic evidence allows. It then describes two formulas that limit those lines, so a country cannot claim a crazy proportion of any ocean.

Both the formulas for drawing lines are based on a contour called the foot of slope. Imagine standing on the shore looking out at sea. The seafloor gradually deepens over many kilometers, then drops down a slope to a much deeper bottom under the distant, central ocean. Along the base of the slope, scientists must determine the foot of slope—the place of maximum steepness—around their coastlines and islands. Generating the evidence for the foot of slope "is where all the science is," Mosher says.

Each of the Arctic Five countries, as they are known, lies along the circular rim of the pie-shaped Arctic Ocean. As they project their shelves from the perimeter toward the center, the pieces are bound to overlap: continental shelves end where plate tectonics has ended them.

Following the formulas can lead to modest overlaps, but another Article 76 provision creates a larger problem. It says a country can claim a wide band of seabed along an underwater ridge that extends from the country's continental shelf, however far the ridge goes—but it does not define what a ridge is. The language "is totally ambiguous," says Larry Mayer, director of the Center for Coastal and Ocean Mapping at the University of New Hampshire. Mayer is seen as the leading U.S. authority on Arctic seafloor and, as it happens, spent a decade as a professor at Dalhousie, where he was Mosher's Ph.D. adviser.

The ambiguity allows geologists, as well as the lawyers in their country's state department, to interpret ridge data differently. The single feature causing the greatest overlap among Denmark, Russia and Canada is the Lomonosov Ridge. It extends 1,800 kilometers from Russia's New Siberian Islands to Canada's Ellesmere Island—right next to Greenland—dividing the Arctic Ocean in half. Some of its peaks rise 3,500 meters from the deep seafloor. The ridge is a gigantic relic from millions of years ago, when the neighboring North American and Eurasian continents began pivoting away from each other, twisting and deforming the expanding Arctic Ocean floor. The ridge's common heritage means Denmark, Russia and Canada

can say it naturally extends from their continental shelves, and they can outline turf along it to call their own. The most notable spot that falls within those outlines? The North Pole.

The scientists say they are just outlining where the geology takes them. But their submission teams can also apply the science to serve certain national strategies. Russia could have outlined extended continental shelf along the Lomonosov Ridge across the center of the Arctic Ocean, all the way to Canada's 200-nautical-mile EEZ, but in its submission to the CLCS it stopped just after the North Pole. It has not stated why. When I contacted two of its team experts, Eugene Petrov and Yuri Firsov, they declined to be interviewed, with Firsov e-mailing that the issues are "rather complicated." Rick Saltus, a senior research scientist at the University of Colorado Boulder, who has long been involved in the U.S. work, says Russia may not have had enough data near the Canadian end of the ridge; generating the details the CLCS looks for is expensive.

Alternatively, he says, Russia may have stopped where it did as a matter of strategy. Why complicate future boundary negotiations with Denmark and Canada? The long section of the Lomonosov Ridge that Russia did include might be more than enough to exploit.

If the Arctic Five countries' claims are upheld, only a small bit of the Arctic Ocean seabed may remain open to the rest of the world, instead of the entire region being a global commons.

Canada has taken a similar approach, outlining the Lomonosov Ridge from its shores outward, stopping just beyond the North Pole and overlapping Russia's outline in that region. Denmark, however, claims the ridge from Greenland across the entire ocean right up to Russia's EEZ. "We are not considering whether any other states would have claims to the same area," says Denmark's lead scientist Finn Mørk, a geophysicist at the Geological Survey of Denmark and Greenland. It is up to negotiators, he says, to work out the overlaps—and who, in the end, can wave a flag from the North Pole.

POLITICS OR SCIENCE?

GIVEN THE VAGUENESS of Article 76, the three declarations for the Lomonosov Ridge might all be legitimate, scientifically. But ultimately which nation secures rights to which territory is not up to the scientists: it is up to diplomats or, potentially, militaries. And rising geopolitical tension could overtake the orderly, science-based process.

First of all, the U.S. submission to the CLCS will add to the overlaps, complicating negotiations. The extent of overlap will not be revealed until the documents are handed in, which will be 2022 at the earliest, according to Evan Bloom, director for ocean and polar affairs at the U.S. Department of State and chair of the U.S. Extended Continental Shelf Project's executive committee. Mayer says the U.S. has all the data it needs. "It's just a huge process to do the analysis," he explains.

The U.S. may be in the weakest negotiating position, however, because it has never signed the UNCLOS, unlike the rest of the Arctic Five. Plenty of U.S. officials and several presidents have recommended signing it, but a handful of treaty-wary senators have stopped the convention from ever being ratified. That may now hurt the country's own cause. "I wish the U.S. knew how much it puts itself at a disadvantage by not being a party to the convention," says Galo Carrera, a marine researcher at Dalhousie, an honorary consul of Mexico to Canada, and a former CLCS chair.

As a result, the U.S. has no need to submit a claim to the CLCS or abide by its review. But Bloom says the U.S. will do both. It has spent $89 million to obtain thorough data. It wants the rest of the world to see that it is following the same criteria as everyone else. That gives the country "very strong standing" in future negotiations, Bloom says. And there really is no other way to make a claim. The federal government could publish a document declaring "this area of seabed is ours," but the world would not recognize it. In a boundary negotiation, Saltus says, a country "would want the CLCS determination in its pocket." In effect, the U.S. recognizes the UNCLOS as customary international law—the legal practice the world follows.

U.S. rhetoric is also making the Arctic more politically complicated. In June the U.S. Department of Defense released its latest Arctic Strategy, which says that although there has been a great deal of cooperation among Arctic nations, it now anticipates an "era of strategic competition" and "a potential avenue for … aggression."

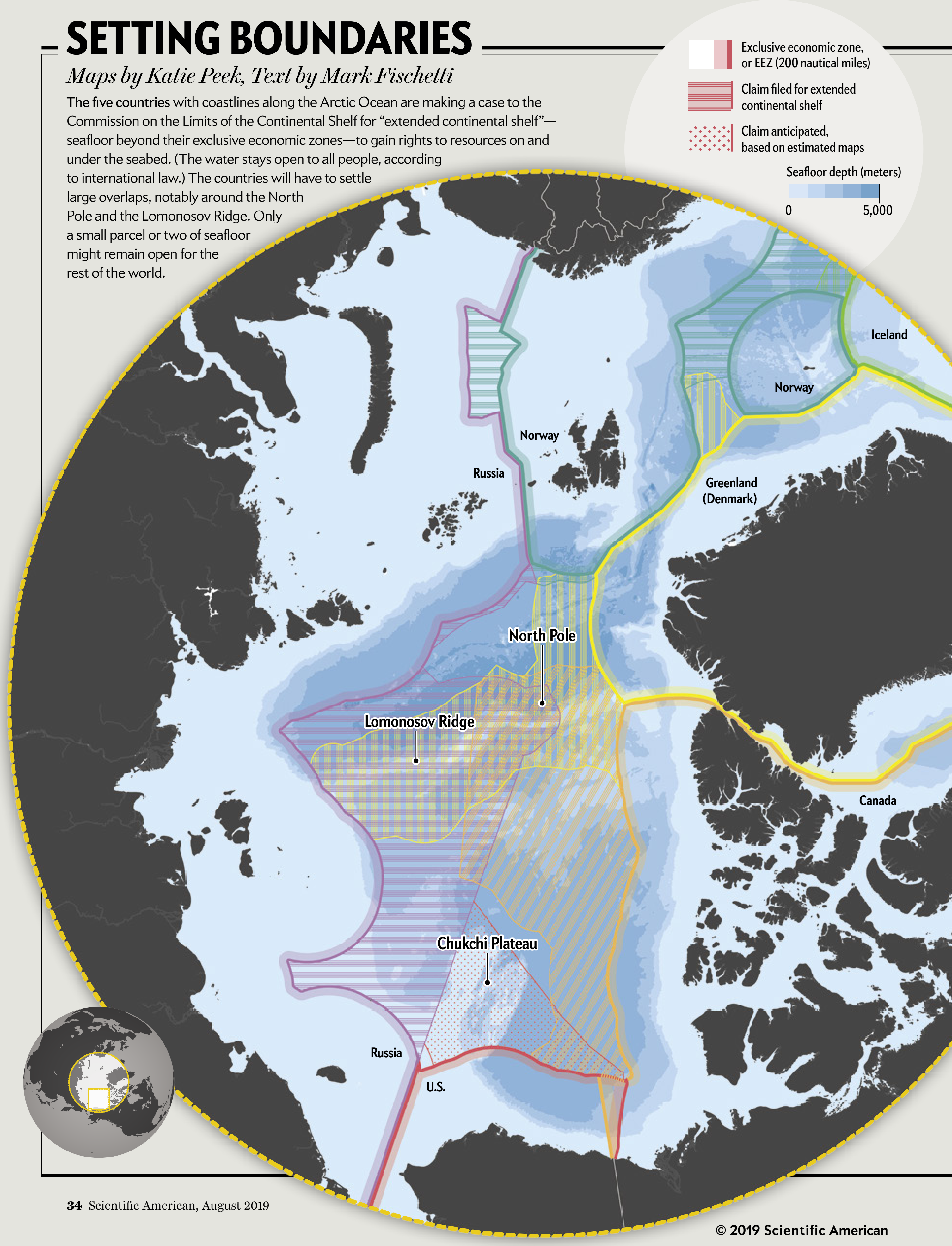
Russia's actions could be interpreted as such. Ever since the country stormed into Ukraine, "the relationship has been strained between NATO and Russia," says Rob Huebert, a political science professor at the University of Calgary and a former associate director of what is now the Center for Military, Security and Strategic Studies there. The Arctic coast offers Russia a critical strategic position for military power, notably nuclear war deterrence, because it is home to important nuclear submarine bases. "You can't separate the politics of the Arctic from the greater geopolitics" of the world, Huebert says, maintaining that Putin "sees the expansion of NATO as a core threat, and he will not allow that to happen." He says Russian jets now buzz Sweden and Finland because those countries are considering joining NATO. In March, Sweden hosted an enormous military exercise in its northernmost region with thousands of NATO troops. Because of Russia's Arctic buildup, U.S. Army General Curtis Scaparrotti told a Senate panel that same month that the U.S. military has to do more up north as well.

Russia may have another reason, beyond military strategy or oil and gas, for controlling big swaths of the Arctic seas. "It is about nationalism," says Andrew Holland, chief operating

SETTING BOUNDARIES

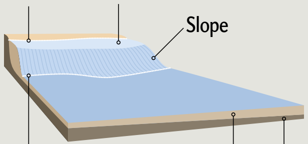
Maps by Katie Peek, Text by Mark Fischetti

The five countries with coastlines along the Arctic Ocean are making a case to the Commission on the Limits of the Continental Shelf for "extended continental shelf"—seafloor beyond their exclusive economic zones—to gain rights to resources on and under the seabed. (The water stays open to all people, according to international law.) The countries will have to settle large overlaps, notably around the North Pole and the Lomonosov Ridge. Only a small parcel or two of seafloor might remain open for the rest of the world.



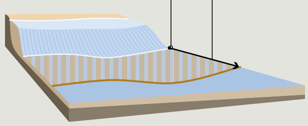
HOW COUNTRIES MAKE THEIR CASE

A country submits documents to the commission outlining the outer edge of its extended continental shelf. It uses one of two formulas (A, B) to reach as far out as they allow, starting at the foot of slope. That line is then constrained by the more lenient of two limits (C, D).

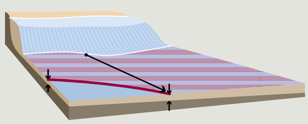


Formulas to delineate outer edge:

A A line 60 nautical miles from the foot of slope

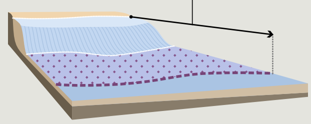


B A line where the thickness of sedimentary rock is at least 1 percent of the shortest distance from the foot of slope

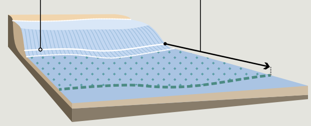


Limits to outer edge:

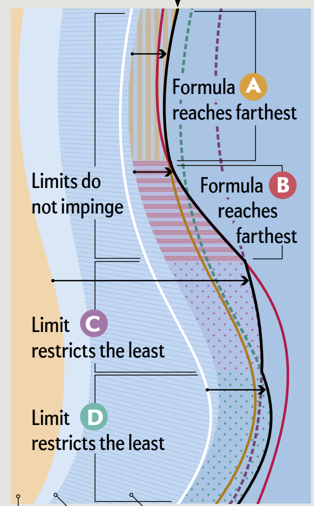
C A line 350 nautical miles from shore

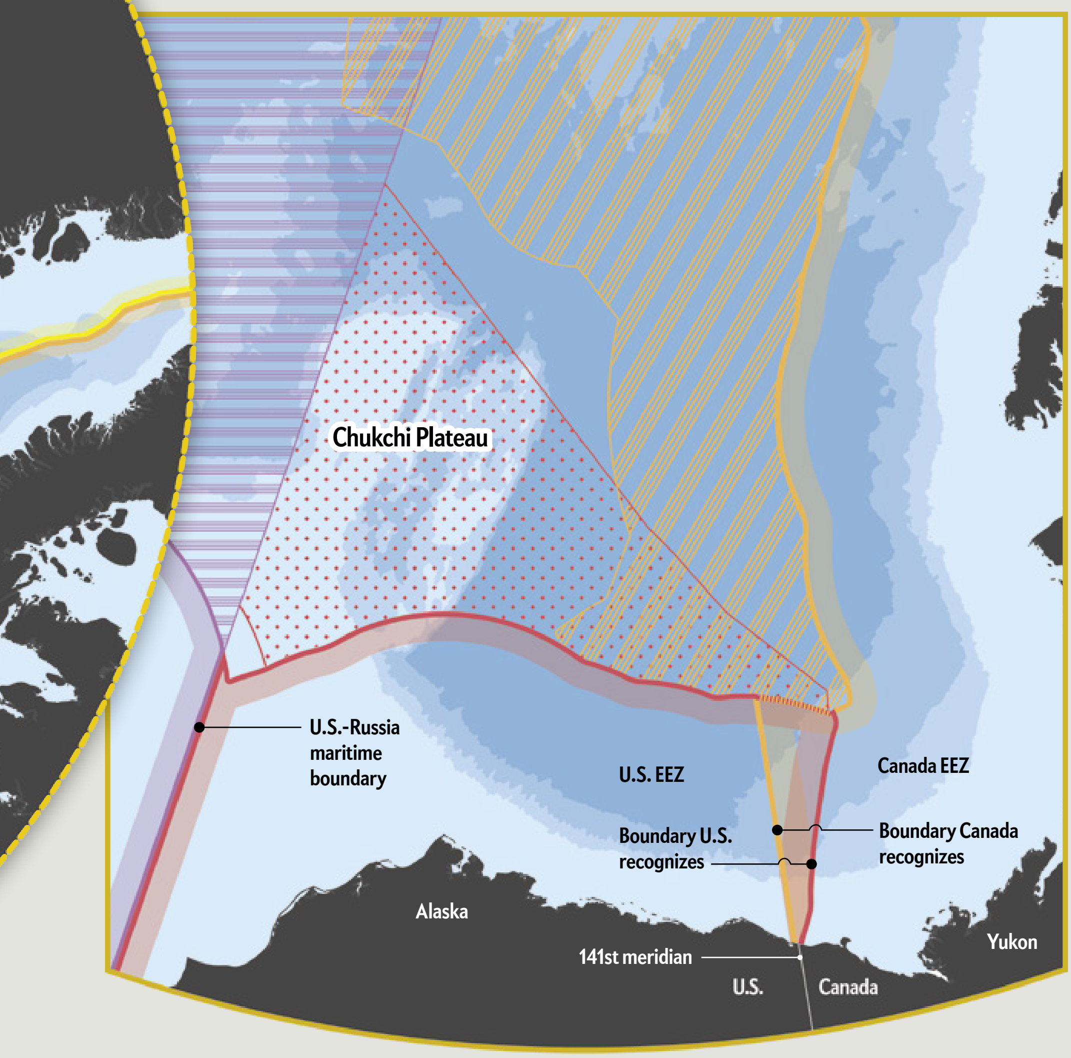


D A line 100 nautical miles from a slope depth of 2,500 meters



Final outer edge of the extended continental shelf





CHUKCHI CONUNDRUM

Resolving seafloor claims involves political and scientific trade-offs.

Pliable Plateau

Russia and the U.S. could say the Chukchi Plateau is a "natural prolongation" of their shelf, depending on how experts interpret the way continents have separated over millions of years. But in 1990 the former Soviet Union and the U.S. negotiated a maritime boundary between their exclusive economic zones (EEZs); Russia elongated that boundary in its submission for extended continental shelf and did not cross it. The U.S. says it will honor the boundary, too.

Economic Impasse

The U.S. and Canada disagree on their EEZ border. Canada extends the 141st meridian land boundary (*orange line*); the U.S. traces a line equidistant to the meandering coasts (*red*). The triangular seafloor in between holds an estimated 1.7 billion cubic meters of natural gas.

Seafloor depth (meters)

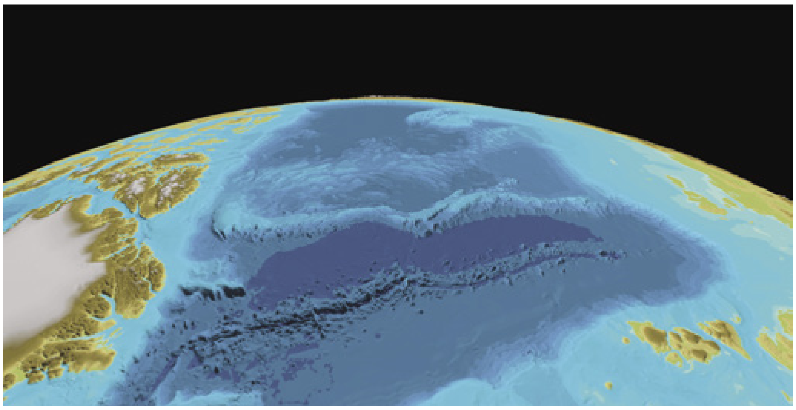
0 — 2,000 — 4,000

SOURCES: IBRU, DURHAM UNIVERSITY (*claim areas*); UNITED NATIONS CONVENTION ON THE LAW OF THE SEA (*claim areas*); MARINEREGIONS.ORG (*EEZs*); GLOBAL SELF-CONSISTENT, HIERARCHICAL, HIGH-RESOLUTION GEOGRAPHY DATABASE (*coastlines*); INTERNATIONAL BATHYMETRIC CHART OF THE ARCTIC OCEAN, VERSION 3.0 (*seafloor depths*)

officer at the nonpartisan American Security Project. "'We are the Russians. We are the Arctic power, and we should have rights to all of this.'"

Other geopolitical experts say the potential for Arctic confrontation is overplayed. Heather Exner-Pirot, a research fellow at the Center for Interuniversity Research on the International Relations of Canada and Quebec and an editor of the annual online *Arctic Yearbook,* which analyzes the state of Arctic politics, disagrees with Huebert, her former Ph.D. adviser. "People think there is competition in the Arctic," she says. "But what it is, really, is an oligopoly of five states that have a monopoly on the Arctic Ocean. They are thrilled with this."

The Arctic Five countries codified this situation in 2008, when they signed the Ilulissat Declaration, an agreement that says each nation will work together to safeguard marine traffic, prevent oil spills and peacefully resolve differences. It also says the countries will block any larger international attempt to govern the Arctic, as well as any other nation that might show up and try to drill for oil or gas without permission. No other countries, and no Arctic indigenous peoples, were involved.



LOMONOSOV RIDGE (*white band in center*) extends across the Arctic Ocean seafloor from Canada and Greenland (part of Denmark) (*left*) to Russia (*right*). All three states say they have rights to exploit it because it is part of their underwater continent.

MARTIN JAKOBSSON *Science Source*

If squabbling among members of the Arctic Five does not jeopardize orderly resolution of seafloor claims, two other wild cards could. China's economic ambitions are one of them. In 2013 President Xi Jinping unveiled the country's Belt and Road Initiative, intended to create an economic network among numerous nations by building extensive infrastructure in them all. China now heads projects in more than 60 countries worth hundreds of billions of dollars. Some world leaders worry that China's real plan is to command an enormous alliance across all of Asia. Part of the initiative is known as the Polar Silk Road, intended to develop Chinese shipping routes across the Arctic and business deals with countries along those corridors. In 2017 Xi held individual summits with the heads of Arctic nations. Not to be outdone, Putin, who has his own Eurasian vision, met one on one with leaders of Finland, Sweden, Norway and Iceland during the fifth International Arctic Forum, held in April in St. Petersburg.

The second wild card is Greenland, which has been a territory of Denmark since 1953. Although Denmark granted Greenland self-rule in 2009, the territory's 2018 political elections were a referendum supporting full independence. What has prevented secession is that the nearly 60,000 residents, who sparsely populate the largest island in the world, depend heavily on Denmark for subsidies and defense. But as ice and snow recede, China is investing in mining there. Other nations, including the U.S., are investing as well. Greenlanders are thinking they could stand on their own. Denmark has already given Greenland the seabed rights to resources within the EEZ around the island.

An independent Greenland could join NATO; the U.S. has a large air force base there. Or it could partner with China, or even Russia, to develop the thawing countryside. If Greenland becomes an independent state, Denmark could hand over the extended continental shelf claims mapped from the island's long coast. In that case, shelf negotiations might have to be recast with Greenland as the government in control—more potential delay.

END GAME

ALTHOUGH LEAD SCIENTISTS from the Arctic Five did not want to say much on the record about future boundary negotiations involving overlaps, some of them seem uneasy with the pace of the CLCS process. Nine of them—including Mosher from Canada, Mayer and Saltus from the U.S., Mørk from Denmark, and Petrov and Firsov from Russia—are working to set a common base of slope for the entire Arctic Ocean, and they are drafting a paper for a peer-reviewed journal. That would make a statement that the countries have calculated their foot of slope within the base of slope—the basis for the formulas—in the same way. Seeing such an agreement, perhaps the CLCS would speed up its reviews.

If the CLCS signs off on the Arctic Five submissions as is, only a small bit of the Arctic Ocean seabed may be left unclaimed. This space, known simply as the Area, might amount to two modest parcels far out at sea, Saltus says. The rest of the world may not be happy with that outcome. Sometimes the Arctic nations think the Arctic Ocean is their backyard, Carrera explains, but many other countries, as well as indigenous peoples, see it as a global commons. They believe they have a right to explore it for resources and to conduct research there.

Some of them think the world should formally establish the Arctic Ocean as a commons. They cite the Antarctic Treaty System as a model. In force since 1961, it sets aside all the land and ice shelves as a scientific preserve and bans military activity. It also protects more than 20 million square kilometers of the Southern Ocean around the continent. But no one lives in the Antarctic. There are no coastal states. It is more remote and more frozen. There is little insight about resources, and it offers no strategic advantage. As the Arctic warms, the once solitary home of indigenous peoples who lived off its wildness instead of trying to master it will be diced up and developed like the rest of the world to its south. Whether science or politics drives that development, it is underway.

SPECIAL REPORT
FUTURE OF THE ARCTIC

A NEW REALITY

Climate change is dramatically altering life at the top of the world

By Mark Fischetti

Illustration by Peter Horvath

On Banks Island in Canada's Northwest Territories, more than 4,000 slow-motion landslides are creeping downhill as thawing permafrost slumps and crumbles. In Siberia, warming earth is forcing underground methane seeps to breach the surface and explode, leaving craters up to 40 meters wide.

Across the Arctic, striking change is the new normal, as is incursion by countries and businesses. Construction, oil and natural gas extraction, shipping and tourism are all on the rise. Climate and human activity are leaving a mark on nature and on the four million people who live in the region.

As interactions widen, science will be important for informing agreements and policies, especially concerning disaster preparedness, environmental protection, economic opportunity, food security, human health and community resilience. Indigenous peoples may be among the most valuable experts. For years they have closely tracked shifting temperatures and receding ice cover, trekked mountains and forests, followed caribou herds, fished seas and maintained biodiversity. Their communities and cultures are also the ones most affected by coming development.

Some indigenous leaders say the Arctic should be governed by cooperative organizations and rules that transcend political boundaries. For example, land and marine spatial planning across large expanses could lay out rights for people, environmental protection and means for constructive dialogue. Ultimately, they say, sustainable use of the future Arctic depends on a healthy environment and a healthy community.

LAND OF CHANGE

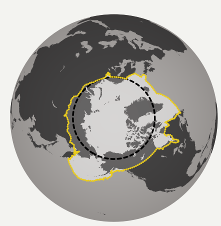
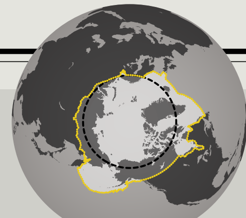


ILLUSTRATION REFERENCE: CHRISTOPH WAGNER *Getty Images* (reindeer); GETTY IMAGES (*snow*)

LAND OF CHANGE

Maps by Katie Peek, Text by Mark Fischetti

Scientists are running out of words to convey how dramatically Arctic landscapes and seascapes are changing. Physical factors such as rising air and sea temperatures, along with disappearing snow and sea ice, are compounding the effects. As a result, living things from algae to trees to caribou are flourishing, floundering or moving; virtually every part of the food web has to adjust. Thawing permafrost could impact the region and the planet the most, releasing enough greenhouses gases to double the global warming that has already occurred.

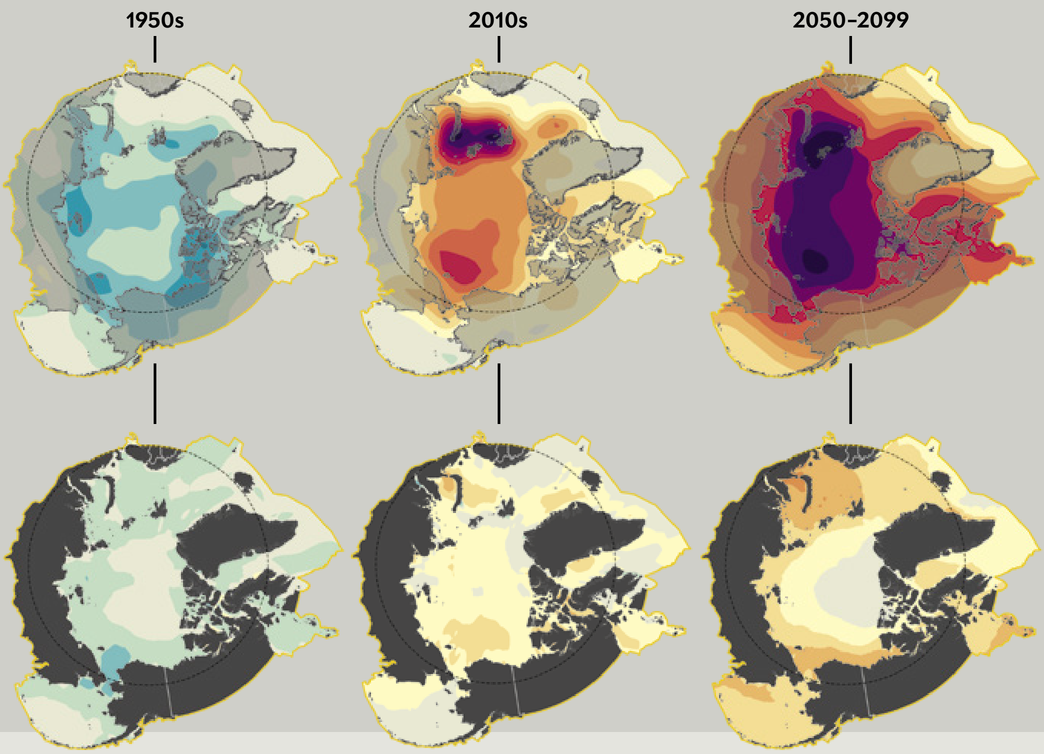


Top of the World

The "Arctic" can be defined in different ways. The maps here follow the international Arctic Council's outline.

Physical Changes

Air, sea and land are transforming rapidly. Each characteristic is mapped across the longest time interval for which comprehensive data exist.



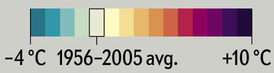
Hotter Air

Average winter air temperatures at the surface in the 2010s have been much warmer than in the 1950s. The second half of this century will be hotter still, according to midrange projections.

Warmer Ocean

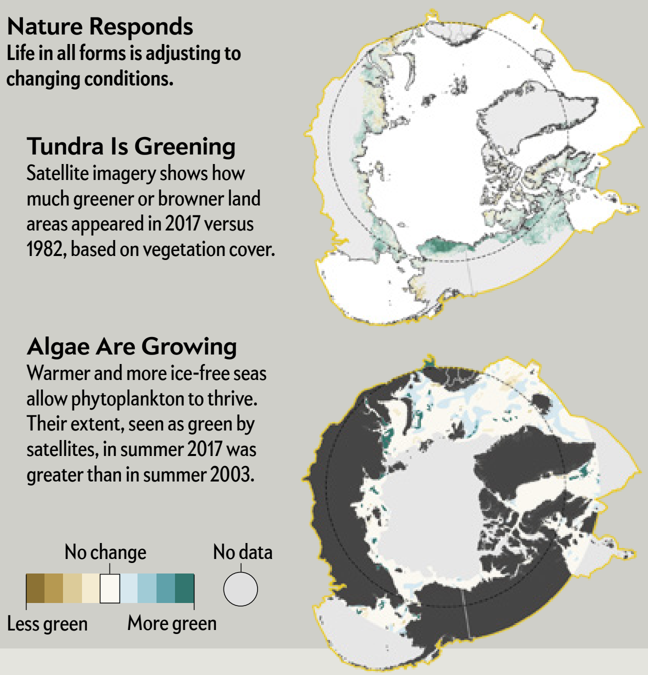
Summer sea-surface temperatures have risen considerably and are predicted to continue upward.

Temperature anomaly compared with 1956–2005 average:



Nature Responds

Life in all forms is adjusting to changing conditions.



Tundra Is Greening

Satellite imagery shows how much greener or browner land areas appeared in 2017 versus 1982, based on vegetation cover.

Algae Are Growing

Warmer and more ice-free seas allow phytoplankton to thrive. Their extent, seen as green by satellites, in summer 2017 was greater than in summer 2003.

North American beaver

The Beaver Effect

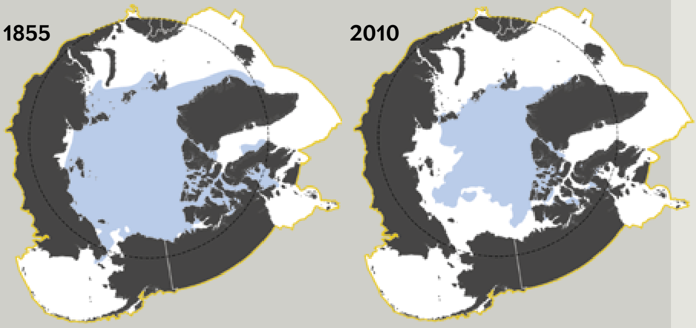
As trees migrate north, beavers follow. They fell the trees and build dams, causing local flooding that thaws permafrost, which releases carbon dioxide and methane. The gases enhance warming, and trees grow farther northward. More beavers arrive, more dams go up, more flooding thaws more ground and warming continues to increase.

Less Sea Ice

Sea ice shrinks to a minimum every September. Much more disappears annually now. The median year for 1850–1859 was 1855 (based on map, sailing and explorer records); the median year for the most recent decade was 2010.

Ice extent in September

Sea ice present

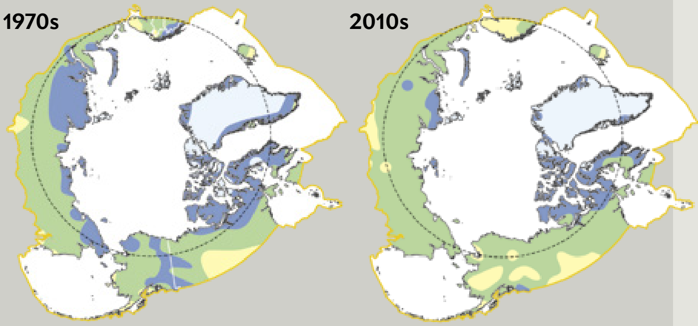


Less Snow

The number of weeks with snow cover has diminished significantly from the winter of 1972–1973 (median for 1970s) to 2008–2009 (median for past 11 years).

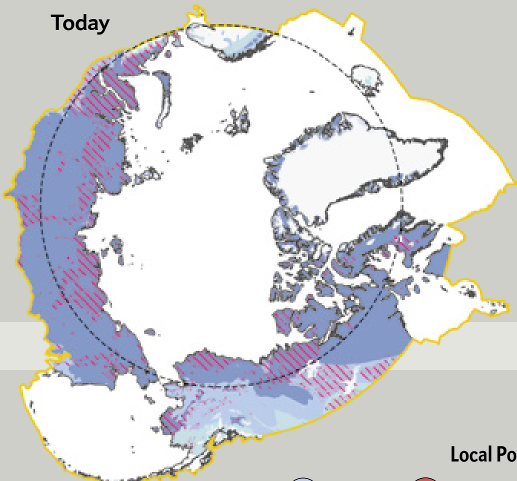
Weeks with snow cover

20 — 50+



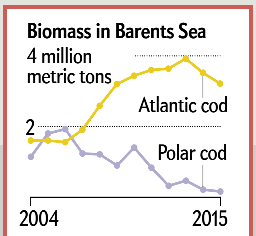
Softer Permafrost

Ground that used to be frozen for most or all of the year—permafrost—is thawing, slowly in some places, quickly in others.



Types of permafrost

- Year-round
- Discontinuous or thaws in summer
- Covers less than a third of the area
- Thawing fastest

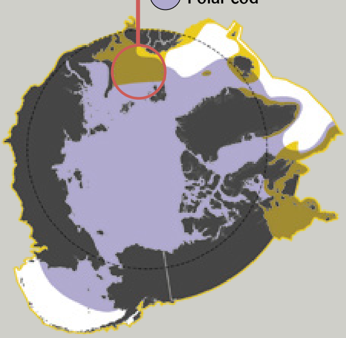


Fish Range

- Atlantic cod
- Polar cod

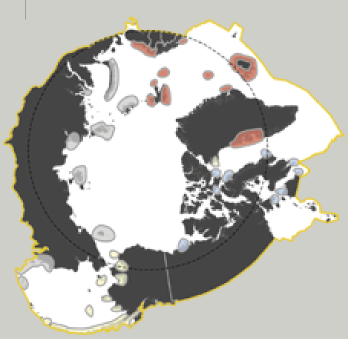
Local Population

- Gaining
- Losing
- Steady
- Unknown



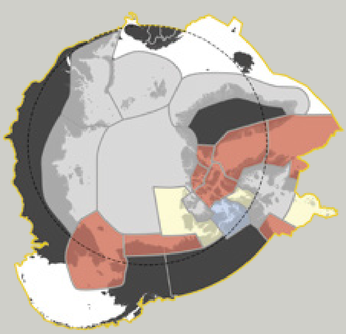
Fish Are Migrating

Polar cod rely on sea ice to spawn. As oceans warm, their numbers are falling, whereas Atlantic cod are moving in from the south.



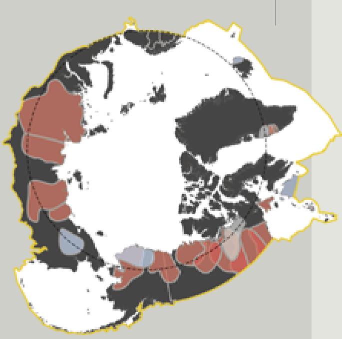
Birds Are Shifting

Thick-billed murres nest in vast coastal colonies and are important prey for humans and animals. Their numbers are waxing in some places, waning in others.



Polar Bears Are Dying

Struggling polar bears are the icon for a melting Arctic. Their demise is widespread.



Caribou Are Wavering

Of the 23 tracked herds of caribou (reindeer), 16 are losing population, five are gaining and two are holding steady.

MORGAN TRIMBLE *Getty Images* (*beaver*); ADRIAN WOJCIK *Getty Images* (*Longyearbyen*); SOURCES: NOAA'S EARTH SYSTEM RESEARCH LABORATORY (*air and sea-surface temperatures*); U.S. NATIONAL SNOW AND ICE DATA CENTER (*sea ice*); NOAA'S NATIONAL CENTERS FOR ENVIRONMENTAL INFORMATION (*snow cover*); MERRITT R. TURETSKY *University of Guelph* (*permafrost*); UMA S. BHATT *University of Alaska Fairbanks* (*tundra greening*); KAREN E. FREY *Clark University* (*primary productivity*); FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS (*cod habitats*); *STATE OF THE ARCTIC MARINE BIODIVERSITY REPORT,* CHAPTER 3.4: "MARINE FISHES." CONSERVATION OF ARCTIC FLORA AND FAUNA (CAFF), 2017 (*cod abundances*); BIRDLIFE INTERNATIONAL, 2018 (*murre breeding locations*); *ARCTIC BIODIVERSITY ASSESSMENT 2013.* CAFF, ARCTIC COUNCIL, 2013 (*murre trends; polar bear trends; reindeer and caribou trends*))

Hotspot Svalbard

Norway's Svalbard archipelago is changing dramatically. Winters are seven degrees Celsius warmer and two months shorter than in 1971. Rain, once uncommon, routinely floods the thawing, slumping soil, as buildings sink into it. The rains can freeze lichens and mosses, however, forcing reindeer to eat the less nutritious kelp that washes up along softening shores. Inland, the Global Seed Vault, once buried in frozen ground, is losing its natural coolant.

Town of Longyearbyen on Svalbard

SPECIAL REPORT
FUTURE OF THE ARCTIC

IS CONFRONTATION INEVITABLE?

Political tension is increasing, but cooperation could still prevail

By Kathrin Stephen

Illustration by Peter Horvath

FIVE U.S. B-52 BOMBERS WERE CONDUCTING A TRAINING MISSION ON March 28 high over the Norwegian Sea in the Arctic Ocean. F-16 fighter jets from Norway were also aloft, part of joint NATO exercises involving 10,000 troops in northern Sweden. Unexpectedly, two Russian Tu-160 bombers crossed into the same airspace. Surprised, Norway scrambled the F-16s to follow the interlopers.

The Tu-160s continued toward the U.K., then circled back home, but their appearance was worrisome. The U.S. and Russian bombers can carry nuclear weapons, and less than two months earlier both countries announced they would withdraw from the Intermediate-Range Nuclear Forces Treaty because they were no longer interested in abiding by its rules. Although the U.S. and Norwegian planes did not enter Russian airspace, Russia could have interpreted the exercises as a signal from NATO that it can deliver nuclear weapons close to the Russian border. Perhaps the Russian military felt it needed to remind the allies that it has ample airpower, too.

It is reasonable to look at what is happening in the Arctic and worry that tensions are rising. Easier physical access because of global warming has placed the region high on the political agendas of the eight states with land or marine territory above the Arctic Circle: Russia, Finland, Sweden, Norway, Iceland, Denmark (via Greenland), Canada and the U.S. Other influential players such as the U.K., Japan and China are paying closer attention to the new benefits a thawing Arctic Ocean offers. The Arctic could hold as much as 13 percent of the world's as yet undiscovered oil and 30 percent of its natural gas, according to the U.S. Geological Survey. Na-

tions are also eyeing increasingly ice-free shipping routes through the Northeast Passage along Russia's coast and the Northwest Passage along Canada's coast, as well as potentially large fisheries.

Bigger than these factors is Russia's apparent desire to dominate the region. At President Vladimir Putin's direction, the country has invested heavily in reopening Arctic military bases and ports. It is establishing an early-warning missile system there. And Russia is expanding its icebreaker fleet to ensure Arctic maneuverability year-round. The first of its new, brawny nuclear-powered LK-60 icebreakers, the *Ural,* launched in May.

Other countries are responding. The U.K. recently announced a new Defense Arctic Strategy. In February the U.S. Congress designated $675 million for a heavy polar icebreaker, and in March the U.S. Navy announced it would send multiple surface vessels through the Arctic Ocean this summer. In April the U.S. Coast Guard published a new Arctic strategy calling for greater investment. At the Arctic Council's 2019 ministerial meeting the following month, Secretary of State Mike Pompeo sharply criticized Russia (and China) for aggressive behavior in the Arctic. These actions could reflect a potential change in policy toward more assertively balancing Russia's influence there. Pompeo even emphasized unilateral action rather than cooperation.

Strategically, the Arctic is tremendously important for Russia and its rivals. Russia's nuclear deterrent is heavily tied to its nuclear submarines, and its most important submarine bases are along its Arctic coast. The flurry of recent activity has raised fears that a more accessible Arctic will lead to a proverbial "cold war" in the region. Since Russia annexed the Crimean Peninsula in 2014, the relationship between NATO and Russia has been especially strained; the concern is that either side could use the Arctic as a bargaining chip in negotiations over other fraught regions such as Syria or the Ukraine. In March, Russia announced it would tighten the requirements for foreign ships traveling through the Northern Sea Route.

Compounding matters, four of the five coastal Arctic nations have submitted claims to the United Nations, under the U.N. Convention on the Law of the Sea (UNCLOS), for rights to exploit their extended continental shelves—seafloor far out into the Arctic Ocean. There are large areas of overlap, particularly among Russia, Denmark and Canada. Russia has been following the UNCLOS procedures because it has a lot to gain, given its very long Arctic coastline and shallow shelf. But if Arctic countries cannot resolve their overlapping claims politically, Russia might not play nice and will have its Arctic military force ready to go.

CONFLICT IS NOT NECESSARILY INEVITABLE, HOWEVER. ARCTIC NATIONS have good reasons to cooperate. And some of the moves they are making may not be as aggressive as they appear. For example, conditions in the Arctic are so harsh that many civilian tasks—such as exploring for oil or monitoring shipping traffic—can be performed only with military equipment and personnel.

Russia's leaders are also well aware that any open conflict could doom development of Arctic oil and gas because that work depends heavily on international partners, including Western nations and companies. Extracting resources, even without ice on the seas, is expensive and technically difficult. Building Russia's Yamal LNG (liquefied natural gas) project, which is only partly offshore and close to the coast, cost $27 billion. Russia was loath to fund this alone, so it took on partners from France and China.

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The country's dependence on outside financing, as well as technical expertise, provides an incentive for restraint, especially in areas of overlapping seabed claims. Russia and Norway—the Arctic states with large stakes in offshore resources—must build a stable investment climate for outsiders. The two nations intended exactly that when they resolved their boundary dispute in the Barents Sea in 2010 in a matter of weeks, after a standoff that had lasted many years.

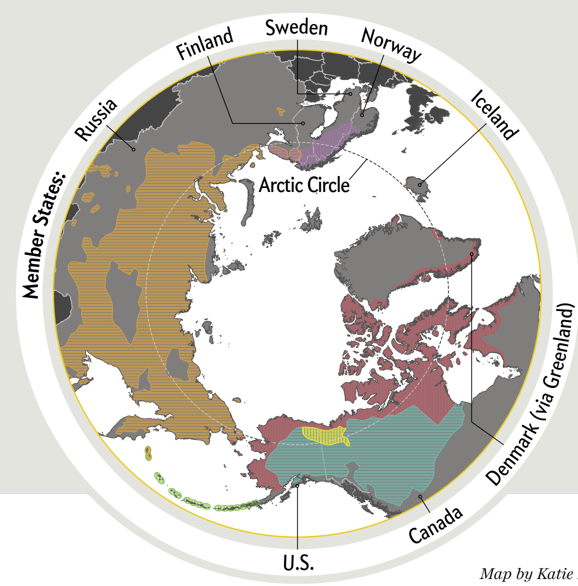
Oil and gas may not even provide much ground for argument. Only Russia and Norway are significantly interested in exploiting the resource because it makes up a substantial part of their export revenues. The U.S. and Canada have much larger and much more easily accessible fossil deposits in non-Arctic areas, such as oil in the Gulf of Mexico, shale gas in various U.S. states and tar sands in Alberta.

Moreover, the vast majority of anticipated oil and gas resources lie within each of the five coastal Arctic nations' exclusive economic zones (EEZs), which extend 200 nautical miles (370.4 kilometers) from the coastlines. As UNCLOS lays out, each country has control over its resources within its EEZ. Certainly some oil

The Human North

Of the four million Arctic residents, about 500,000 are indigenous peoples. They have organized into six regional groups that participate in the Arctic Council, a cooperative forum, along with eight country members. The Russian Association of Indigenous Peoples of the North is the largest regional group, representing 244,000 individuals.

Arctic Council Members:
- Inuit Circumpolar Council
- Russian Association of Indigenous Peoples of the North
- Gwich'in Council International
- Aleut International Association
- Arctic Athabaskan Council
- Saami Council



Map by Katie Peek

PRECEDING PAGES: GETTY IMAGES (*flags, tanks, ice and water*); THIS PAGE: SOURCE: PHILIPPE REKACEWICZ *UNEP/GRID-ARENDAL*

and gas deposits are expected farther out on the extended continental shelf, where the overlapping claims occur, but because UNCLOS rules would support large regions of Russia's claims, there is little reason to think its leaders would torpedo peaceful resolution of those overlaps.

Above all, Arctic resources need to be profitable to be developed. Oil at $80 a barrel—a price not seen since October 2014—might justify digging at some offshore fields, but certainly not those far away, in the extended shelf area. The fate of the Shtokman gas field, inside Russia's EEZ in the Barents Sea, is a case in point. Discovered in 1988, it is one of the largest fields in the world, with an estimated 3.8 trillion cubic meters of gas. In the early 2000s Putin asserted repeatedly that Russia would develop the field. But with the shale gas revolution in the U.S. and the glut of gas on the world market by 2010, the project was eventually shelved. Any Arctic claims beyond the EEZs are mostly symbolic. They are about securing access to distant resources in case they become valuable someday, not about a "race" to exploit resources before other nations do.

Aggression over Arctic shipping routes also does not seem likely. Despite the intrepid allure, most shippers do not consider the passageways to be competitive with global trade routes through the Suez and Panama Canals, even though those established routes are longer. The seasonal nature of the Arctic corridors (winter ice will persist for years), plus harsh weather and insufficient infrastructure for meeting schedules on time, considerably reduce the relevance of the Arctic routes for international maritime trade.

In September 2018 the first ever transit through the Northern Sea Route by a container ship, operated by Danish shipping company Maersk, was considered a one-time trial. It did not stand for the beginning of regular trade transits. The chief technical officer at Maersk concluded: "Currently, we do not see the Northern Sea Route as a viable commercial alternative to existing east-west routes." Naval traffic in the high north could help bring in material for Russia's new port in Sabetta and for shipping liquefied natural gas out of the Yamal region, especially during the summer months, but these tasks involve predominantly Russian ships and have nothing to do with international maritime trade.

Many countries and companies had hoped to venture into the Arctic to catch more fish because important species such as Atlantic cod and Pacific salmon are migrating north. But profits are highly uncertain. In 2009 the U.S. closed large areas of its EEZ in the Chukchi and Beaufort Seas off the coast of Alaska to commercial fishing because data on the sustainability of fisheries there were lacking. In 2015 the five countries with coastlines along the Arctic Ocean adopted a de facto moratorium on commercial fishing in the high seas (beyond their EEZs). Then, in 2018, the countries signed a ban on commercial fishing there for 16 years; Iceland, the European Union, China, Japan and South Korea also signed on. The main purpose is to create time to gather deep scientific data on fisheries and to design a sustainable and orderly commercial utilization of them.

IN ASSESSING THE LIKELIHOOD OF FUTURE CONFLICT, IT IS important to remember that the Arctic region has historically been a place of international cooperation: Arctic countries, some non-Arctic states and representatives of Arctic indigenous nations have been working together peacefully for many years. In 1991 the eight states with Arctic territory and their native peoples adopted the Arctic Environmental Protection Strategy, which fostered cooperation in monitoring and conserving the territory. The agreement led the parties to establish the Arctic Council in 1996. It has become the central Arctic forum and consistently generates successful, cooperative initiatives and decisions. Today the council also includes nongovernmental organizations, scientific bodies and U.N. associations. In 2018 the council was nominated for the Nobel Peace Prize.

The council has been criticized for not addressing military and security issues, yet these are excluded from its mandate. Diplomatic channels are certainly needed to tackle security, but the council is not the place for that. States have already created some of these channels, such as the Arctic Security Forces Roundtable and the Arctic Coast Guard Forum, which are part of so-called confidence and security measures set up among nations precisely to defuse potential tensions. To resolve overlapping seabed claims, states should negotiate directly, just as they do already over other frictions.

Conflict is often a matter of perception. Russia's tighter rules for traversing the Northern Sea Route could actually be beneficial if they lead to safer navigation and greater environmental protection. Rules for sea lanes close to coastlines are not unique to Russia or the Arctic; the Suez and Panama Canals have plenty of rules that shipowners must comply with. A new U.S. heavy polar icebreaker, the only one the country would have, could best be used to improve access to its own Arctic waters year-round. Furthermore, icebreakers are not military boats, and even if they were, one ship is not a credible threat to Russia's large icebreaker fleet.

Actions that appear to be provocative may have other explanations. For many Russian citizens and indigenous peoples, the Arctic is central to their identity, building on centuries of exploring and mastering the north. When a Russian submarine expedition planted a flag on the North Pole seafloor in August 2007, the stunt was not a land grab; it was a show, intended for a domestic audience, symbolizing Russia's ability to reach even the farthest points in the Arctic.

As it can anywhere in the world, confrontation could still arise, perhaps from an unexpected source. Since 2013 Chinese ships have made at least 22 commercial voyages through the Northeast Passage, among the largest non-Russian uses of the route. China is also attempting to reframe the Arctic as a global theater. In January 2018 the government released a white paper called "China's Arctic Policy" that declares that "the Arctic situation now goes beyond its original inter-Arctic States or regional nature." But China's arrival does not mean the stakes are higher. Russia and Greenland are welcoming its investments. Economic cooperation could encourage political cooperation and carry the day. SA

MORE TO EXPLORE

Geologic Structures of the Arctic Basin. Edited by Alexey Piskarev, Victor Poselov and Valery Kaminsky. Springer International Publishing, 2019.

Arctic Council: **https://arctic-council.org**

International Arctic Forum, St. Petersburg, Russia, April 9–10, 2019: **https://forumarctica.ru/en**

United Nations Convention on the Law of the Sea: **www.un.org/depts/los**

FROM OUR ARCHIVES

The Aeroplane in Arctic Exploration. Burt M. McConnell; September 30, 1916.

The Arctic Ocean. P. A. Gordienko; May 1961.

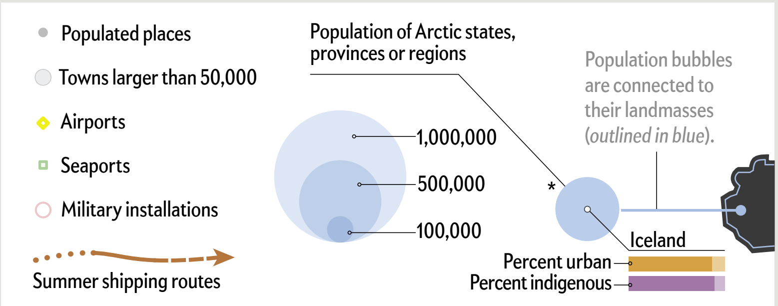
The Dinosaurs of Arctic Alaska. Anthony R. Fiorillo; December 2004.

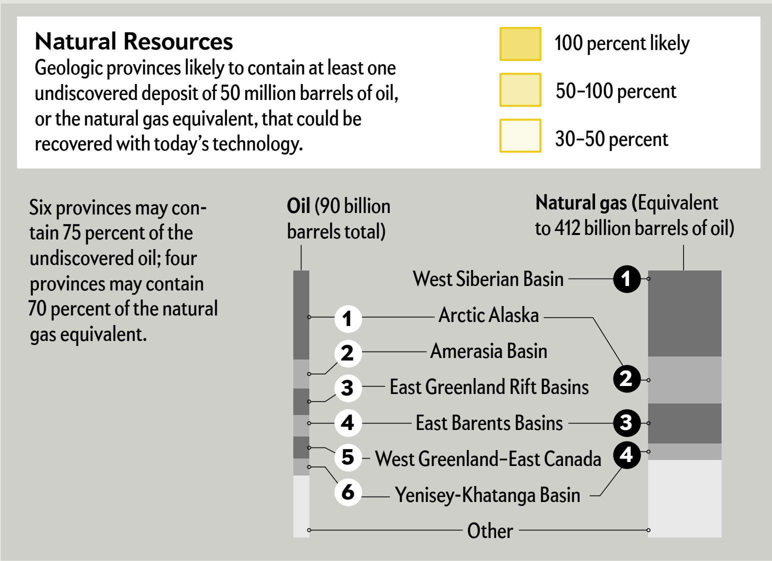
scientificamerican.com/magazine/sa

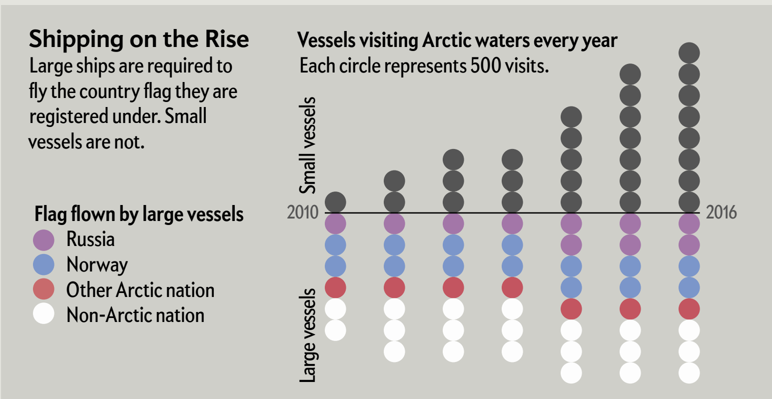
THE BUSY NORTH

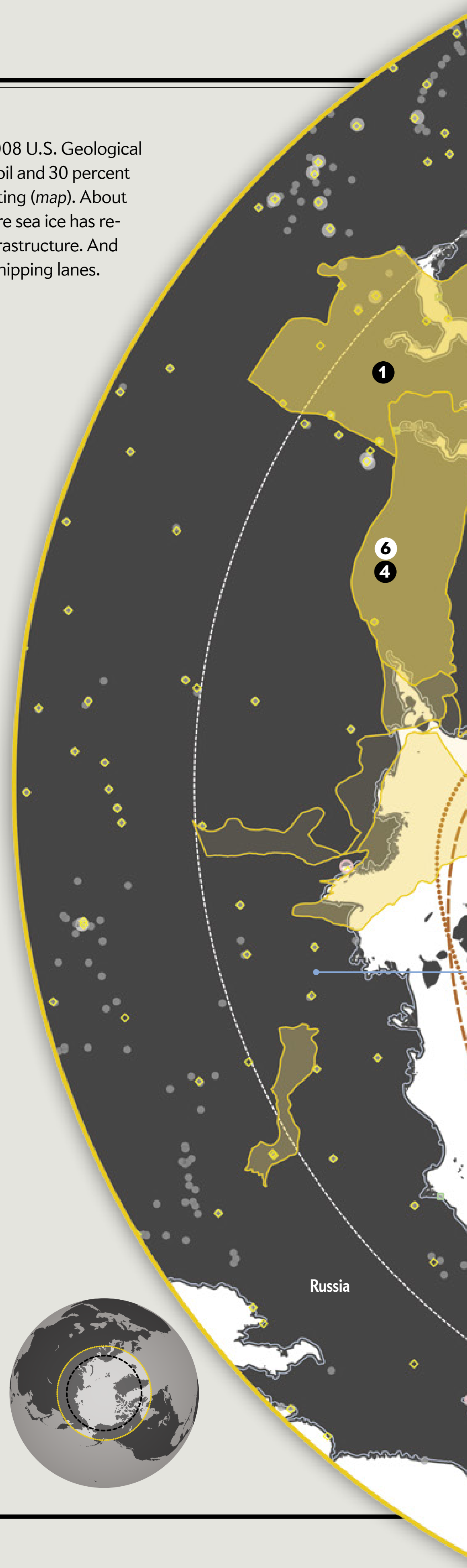
Map by Katie Peek, Text by Mark Fischetti

As the Arctic thaws, it becomes much more accessible—and desirable. An exhaustive 2008 U.S. Geological Survey study determined that 13 percent (90 billion barrels) of the world's undiscovered oil and 30 percent (1,670 trillion cubic feet, or 47 trillion cubic meters) of its undiscovered natural gas lie waiting (*map*). About half the Arctic Ocean is less than 500 meters deep, readily reachable by drilling rigs where sea ice has retreated. Countries, notably Russia, are building numerous airports, seaports and other infrastructure. And they are expanding military installations to protect assets and sustain increasingly busy shipping lanes.









*Common practice uses circles scaled by area, but that can create an inaccurate visual impression of relative values. Here circles are scaled with their radius = (population value)$^{2/3}$.

†Indigenous and/or urban data not available.

SOURCES: U.S. GEOLOGICAL SURVEY (*oil and gas data*); GREG FISKE *Woods Hole Research Center,* WITH DATA FROM SPACEQUEST.COM (*shipping data*); *THE INDIGENOUS WORLD 2019,* EDITED BY DAVID N. BERGER ET AL. INTERNATIONAL WORK GROUP FOR INDIGENOUS AFFAIRS, 2019 (*Sami and Inuit populations*); STATISTICS FINLAND; STATISTICS SWEDEN; STATISTICS NORWAY; STATISTICS ICELAND; STATISTICS GREENLAND; STATISTICS CANADA; U.S. CENSUS BUREAU; RUSSIAN FEDERAL STATE STATISTICS SERVICE; ARCTIC PORTAL (*Northwest and Northeast Passages*); INTERNATIONAL INSTITUTE FOR STRATEGIC STUDIES (*military installations*); HERITAGE FOUNDATION (*military installations*); GEONAMES GAZETTEER (*populated places, airports*); WORLD PORT INDEX (*ports*)

Russia
Finland
Sweden
Norway
Iceland
Greenland Sea
Kara Sea
4
3
Svalbard (Norway)
Barents Sea
Novaya Zemlya
Franz Josef Land (Russia)
3
Northern Norway
Iceland
Northern Sweden†
Northern Finland
Greenland
Greenland (Denmark)
Northern European Russia†
Northwest Passage
5
Laptev Sea
Ellesmere Island
Baffin Bay
Northern Canada
Northern Siberia
New Siberian Islands
Alaska (U.S.)
East Siberian Sea
Hudson Bay
Northern Sea Route
Northeast Passage
Beaufort Sea
2
Chukchi Sea
1
2
Arctic Circle
U.S.
Canada

ANIMAL BEHAVIOR

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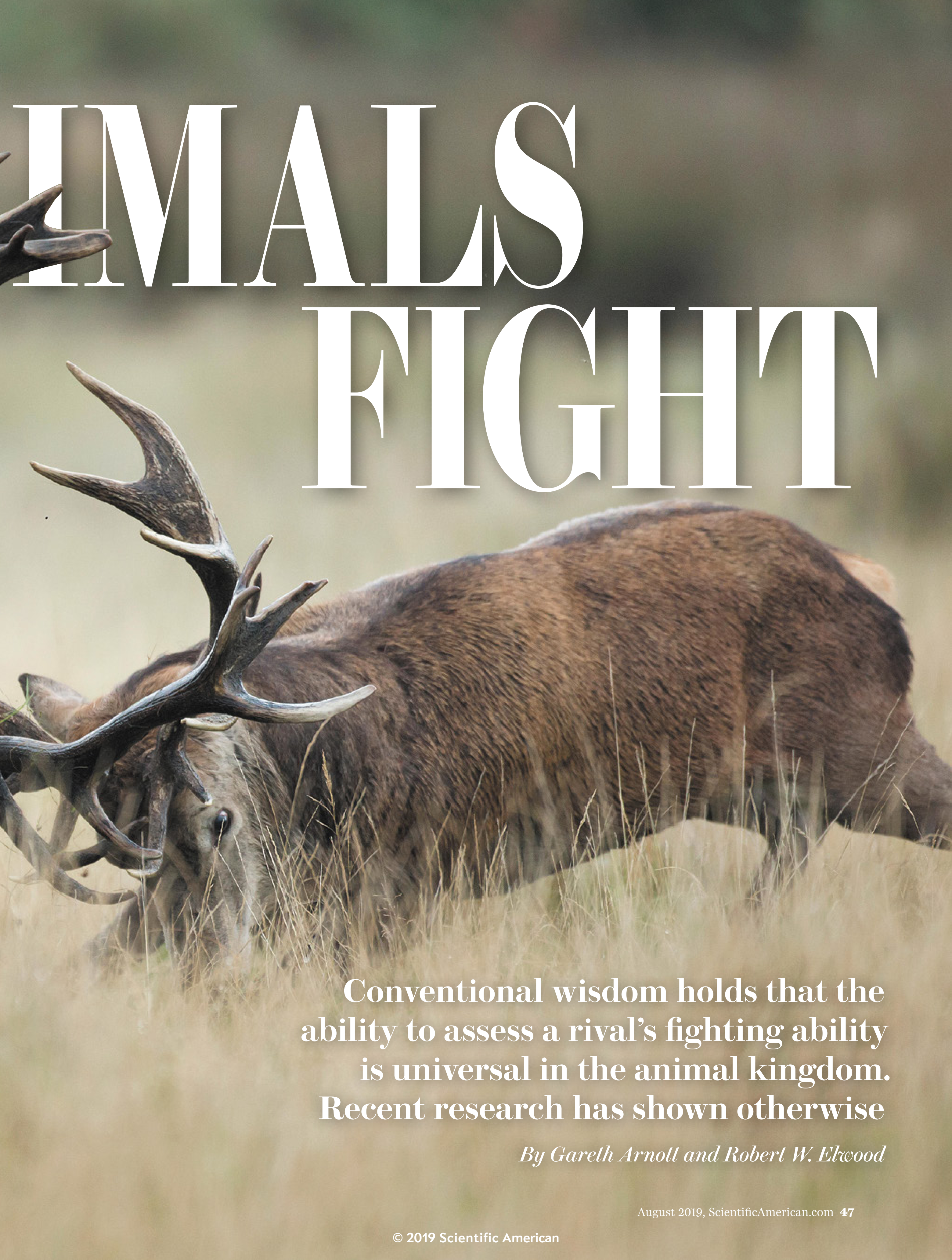


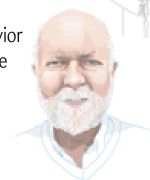
IMALS FIGHT

Conventional wisdom holds that the ability to assess a rival's fighting ability is universal in the animal kingdom. Recent research has shown otherwise

By Gareth Arnott and Robert W. Elwood

Gareth Arnott is a senior lecturer in animal behavior and welfare at Queen's University Belfast in Northern Ireland. His research focuses on animal contest behavior and animal welfare.

Robert W. Elwood is professor emeritus of animal behavior at Queen's University Belfast and a former president of the Association for the Study of Animal Behavior.



IN A SCENE FROM THE 2013 BBC DOCUMENTARY SERIES *AFRICA,* A GIRAFFE APPROACHES from a distance, ambling across the golden sand of the Kalahari. "A young male," narrator David Attenborough announces. The newcomer heads toward another giraffe, Western showdown music warbling on the soundtrack. "The old bull won't tolerate a rival," Attenborough warns, as the giraffes begin to clash. "Pushing and shoving, they size each other up. The young rival seems to think he has a chance and attacks." Moments later he slams his powerful neck into the old male's, and the fight is on—a bloody battle for territory. "The stakes are high," Attenborough explains. "To lose means exile in the desert."

Wildlife documentaries commonly include such footage of animals engaged in aggressive contests. It's not surprising, given the dramatic scenes that ensue. But have you ever wondered about the decision-making processes that underlie these encounters? We have been lucky enough to devote a large part of our research careers to this fascinating topic. And our work has generated some surprising insights into what animals are thinking when they face off.

Animals compete for resources, such as territory, food and mates. Sometimes these contests are mild and cause no physical harm. Other times they are violent and end in severe injury or death. Ultimately they result in unequal distribution of resources, have major effects on reproductive fitness and thus drive evolution. A creature that gathers information can benefit by avoiding potentially lethal fights with bigger, stronger opponents.

We humans are remarkably skilled at assessing the fighting ability of others and quickly learn to not pick fights with individuals larger than ourselves. In laboratory tests, human subjects are able to accurately gauge the power of males after briefly viewing photographs of their torsos or faces or listening to their voices. The judgment is spontaneous—members of both sexes reach it in less than 50 milliseconds. This ability reflects the importance of making accurate assessments of opponents during human evolution.

Are nonhuman animals as good as we are at evaluating rivals? Documentaries such as the ones Attenborough narrates so eloquently often describe the animals' motivations in such terms. But relatively few of these species have actually been shown to make these kinds of assessments. In fact, our own research suggests that many creatures use different information when deciding whether or not to compete.

DISPLAY OF FORCE

ANIMALS TYPICALLY PERFORM ritualized displays prior to engaging in combat. For example, male deer stags competing for access to females will engage in elaborate "roaring contests" and strut side by side in "parallel walks." Researchers have commonly interpreted these behaviors as means by which each of the opponents can provide information for the other to assess. If the display can settle the contest, there would be no need to engage in a fight in which injury or even death is likely. It is better to spend energy for a short time so that the opponent that perceives itself as the weaker of the two can withdraw, so the thinking goes. We call this phenomenon mutual assessment, and it is central to a game theory model of fighting known as sequential assessment.

Game theory is a branch of applied mathematics that was initially developed by economists to model human strategic decision-making. Biologists were quick to spot the utility of game theory for evolutionary biology, with John Maynard Smith and George Price being the first to use this framework for studying animal contests. The sequential assessment model proposes that contests should be easily settled by displays if the opponents differ widely in prowess, with fights occurring only when

IN BRIEF

Scientists long thought that in competitions for resources, all animals have the capacity to gauge the fighting ability of their opponents in relation to themselves—a strategy called mutual assessment.

Studies carried out in the past decade, however, have revealed that many species use different strategies in deciding whether to fight or retreat. Most seem able to assess only themselves and not rivals.

Exactly what determines which strategy an animal uses is uncertain, but cognitive ability may play a key role, the idea being that mutual assessment is more cognitively challenging than other tactics.

PRECEDING PAGES: VINCE BURTON *Alamy*

SIAMESE FIGHTING FISH assess one another's fighting ability and show greater aggression toward more formidable opponents.

JANE BURTON *Nature Picture Library*

they are closely matched. As the contest escalates, it will become increasingly costly, but it will also provide increasingly accurate information, and so mutual assessment will continue throughout the contest. The model predicts that the greater the difference in fighting ability between the opponents is, the shorter the contest will be. And indeed for years biologists found exactly this negative relationship in the contests of virtually every species they studied. (To measure fighting ability in contests, biologists use a proxy measure, typically body size or weight.) As a result of this body of work, mutual assessment came to be seen as a fundamental ability of all animals.

In the rush to embrace the notion of a universal capacity for mutual assessment, however, some other interpretations of animal contests went unnoticed for the most part. With mutual assessment, we would expect large losers to persist longer than small ones in contests because the decision of the loser to quit is based partly on the animal's own size or fighting prowess. And if the loser gathers information about the winner, then it should quit sooner if the winner is large. Although few studies examined these associations, some of them showed the predicted positive relationship between loser size and persistence. But there was a hitch: the link between winner size and fight duration was not different from random. This finding suggested that in these instances the loser had information about itself but not about the opponent. These animals were either unable to gather the information, or the information was too costly to gather, or they chose not to use information that would most likely enable them to make optimal fight decisions. In any case, they were exhibiting self-assessment rather than mutual assessment.

Some of these early examples of self-assessment came from the lab of one of us (Elwood). In 1990 he and his colleagues documented this tactic in amphipods, which are small, shrimplike animals. In this species, males engage in a tug-of-war for females, with one male literally grabbing a female from another male's clutches. Unsurprisingly, they found that larger males are more successful than their smaller counterparts at making and resisting takeovers. And yet the competitors did not appear to be assessing one another: whereas loser weight and contest duration showed a strong positive relationship, winner weight and contest duration were not linked at all.

The biology community largely dismissed this finding as aberrant. But there were other examples, such as that of *Metellina mengei,* a species of orb-weaving spider. During contests between males for access to females, the spiders would stop grappling and stretch out their very long front legs, apparently comparing them. They looked for all the world like they were exchanging information. But here again winner size had no bearing on contest length, showing that this display did not affect the spiders' decisions. The males were unable to evaluate one another, only themselves.

The discovery of self-assessment rather than mutual assessment in the orb-weaving spiders prompted zoologist Phil Taylor, now at Macquarie University in Sydney, to get in touch with Elwood. He was preparing a paper on fights in a species of jumping spider and was surprised to find self-assessment rather than mutual assessment in that animal, too. This contact led to a collaborative investigation into why, if the animals use self-assessment, the most common analysis predicted they would use mutual assessment.

Taylor and Elwood used a computer simulation to model a population of animals engaging in contests using self-assessment rules, in which the loser gathers no information about the winner's ability. The results showed a negative relationship between size difference and contest duration—the more the opponents differed in size, the shorter the contest—exactly the same relationship predicted for mutual assessment. The reason

is that with a large size difference the loser would necessarily be very small, whereas with a small difference the loser is more likely to be somewhat bigger. Thus, if the result is driven only by the loser, but the analysis uses the size difference, then it will appear to support mutual assessment. In other words, the tool that biologists had used for many years to study competing animals could give a false impression of their assessment abilities.

Studies of stalk-eyed flies—bizarre-looking insects whose eyes are situated on the tips of antlerlike stalks that stick out from their heads—illustrate the problem. Male flies compete for food and females. An early study that relied on size difference concluded that these animals compare their eye stalks to determine the winner. Researchers subsequently reanalyzed the original data using the winner and loser size separately with fight duration. This approach showed clearly that the loser uses information about its own size in deciding whether to continue competing but must not have information about winner size, because that factor has no effect on how long the contest lasts.

A positive or nonsignificant relationship between winner size and contest duration, coupled with a positive relationship between loser size or fighting prowess and contest duration, indicates what we call “pure self-assessment”—the participants are deciding whether to compete or retreat solely on the basis of the information they have about themselves. But if we detect a *negative* relationship of winner size to contest duration, that does not necessarily mean that the loser is gathering information about the winner. Instead another decision process, dubbed cumulative assessment, may be at work. With cumulative assessment, the animals can inflict costs on one another, and the larger the size difference, the greater the costs will be for the smaller contestant, which then gives up as soon as a threshold of costs is reached. It might seem like splitting hairs, but there is a major difference between cumulative assessment and mutual assessment. The former does not involve any direct assessment of the opponent; the contest is settled only after costs have accumulated. The latter does not involve a threshold; rather the information gathered about the opponent and self informs the decision to keep competing or throw in the towel.

Although cumulative assessment and sequential assessment produce the same negative correlation between winner size and contest duration, we have some tools for determining which of the two decision processes animals are using when they compete. First, we can set up contests in the lab wherein participants in each contest are matched for size, but average size varies from contest to contest. If the opponents are using cumulative assessment, the eventual loser knows only its own state and thus large losers should persist for longer. In this case, we would expect to see a positive correlation between average size and duration. In contrast, with sequential assessment the decision is based on relative size difference, and with size matching there is no difference regardless of the absolute pairs. We would thus expect to see no link between average pair size and contest duration if the opponents are using sequential assessment.

We can also use the nature of escalation and de-escalation of the contests to discriminate between the two decision strategies. Animals using cumulative assessment should exhibit phases of escalation interspersed by phases of lower-cost activities. Those using sequential assessment, on the other hand, should progress linearly from low- to high-cost activities.

DECISIONS, DECISIONS

THE REVELATION that animals use different forms of assessment when competing, along with the development of research protocols that can discriminate among these strategies, has led to a resurgence of interest in animal contests. Studies of a wide range of species have emerged in the past decade and from them many new examples of creatures that use one or the other of these three main strategies. Interestingly, most of them show self-assessment.

Other studies have shown that some species use a combination of approaches to figure out when to back down from a contest and when to go to the mat. For example, in mangrove killifish, individuals compete over territory. Researchers led by Yuying Hsu of National Taiwan Normal University found that opponents decided whether to fight based on prefight displays. During this phase of the encounter, the larger one opponent was, the more likely the smaller contestant was to back down before the encounter escalated to fighting. Those rivals that were closer in size tended to escalate to fighting. They appeared to get no further information about their opponents after the fight began, however. This strategy, termed switching assessment, seems to be a mash-up of mutual assessment followed by self-assessment.

Our studies of hermit crabs revealed yet another form of decision-making. Hermit crabs salvage the shells of dead snails and use them to protect their delicate abdomen. The crabs will fight for access to a rival’s shell. We found that during these attempted takeovers the opponents get different information depending on their role. Attackers seemed to receive little or no information about defenders, whereas defenders were influenced by the way the attackers fought. Thus, within the same contest one role seemed to use self-assessment, whereas the other used mutual assessment.

The existence of all these forms of assessment raises an intriguing question: What determines which decision-making strategy an animal employs? One possible factor is cognitive ability. Some experts have argued that just knowing one’s own state is simple but that integrating or comparing it with the state of the opponent is more cognitively challenging. This idea remains to be systematically tested, but a quick survey of taxa that differ in their cognitive sophistication provides tentative support for it. For instance, sea anemones have a simple neural network, and analy-

MAXIMILIAN WEINZIERL *Alamy* (1); SUE DALY *Nature Picture Library* (2); ALEX MUSTARD *Nature Picture Library* (3)

FIGHT CLUB: House crickets (*Acheta domesticus*) (*1*) use cumulative assessment to make decisions about fighting. Beadlet anemones (*Actinia equina*) (*2*) employ self-assessment. In contests between common hermit crabs (*Pagurus bernhardus*) (*3*), attackers use self-assessment, whereas defenders use mutual assessment.

ses of their fights suggest they use self-assessment. At the other extreme, complex animals with refined perceptual systems, such as cuttlefish, have been found to use mutual assessment.

In line with this pattern, we expect that mammals, with their large, highly developed brains, will use mutual assessment. But few experiments of the kind needed to distinguish among the various assessment models have been carried out on mammals. A mammal for which we do have some experimental data on assessment is the domestic pig. One of us (Arnott) has been working with Simon Turner of Scotland's Rural College and Irene Camerlink of the University of Veterinary Medicine Vienna to study pig aggression with an eye toward improving the welfare of farmed animals. Pigs naturally form dominance hierarchies. During pig farming it is routine practice to regroup pigs together at various stages of the production cycle. Whenever the animals are regrouped, a period of intense aggression ensues as the animals hash out a new hierarchy. These repeated bouts of aggression pose a major welfare issue.

When we took a closer look at this aggression, we determined that pigs use mutual assessment but require prior contest experience to become proficient at it. The next step was to see if we could provide the necessary experience in a manner that avoids costly aggression. To that end, we decided to experiment with manipulating the pigs' early-life rearing environment. We found that piglets that were allowed to mingle with another litter prior to weaning subsequently developed enhanced social skills that enabled them to have shorter contests when introduced to an unfamiliar individual in later life. Our results suggest that simple early-life socialization may be an effective, practical intervention that farmers can adopt to curb fighting among adult pigs during regrouping.

One more aspect of contests warrants mention in the discussion here. Although cognitive capacity probably helps to determine which kind of assessment an animal uses, it is not the only factor at work. The value of the resource to be won or lost can itself influence decision-making. The shells of hermit crabs are a prime example. During contests over shells, one crab termed the attacker (usually the larger crab) approaches and grasps the shell of the defender, and the defender then withdraws into its shell. The attacker then vigorously hits its shell against the defender's again and again. This shell rapping, as it is known, ends with either the defender being dramatically evicted or the attacker giving up and retreating empty-handed.

We have found that the crabs consider multiple aspects of shells when determining how hard to fight for them. A key variable is the size of the shell relative to the size of the crab—the ideal size is small enough to carry around with minimal energy expenditure but big enough to accommodate a certain amount of growth. The crabs modify their behavior depending on their assessment of their own shell and that of their opponent. When attackers have poor shells and their opponents have good shells, the attackers are more likely to escalate aggression and take their opponents' shell; when defenders have poor quality shells, they will oppose the seizure less vigorously.

So next time you are watching a wildlife documentary with animals fighting, you will know there is a lot going on in that interaction. In many cases, though—as in that of the giraffes—whether the creatures are truly "sizing each other up" remains to be determined, despite what the narrator may tell you. SA

MORE TO EXPLORE

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MEDICINE

DARWIN'S CANCER FIX

Principles of evolution and natural selection drive a radical new approach to drugs and prevention strategies

By James DeGregori and Robert Gatenby

Illustration by Maria Corte

THIS YEAR AT LEAST 31,000 MEN IN the U.S. will be diagnosed with prostate cancer that has spread to other parts of their body, such as bones and lymph nodes. Most of them will be treated by highly skilled and experienced oncologists, who have access to 52 drugs approved to treat this condition. Yet eventually more than three quarters of these men will succumb to their illness.

James DeGregori is a professor of biochemistry and molecular genetics at the University of Colorado Anschutz Medical Campus and is author of *Adaptive Oncogenesis: A New Understanding of How Cancer Evolves Inside Us* (Harvard University Press, 2018).

Robert Gatenby is a physician and chair of the radiology department at the Moffitt Cancer Center in Tampa, Fla. He is also a member of the integrated mathematical oncology department there.

Cancers that have spread, known as metastatic disease, are rarely curable. The reasons that patients die despite effective treatment are many, but they all trace back to an idea popularized in 1859 by Charles Darwin to explain the rise and fall of species of birds and tortoises. Today we call it evolution.

Think of a cancer cell like Darwin's Galápagos finches, which had slightly different beaks on various islands. Finches eat seeds, and seeds on each island had different shapes or other characteristics. The bird with a beak shape best matched to the local seed got the most food and had the most offspring, which also had that particular beak shape. Birds with less adaptive beaks did not make it. This natural selection ensured that different finch species, with various beaks, evolved on each island. The key is that when two groups of critters compete in the same small space, the one better adapted to the environment wins out.

Cancer cells evolve in a similar manner. In normal tissue, regular noncancer cells thrive because they are a good fit for the biochemical growth signals, nutrients and physical cues they get from surrounding healthy tissue. If a mutation creates a cancer cell poorly adapted for those surroundings, it does not stand much chance initially: normal cells outcompete it for resources. But if the surroundings are further damaged by inflammation—sometimes a growing cancer can cause this itself—or old age, the cancer cell does better and starts to outcompete normal cells that used to crowd it out. The change in the surroundings ultimately determines a cancer cells' success.

This is a theory we call adaptive oncogenesis, and we have found evidence that supports it in the way cancer takes off when we change its cellular environment in experimental animals, although the internal workings of the cancer cell have not changed. Doctors have also observed this acceleration of cancer in humans with tissue-disturbing ailments such as inflammatory bowel disease. The overall implication is that we can best understand cancer by looking at its surroundings rather than solely focusing on the mutations inside a cell. By reducing tissue alterations caused by processes such as inflammation, we can restore a more normal environment and—as we have shown in animal studies—prevent cancer from gaining a competitive edge.

Our evolutionary perspective also has inspired a different approach to cancer therapy, one that we have successfully tested in small clinical trials. Doctors dump a lot of chemotherapy drugs on a cancer in an effort to kill every last trace of the threat, and at first this often looks like it works. The tumor shrinks or goes away. But then it comes back and is resistant to the drugs that once killed these cells, akin to crop-destroying insects that evolve resistance to pesticides. In a clinical trial with prostate cancer patients, one of us (Gatenby) tried an alternative to the scorched-earth approach, applying only enough chemo to keep the tumor tiny without killing it entirely. The goal was to maintain a small population of vulnerable chemosensitive cells. That population did well enough to prevent cells with an unwanted new trait—chemoresistance—from taking over. In a group of patients in which tumors usually start growing uncontrollably after 13 months, this regimen has kept tumors under control for 34 months on average—with less than half the standard drug dose.

The results of our prevention and therapeutic strategies may point to a way to ward off cancer before it becomes a danger to life and limb and to save many patients for whom a regimen of giant, toxic drug doses has failed.

WHY DO WE GET CANCER?

IF YOU ASKED almost any doctor or cancer researcher, "Why is aging, smoking or radiation exposure associated with cancer?" you would probably get a short answer: "These things cause mutations." This assessment is partly true. Exposure to cigarette smoke or radiation does cause mutations in our DNA, and mutations do accumulate in our cells throughout life. The mutations can provide cells with new properties, such as hyperactive growth signals for cell divisions, reduced death rates or even an increased ability to invade surrounding tissue.

Yet this simple explanation, focused on changes within cells, overlooks the fact that a major driver of evolutionary change in any single cell—or in entire collections of them, such as human beings—is outside, in the cell's environment.

We know that the evolution of species on the earth has been highly dependent on environmental perturbations, including dramatic changes to landmasses, the gases in the air and water, and ambient temperature. These changes led to selection for new adaptive features in organisms, producing amazing diversity. As Darwin wrote in *On the Origin of Species* in 1859, "Owing to this struggle for life, any variation, however slight and from whatever cause proceeding, if it be in any degree profitable to an individual of any species, *in its infinitely complex relations to other organic beings and to external nature,* will tend to the preservation of that individual, and will generally be inherited by its offspring" (emphasis added). Darwin proposed that competition for limited resources would drive selection for individuals with traits that were best adapted to the environment. And when environments changed, so would these pressures, selecting

IN BRIEF

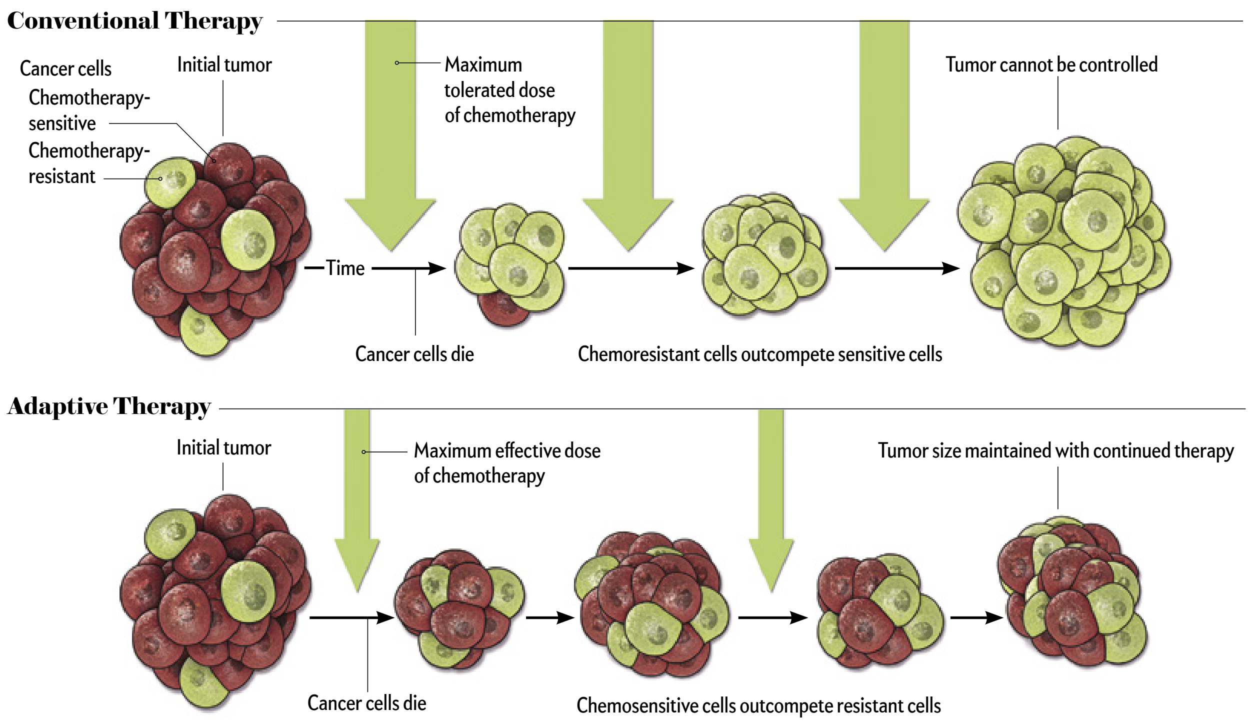
Medical efforts to defeat cancer typically focus on malignant mutations within a cell and administer large doses of toxic drugs in an attempt to eradicate the disease.

A new concept emphasizes that cancer growth is stimulated by changes outside the cell, alterations in the surrounding tissue that accelerate the evolution of cancerous traits.

The evolutionary approach, tested in animals and humans with advanced prostate cancer, sharply limits the natural selection of cancer cells through a more judicious use of chemotherapy.

Controlling Cancer

Oncologists typically treat aggressive cancers with strong responses. They hit the tumor with the "maximum tolerated dose," or the heaviest amount of anticancer drugs that a patient can take. Because cancer drugs also affect normal cells, the dangerous effects on the patient's body are the only real limit on dose size and treatment length. But research that looks at tumor growth from an evolutionary perspective indicates this scorched-earth strategy may be one reason that tumors rebound and kill patients. Any cancer cells that survive the initial assault have traits that let them resist the drug, and they grow readily in ravaged and drug-saturated tissue. An alternative called adaptive therapy aims to use smaller doses that prevent the tumor from evolving total resistance. Tests in prostate cancer patients show that the first round of treatment shrinks the tumor but allows a few cancer cells that remain sensitive to the drug to survive. Those cells keep rival, drug-resistant cells from taking over the tumor if it grows back. Because the tumor contains these sensitive cells, a second round of treatment knocks the size back down, and subsequent rounds have similar effects.



for new traits that were better tuned to the new surroundings.

Similar Darwinian dynamics should apply to the evolution of cancers in our body. Even though we trained as a molecular biologist (DeGregori) and a physician (Gatenby), evolution and ecology have always fascinated both of us. Our extensive reading in these areas, while initially driven by what we thought was curiosity unrelated to our day jobs, revealed unappreciated parallels between the driving forces of evolution and our observations of cancer development and cancer patients' responses to therapy.

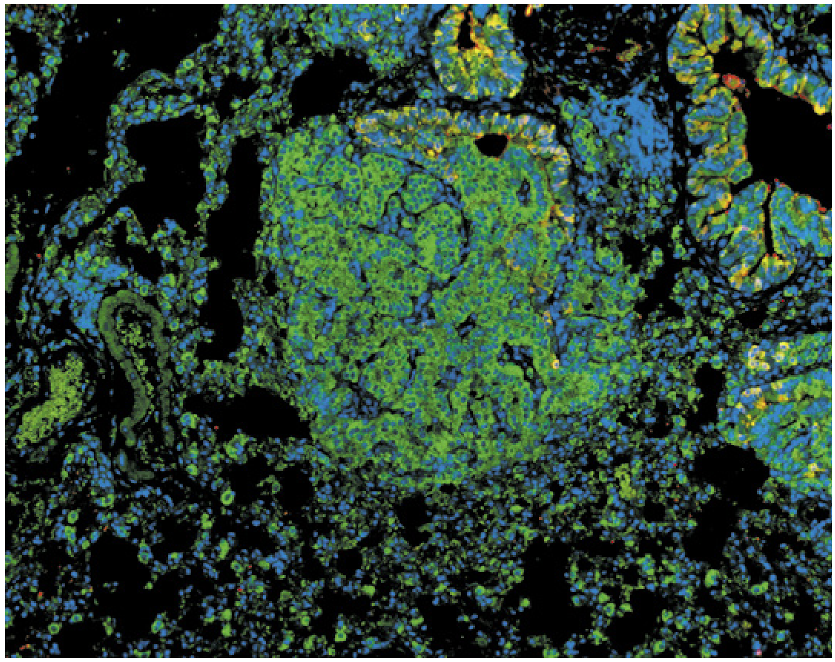
For instance, cancer researchers typically believed that a cancer-causing mutation would always confer an advantage to a cell that acquired it, but we recognized a classic evolutionary principle at work: A mutation does not automatically help or hinder an organism. Instead its effects are dependent on features of the local environment. In Darwin's finches, there is no "better" beak shape per se, but certain beaks improve survival under certain conditions. Similarly, we reasoned that a mutation that turns on a cancer-causing gene does not provide an inherent advantage to the cell and can, in fact, be disadvantageous if it makes that cell less able to use the resources of the tissue immediately around it.

We were also inspired by the punctuated equilibrium theory of paleontologists Niles Eldredge and Stephen Jay Gould, who noted that species often maintain stable traits through millions of years of fossil records, only to suddenly evolve rapidly in response to a dramatic environmental change. This concept stimulated our ideas about the way that some tissues could be initially unfavorable to cell mutations, but changes in those tissues, such as damage and inflammation in a smoker's lungs, could stimulate evolutionary change—sometimes leading to cancer.

We first saw this dynamic at work with aging-associated changes in bone marrow that led to the development of leukemias. Working with groups of young and old mice in DeGregori's Colorado lab, Curtis Henry, now at Emory University, and Andriy Marusyk, now at the Moffitt Cancer Center, created the same cancer-causing mutations in a few of the mice's bone mar-

Illustration by Mesa Schumacher

row stem cells. The results showed that the same cancer-causing mutations can have very different effects on the fate of these cells, depending on age: the changes promoted the proliferation of mutated cells in the old mice but not in the young ones. And the determining factor did not appear to be in the mutated cells but in the metabolism and gene activity of the normal cells around them. For example, the activity of genes important for stem cell division and growth was reduced in nonmutated stem cells in the bone marrow of old mice, but it was restored in these cells when we introduced the cancer-causing mutation. Yet the mutation that helped these cells had bad effects on the mice. These stem cells normally generate key players in the body's immune system, but the population explosion of the cancer-mutated version of the cells instead led to the development of leukemias.



EARLY TUMORS, such as this one (*bright green*) in lung tissue, grow because they develop traits that let them outcompete normal cells.

On the other hand, the fit young stem cells in the tissues of a young mouse already had levels of growth and energy use that nicely matched what their surroundings could provide. Therefore, such cells did not benefit from the cancer-causing mutations when we introduced them. The mutated cell populations did not grow. By favoring the status quo, youth is tumor-suppressive.

Why does any of this matter? Although we can avoid some mutations by not smoking and keeping clear of other mutagenic exposures, many, if not most, of the mutations that we accumulate in our cells during life cannot be dodged. But this new focus on tissue environments introduces a way to limit cancer: reversing tissue alterations caused by aging, smoking and other insults will reduce the success of cancer-causing mutations. The mutations will still occur, but they will be much less likely to give cells an advantage and thus will not grow in number.

Of course, there is no Fountain of Youth to reverse or prevent aging. Doing the things we know we should, such as exercising, eating a balanced diet and not smoking, can improve the maintenance of our tissues, which may be the best strategy we can use for the moment. But if we can figure out what key tissue environmental factors favor cancer development, we should be able to change these factors to limit malignancies. Indeed, in our mouse experiments, we showed that when we reduced the activity of inflammation-causing and tissue-damaging proteins in old mice, cells with the cancer-causing mutations did not proliferate; normal cells maintained their dominance. But we must proceed cautiously. Blocking inflammation in mice living in sterile cages may reduce cancer, but a similar strategy in people in the real world could limit defenses against infections because inflammation is part of our immune response.

FROM PREVENTION TO THERAPY

IN ADDITION to primary prevention, an evolutionary understanding can help make therapies for existing cancers more effective by reducing the nasty tendency of such cells to develop drug resistance. The evolution of resistance happens in other realms. Perhaps the most familiar example is the centuries-old contest between farmers and crop-destroying insects. For more than a century pesticide manufacturers produced a steady stream of new products, but the pests always evolved resistance. Eventually manufacturers recognized that trying to eradicate the pests by spraying high doses of pesticides on fields was making the problem worse because of an evolutionary process termed competitive release.

To understand competitive release, remember that all the insects within a large population occupying a field are continuously competing with one another for food and space, and they are not identical (as is also the case for cancer cells). In fact, for nearly every trait, including sensitivity to a pesticide, there is inevitable variability within a population. By spraying a large amount of insecticide (or administering a large dose of chemotherapy), the farmer (or oncologist) may kill the vast majority of insects (or cancer cells). Yet a few insects (or cells) have traits that make them less vulnerable, and with the highly vulnerable organisms removed, the resistant ones begin to spread. A farming strategy called integrated pest management tries to deal with this situation by using pesticides sparingly. Rather than trying to eradicate the pests, farmers spray only enough to control them and lower crop damage without resulting in competitive release. In this way, sensitivity of the pest to the pesticide is maintained.

The medical community has learned a similar lesson with antibiotics: excessive use must be stopped to curtail the constant evolutionary cycle that produces the development of drug-resistant pathogens. But this lesson has not yet taken hold in the cancer field.

MOUMITA GHOSH

Like farmers who used to blast fields with huge amounts of insecticides, doctors today typically give chemotherapy to patients at "maximum tolerated dose (MTD) until progression." Nearly all cancer drugs also damage normal tissues in the body, and these side effects can be very unpleasant and even fatal. MTD means the drugs are given in amounts that fall just short of killing the patient or causing intolerable side effects. Giving the same treatment "until progression" emerges from a traditional metric of treatment success, based on the tumor's change in size. Drugs are deemed successful when the tumor shrinks, and the treatment is abandoned if it gets bigger.

To most patients and doctors, treatment designed to kill the maximum number of cancer cells with relentless administration of the greatest possible amount of lethal drugs feels like the best approach. But as in the control of insects and infectious diseases, this strategy, in the setting of an incurable cancer, is often evolutionarily unwise because it sets in motion a series of events that actually accelerate the growth of drug-resistant cancer cells.

The other evolutionary lesson learned from pest control is that a "resistance management plan" can keep unwanted populations in check, often indefinitely. Can this strategy also lead to better outcomes for patients with incurable cancers? The answer is not yet clear, but there are hints from experimental studies and early clinical trials that it could do just that.

An evolution-based strategy for a patient who, after a month on an anticancer drug, had a 50 percent reduction in tumor size would be to stop treatment. This approach would be used only when we knew from past experience that available treatments—chemo, hormone therapy, surgery, immune system boosters—could not cure the cancer in this patient. Because a cure would not be achievable, the goal would instead be to keep the tumor from growing and metastasizing for as long as possible. By stopping therapy, we would leave behind a large number of treatment-sensitive cancer cells. The tumor would then begin to grow back and eventually reach its previous size. Yet during this regrowth period, because no chemotherapy would be administered, the majority of tumor cells would still be sensitive to the anticancer drug, not resistant to it. In effect, we would use the sensitive cells that we could control to suppress the growth of the resistant cells that we could not control. As a result, the treatment would be able to maintain tumor control much longer than the conventional approach of continuous administration of maximum dose and, because the drug dose would be significantly reduced, with much less toxicity and better quality of life.

Gatenby's lab began by investigating the approach in 2006 using mathematical models and computer simulations. Although such models had rarely been employed in cancer-treatment planning, the large number of possible treatment options required us to adopt an approach, common in physics, in which mathematical results help to define experimental methods that are likely to be successful. Our models defined the levels of drugs we wanted to test. The next step was to try those doses in mouse experiments, and doing so confirmed that tumor control could be greatly improved by evolution-based strategies.

The results were good enough to prompt a move into the clinic and a test on human cancer patients. We were joined in this effort by Jingsong Zhang, an oncologist at the Moffitt Cancer Center, who treats men with prostate cancer. With the help of Zhang, along with mathematicians and evolutionary biologists, we developed a model of the evolutionary dynamics of prostate cancer cells during treatment. We used this model to simulate the responses of prostate cancer to a variety of drug doses administered by an oncologist. Then we ran these encounters over and over again until we arrived at a series of doses that kept the cancer in check for the longest time without increasing the population of drug-resistant cells.

Next we asked patients with aggressive prostate cancer that had already metastasized to other locations—the kind that doctors cannot completely eliminate from the body—to volunteer for a clinical trial. So far the patients have had excellent outcomes. Of the 18 people enrolled, 11 are still in treatment. Standard therapy typically maintains control of metastatic prostate cancer for an average of about 13 months. In our trial, average tumor control is at least 34 months, and because more than half of our patients are still being treated actively, we cannot yet place an upper limit on how well they do. Furthermore, this control is being achieved using only 40 percent of the drug dose that patients would have received in standard treatment. But it is still early days for this treatment approach. Just because it works in prostate cancer does not mean it works in stomach cancer, for instance. And it may be tough to convince patients, even those with an incurable disease, that the best approach is not to kill as many cancer cells as possible but as few as necessary.

THE RULES OF CANCER

IN MANY WAYS, the evolutionary model of cancer development and treatment serves to dispel the "mystery" of cancer. The proclivity of the disease to strike without any clear cause, along with its ability to overcome and return even after highly effective and often highly toxic therapy, can be viewed by patients and caregivers as both hopelessly complicated and magically powerful. In contrast, understanding that cancer obeys the rules of evolution like all other living systems can give us confidence that we have a chance to control it. Even without a cure, by using our understanding of evolutionary dynamics, we can strategically alter therapy to get the best possible outcome. And prevention strategies can be geared toward helping to create tissue landscapes in the body that favor normal cells over cancer cells.

For more than a century the cancer research community has sought "silver bullets"—drugs that can eliminate all cancer cells while sparing all normal cells. Cancer has been taking advantage of evolution to sidestep these drugs. But we can use evolution, too. We have the opportunity to expand the work of Darwin and his successors to develop more realistic approaches to both prevent and tame this deadly disease. SA

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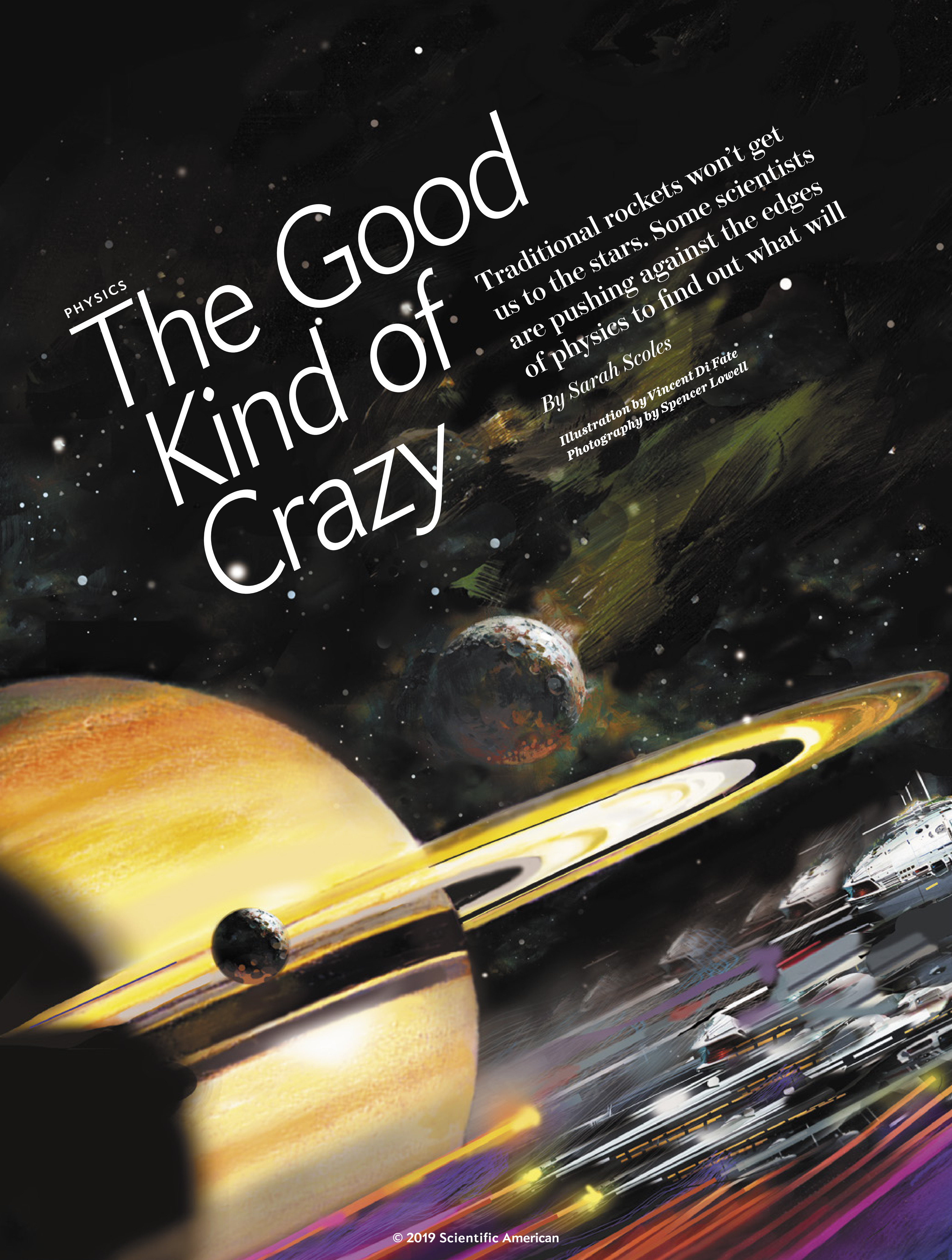


PHYSICS

The Good Kind of Crazy

Traditional rockets won't get us to the stars. Some scientists are pushing against the edges of physics to find out what will

By Sarah Scoles

Illustration by Vincent Di Fate
Photography by Spencer Lowell

Sarah Scoles is a Denver-based freelance science writer, a contributing writer at *WIRED Science,* a contributing editor at *Popular Science,* and author of the book *Making Contact: Jill Tarter and the Search for Extraterrestrial Intelligence* (Pegasus Books, 2017).

WHEN HEIDI FEARN, A THEORETICAL PHYSICIST AT CALIFORNIA STATE UNIVERSITY, FULLERTON, returned from sabbatical in 2012, she found a surprise in the laboratory adjoining her office: a man, an *old* man named James F. Woodward. Fearn knew him from around—he was a professor of science history and an adjunct professor of physics. With white hair and eyes perpetually peering over the top of his glasses, he fit the part. Still, she thought, "What the heck is this guy doing in my back room?"

IN BRIEF

Chemical rockets and electrical engines will never propel spacecraft fast enough to reach other star systems in reasonable time frames.

NASA is funding studies of exotic propulsion technologies that might turn out to be crazy—but might also pan out.

One project is investigating the so-called Mach effect; the idea is to use the principle of inertia to generate thrust.

He was, it turns out, being shuffled around spacetime: The university had recently commandeered Woodward's office for a newly created Gravitational Wave Physics and Astronomy Center. The institutional authorities had transferred him into this relatively unused spot.

At first, Fearn viewed him as an intruder, but soon her perspective shifted. Woodward was researching a fringe topic—one way outside Fearn's normal purview. She specialized in quantum optics, how light interacts with matter—a much more mainstream subject than Woodward's interest: a hypothetical form of spacecraft propulsion so powerful that—if real—it could potentially push our species out to the stars.

Or so he claimed. Fearn, whose shaved head and smirk suggest constant skepticism, was not so sure. "I wasn't really convinced that what he was doing was correct," she says. When she walked by every day, what Fearn saw resembled a Physics 101 lab experiment more than a futuristic propulsion system. Woodward's setup had a bolted-down balance with a metal cage on one side, wires running to and fro, and counterweights on the other side. "You can create some very large gravitational effects just by pushing on stuff," Woodward promised her—specifically, the stuff inside the metal box.

He claimed he could induce tiny, ultraquick variations in an object's mass, making it lighter and then heavier. And then, by tugging and shoving it back and forth strategically as its mass changed, he could create *thrust.* He showed her little blips on the output graph, each a *vroom. Right,* Fearn thought. But she side-eyed that graph daily. "Every time I walked past, the blip seemed to get bigger and bigger," she says. Eventually Woodward asked if she wanted to help.

She had tenure, and she liked *Star Trek,* so "Yeah, sure," she said. Working together since then, the odd couple has been developing MEGA: the Mach effect gravity-assist drive. And although it is still on the outer limits of mainstream science, it has gained credibility. Three other labs have seen similar thrust from copycat setups, and MEGA has netted two of NASA's most competitive grants.

These are not just any grants, though. They come from the agency's spaciest department: the NASA Innovative Advanced Concepts (NIAC) Program, which funds research that would be "huge if true." In 2017 and 2018 advanced propulsion—sending more mass through more space in less time using less fuel than traditional rockets—has accounted for around 20 percent of the awards. These projects range from really exotic to merely eccentric, but they all diverge from the traditional path and aim for somewhere new.

THE EDGE OF SCIENCE FICTION

THE NIAC GRANTS are trying to remedy the fact that propulsion has stood relatively still since the mid-1900s. Most spacecraft use chemical propellants, the space version of gasoline. In conventional rockets, these chemicals combine and react with one another to heat up and expand. Too big for their chamber's britches, they shoot out the back of the craft, creating thrust. Thrust is simply using force in one direction to create

IN THEIR SHARED LAB, James F. Woodward (*left*) and Heidi Fearn (*right*) search for a new means of space travel.

an equal force in the opposite direction. When you push into the wall of a swimming pool, thrust is what pushes you back.

Fuel, though, is heavy and inefficient. To get truly huge thrust, a vehicle would need to carry so much gas that it would never get off the ground. For missions to other solar systems or even travel within our solar system at a much quicker pace, chemical fuel is just not going to cut it. "There's only so much energy in those propellants," says John Brophy of NASA's Jet Propulsion Laboratory (JPL). He leads another NIAC-funded project called A Breakthrough Propulsion Architecture for Interstellar Precursor Missions. "It doesn't matter how smart you are, how big a nozzle you make, you can't beat that problem," Brophy notes.

A few deep-space projects, like NASA's Dawn mission to the asteroid belt, have instead used electric propulsion. Such systems typically use electric power to accelerate charged particles, which can then shoot from the rocket at speeds up to 20 times faster than traditional fuels. But these, too, have been stuck in a rut. "It turns out that almost all the electric thrusters that have been invented were invented in the 1950s and 1960s," says Dan M. Goebel, a senior research scientist at JPL. "It's like there almost hasn't been a new idea since then."

NIAC, though, is all about new ideas. The program functions as NASA's venture capital arm, in that it supports technologies that *might* pan out, big-time. "Crazy" stuff, according to Jason Derleth, NIAC's program executive. "What I mean by 'crazy' is something nobody is thinking about," Derleth says. Something 10 times better than current technology, swooping in to push on the sluggish status quo. In start-up-world-speak, this would be called "disruption."

As an example, Derleth cites the work of Philip Lubin of the University of California, Santa Barbara. A few years ago Lubin proposed a project nicknamed Starchip Enterprise: a tiny satellite equipped with a "light sail" (a new iteration of an idea that predates the project). From Earth orbit, powerful lasers would shoot toward the sail. When they hit, the sail would reflect the light, and its momentum would thrust the spacecraft forward. NIAC awarded Lubin grants in 2015 and 2016, and he now works with a project from the Breakthrough Initiatives to send a laser-powered light sail to the closest star. This is the good kind of crazy, which NIAC likes. "It's just crazy enough that it might work," Derleth says. "NIAC is for going up to the edge of science fiction but not crossing over." He adds, "We do our best to not cross over."

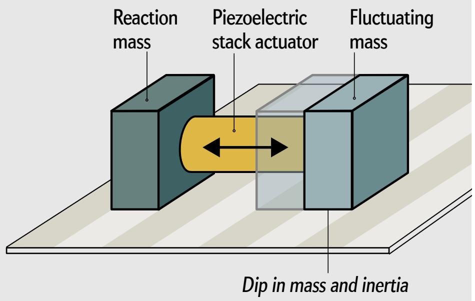
But the gap between science and fiction is fractional, at these low "technology readiness levels" (TRLs), a rating system NASA uses to assess how mature an innovation is. The solar panels on its Mars InSight lander rate a TRL 9, meaning already out in space, working. NIAC, though, seeks TRLs 1, 2 and, sometimes, 3—early-stage projects that need more baking before they are deployed in the real world.

Around 200 groups typically submit NIAC Phase I proposals every year, and the agency okays just 15 to 18. With $125,000 apiece, scientists get nine months to do "a quick turn of the crank to see if something is really

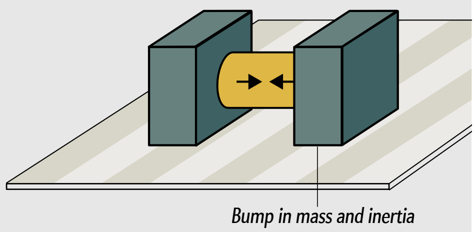
Mach Effect Thrust

To push a spacecraft faster than conventional rockets can, scientists are turning to novel, sometimes exotic, concepts. One proposal is to harness the so-called Mach effect—the idea that when you accelerate an object, you can change its mass slightly, and that these fluctuations can achieve thrust—a push in one direction—without expelling propellant.

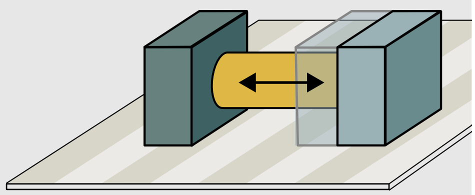
Step 1
Two masses are separated by a stack of piezoelectric disks, which are ceramics that expand and contract when an alternating voltage is applied to the stack. As the stack expands, the mass on the right becomes lighter. Its inertia dips, making it easy to push forward.



Step 2
As the piezoelectric stack contracts, the fluctuating mass on the right becomes more massive. That bumps up its inertia, making it harder to pull back. The constant mass on the left is dragged forward more than the backward movement of the fluctuating mass on the right, shifting the center of mass forward.



Step 3
As this cycle repeats, the center of mass of the total system moves forward and accelerates.



feasible," Derleth says. If no deal breakers pop up, researchers can apply for the $500,000 Phase II grant. "It is one of the hardest proposals to write, with the lowest win rate in aerospace," he says. "I consider these folks to usually be the cream of the crop."

Eight of the 47 projects funded in the past two years and three Phase II selections have dealt with advanced propulsion. But NIAC is taking a gamble on every project—hoping at least some represent a true outside force, something that can push propulsion in a new direction.

THE PRINCIPLE OF INERTIA

"This has not been an exploration guided by genius and profound insight," Woodward says one February day over a video conference call. He and Fearn are sitting in the office that has become their joint headquarters, where a box of tissues sits next to a pair of forceps. Fearn's office, empty, shows on a screen, forest-tall metal bookshelves bungee-corded together in the background. Together—as Fearn proclaims the project belongs to Woodward and Woodward protests with equal and opposite force—they describe how MEGA might work. It begins with inertia.

It is a simple principle, one you experience every day: the tendency of things to keep moving in the same direction they already are or to stay stopped if they are standing still. But scientists lack a solid explanation for why inertia exists. It just kind of ... is. In the late 1880s Austrian physicist Ernst Mach came up with the seed of one idea: inertia is the result of all the gravitational influence of all the matter in the universe.

Anything inside a spacecraft engine, then, feels a gravitational pull from nearby stuff as well as that billions of light-years distant. And an object's mass will change a bit every time it accelerates or decelerates relative to all that stuff. Other physicists around the same time, including Benedict Friedlaender and August Föppl, held similar relativistic ideas.

But Albert Einstein is actually the one who named this "Mach's principle," after reading Ernst Mach's earlier musings on the subject. More modern physicists—including the late Donald Lynden-Bell, who in 1969 first proposed that the centers of galaxies contain supermassive black holes—have taken up the cause. As a student, Lynden-Bell became intrigued by the idea, and his adviser gave him a 1953 paper by physicist Dennis Sciama, who articulated the most complete version of Mach's idea. Sciama's work is what inspired Woodward, too. Although Lynden-Bell maintained interest throughout his career, it was a side project; he subscribed to a research philosophy almost the opposite of Woodward's: "Doing bread-and-butter science, straightforward extensions of what is known in order to elucidate new phenomena, is the main job," he wrote in 2010. "We should not spend all our time groping at great problems that may be beyond our capacity."

Woodward disagrees, hewing more to a "go big or go home" ethos. And so he has continued to try to apply Mach's principle to spacecraft engines. Engineer Marc Millis, who used to head NASA's Breakthrough Propulsion Physics Program, sees promise here. "Unlike other claims, the [Mach effect thruster] … is rooted in open questions in physics," he says.

The idea of a thruster based on Mach's principle goes like this: By deforming an object, you accelerate its innards (imagine crumpling a piece of paper—when

Illustration by Jen Christiansen

you crush it, you are moving its parts). And when you accelerate something, you change its energy. If you change its energy—according to Einstein's revelation that $E = mc^2$—you change its mass. If you change its mass, you affect its inertia. And if you mess around with inertia, you are messing with how the object relates to the entire rest of the universe.

What this means, in a practical sense, is hard to say. But Woodward and Fearn have tried to bring these ideas down to earth. Inside their space drive is a clamped-together stack of "piezoelectric disks," ceramics that expand and contract (like pieces of paper crumpling and uncrumpling) when shocked with a voltage. Some of that acceleration changes the internal energy of the disks, which then changes their mass: They grow heavier, lighter, heavier, lighter. If you pull on them when they are light and shove them away when they are heavy, you get thrust—without having to use any fuel. "Picture yourself standing on a skateboard with a 10 pound brick attached to you via a bungee cord," wrote Woodward's former graduate student, Tom Mahood, in an attempt to make this all slightly understandable, which was posted on his Web site in April 2012. "If you throw the brick away from you, you and the skateboard will move in one direction, and the brick will head in the opposite direction." Thrust! It is not a perfect analogy, Woodward points out—but he admits he has never been able to come up with a physical metaphor that both makes sense and is totally correct.

It sounds sketchy, and some scientists believe it violates the principle of conservation of momentum, but some studies (and Woodward and Fearn) disagree. Yet the idea caught the attention of Gary Hudson, president of the Space Studies Institute, a California-based organization once headed by famed theoretical physicist Freeman Dyson. The group set up an Exotic Propulsion Initiative in 2013, with first funds going toward Woodward and Fearn.

Woodward soon began sending copies of his setup to people at other labs, so they could try to replicate the thrust. And Fearn and Lance Williams, then a scientist at Aerospace Corporation, a federally funded research and development center in El Segundo, Calif., suggested that the Space Studies Institute run a workshop for advanced propulsers.

Because Williams lived in Colorado and knew it was a pretty place to hole up even if all the participants reneged on their RSVPs, the group settled on Estes Park in the fall of 2016, when aspens on the steeply pitched mountainsides turn the red-orange-fire color of (conventional) rockets. The conference's motto, "Bury the Hatchet," urged cooperation between competitors, and the meeting even had an official lapel pin: a hatchet and shovel crossed into an X.

REPLICATING THE RESULTS

ON THE FIRST DAY, Hudson stood before the gathered crowd, wood paneling and white boards behind him. "In the past, our work has been very solidly grounded in engineering and physics," he said, "and of course exotic propulsion is a pretty controversial subject." But, he went on, it has intrigued him for a long time. Science-fiction writer Arthur C. Clarke once told him that if he wanted to get far from this planet—and come back—he needed one thing: "A physicist who will give you a straight answer to the question, 'What is inertia?'"

"I remembered those words," Hudson said. "The first physicist I encountered who gave me a straight answer was Jim Woodward."

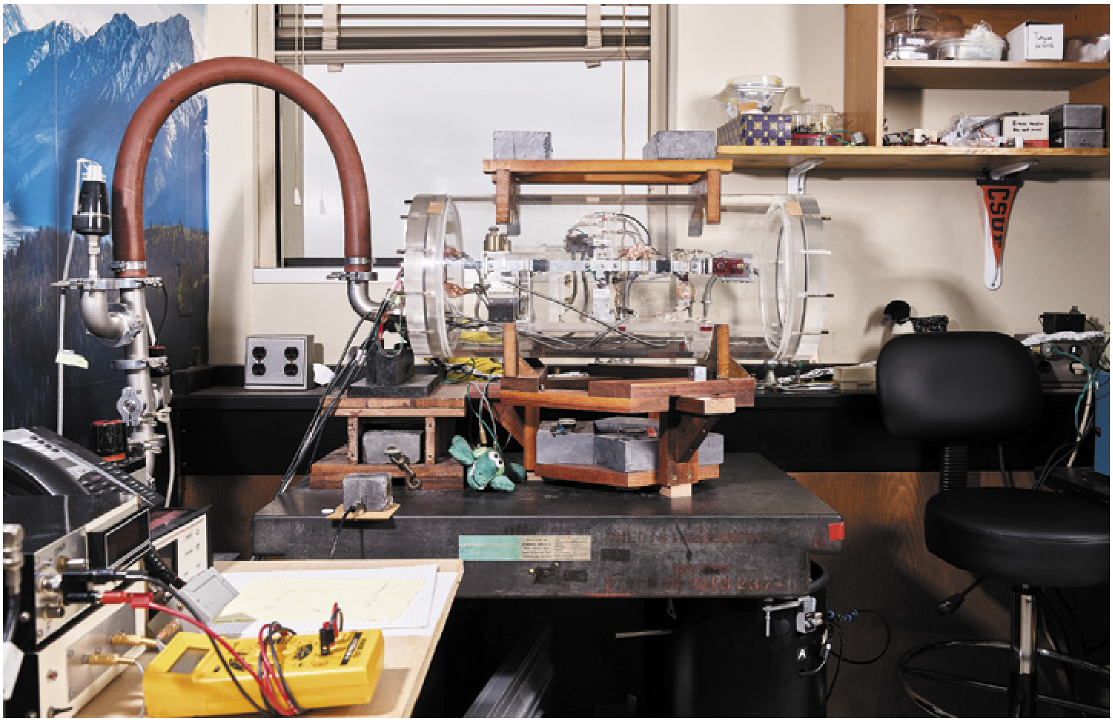
And as the conference tripped along, others' results seemed to—at least to some degree—back up Woodward and Fearn's measurements. They showed thrust from the MEGA setup when the thruster was turned on and not when it was turned off. On the third day, Nembo Buldrini of FOTEC Research and Technology Transfer, an Austrian engineering firm, stepped to the front of the room. He usually evaluates the effects of electric thrusters, but a few years before, Woodward had sent him a Mach effect device.

Buldrini brought up a plot showing his results, side by side with Woodward and Fearn's. "The first thing that is evident is the shape of the curve," he said. Indeed, both showed a dip when the device turned on, a constant thrust while it was powered up, and then an offset spike when it switched off. The thrust numbers differed by an order of magnitude—perhaps, Buldrini said, a problem of calibration. Perhaps not. (Woodward also notes that differences in the balance equipment could account for differences in magnitude.)

Two other groups had similar data with similar thrust patterns. Martin Tajmar of the Technical University of Dresden had only preliminary results, but George Hathaway, an electrical engineer who runs his own consulting firm, had more data. During his presentation, he wore no shoes—only socks with rainbow-colored Einstein faces splashed all over them. His lab, he said, had done its work on antiseismic tables, to make sure the planet's shaking did not mess up off-Earth travel results. And the thrust held up.

After the workshop's early-stage replications, NIAC took notice and gave Woodward and Fearn a 2017 Phase I grant. Which is not, of course, to say either that the thrust is definitively real and not some systematic error—or that, if it is real, the Mach effect causes it. In 2018 Tajmar presented a paper as part of his SpaceDrive project, an initiative to try to replicate, or rule out, fantastic(al) propulsion claims. And, in fact, that study showed anomalously high thrusts—meaning the blips might not be thrust at all but an error or some other phenomenon. At the Space Studies Institute's 2018 workshop, a software engineer named Jamie Ciomperlik presented a simulation showing how vibrations in the system could masquerade as oomph.

In May 2019, moreover, Tajmar published another SpaceDrive paper online, and when he subtracted out other effects that may masquerade as thrust, there was no thrust to see. "Our results challenge the validi-



MEGA, the Mach effect gravity-assist drive, aims to demonstrate a new technique for producing thrust.

ty of the genuine thrust claim on the Mach Effect thruster," Tajmar says. "But further research is needed to definitely confirm that." Woodward says he believes the setup was not configured correctly. The team plans to present new data later this year, and Tajmar says that even if the thrust returns, he does not think the underlying theory is correct.

Millis tends to agree—both that teams could be seeing a false positive and that, if not, the device is not necessarily demonstrating the Mach effect. In some ways, though, the underlying theory matters less than the empirical demonstration. As Lance Williams said during the 2016 propulsion workshop, "If you can levitate a cannonball in front of us, we don't care what the theory is."

"Skeptical doubt is healthy, and the only way to resolve doubt is irrefutable evidence," says Millis, who recently spent three months at Tajmar's lab chasing that evidence. "Despite the replications, [the thrust] still might turn out to be a common measurement artifact," he says. "Then again, it may be a genuine new phenomenon." Although the science is far from settled, MEGA's Phase I results impressed NASA enough that the agency gave the group a Phase II grant in 2018.

LASERS, ANTIMATTER AND NUKES

WOODWARD AND FEARN's experiment is the most exotic of NIAC's propulsion grants. And not all the other researchers who have NIAC funding agree that "exotic" is the way to go.

Brophy's A Breakthrough Propulsion Architecture for Interstellar Precursor Missions is pinning its hopes on lasers. Similar in some ways to Lubin's light-sail lasers, Brophy's lasers will shoot from orbit, beaming light to panels that—like solar panels—turn it into electric power. That electricity feeds into a propulsion system pumped full of lithium. The voltage whacks electrons off the lithium atoms, leaving them with a positive charge. An electric field then accelerates them and routes them out the back of the spacecraft. Brophy wants it to travel 20 times faster than the Dawn spacecraft's ionic propulsion system—whose development he led—for a speed of around 200 kilometers per second.

But the project is still a moonshot. The team is not sure it can point the laser accurately enough or that it can assemble such a big laser array in space or make light-converting panels that generate the necessary 6,000 volts. "That's why it's a perfect NIAC study," Brophy says. "[NIAC experiments are] intentionally right at the ragged edge of whether they are feasible or infeasible."

And some are trying to break away from the electric trajectory altogether. Another NIAC project is targeting an antimatter engine by "cooling down" positrons, which have the same mass as electrons but the opposite charge. In their natural state, these antimatter particles are hotter than the surface of the sun, making them hard to work with and store. But cooled down, they can be kept and controlled and—as this project does—smashed into electrons. The resulting gamma rays could fuel a fusion reaction that then propels the spacecraft.

Another idea braids a beam of neutrons and a beam of laser photons so that the particles do not spread out, or diffract, as they travel through space. The neutron beam corrals the photons by refracting them, or bending their path, and the laser beam's electric field "traps"

the neutrons. The team claims a beam made with a 50-gigawatt laser, shot onto a sail on the spacecraft, could accelerate a one-kilogram probe on a 42-year mission to the nearest star system.

And then, of course, there are nukes. Robert Adams of NASA's Marshall Space Flight Center has a NIAC project called Pulsed Fission-Fusion (PuFF), which combines two nuclear strategies. "The only way we've developed anything fusion-related is with a fission trigger," he says—in other words, using an easier-to-make fission reaction to create conditions extreme enough to kick-start fusion. But a fission-fusion trigger is a lot like a bomb, so Adams started to dream up systems that could *not* be repurposed by a criminal, and he happened on a concept called the Z-pinch. If you generate an electric current in a plasma (in this case, made of lithium), you can use the magnetic field it induces to compress, or pinch, something—in this case, a target made of uranium and deuterium-tritium.

The squished uranium goes critical, and its fission energizes the deuterium-tritium enough to start fusion. Fusion makes neutrons, which get involved in more fission, which raises the thermostat and therefore the fusion rate. The two-stage explosion has the power of a few kilograms of TNT. Nothing to end the world with—but enough that, applied steadily and with a bunch of parallel devices, a 25-metric-ton craft could get to Mars in 37 days (compared with the nine months or so it takes with a chemical engine). In 2018, after applying for it five times, Adams finally got a Phase II grant.

You can think of Adams's biggest problem in terms of a Twinkie. Try to squeeze the Twinkie—that fission-fusion target—uniformly. Impossible! The spongy yellow bread bleeds down into the white filling; the filling squirts out the sides. In PuFF, that leakage means squished-away energy, leaving you without enough to rev up fusion. In the past, that issue was the end of the path for researchers. "They gave up on it and started going down these other roads," he says. None of those roads, though, have led to giant leaps in space propulsion.

A NEW DIRECTION

A HISTORICAL PARALLEL to Adams's project provides a lesson about one reason propulsion has stalled. From 1958 to 1964 the military and NASA spent $11 million ($93 million in today's dollars) on an effort led by Freeman Dyson to develop a nuclear-based propulsion system named Orion, very similar to PuFF. The project's motto? "Mars by 1965, Saturn by 1970." It was not quite military, but it verged on too explosive for NASA, so both organizations wavered in their commitment. Finally, it became a no-go when, in 1963, the U.S. signed the Nuclear Test-Ban Treaty, illegalizing necessary experiments. "This is the first time in modern history that a major expansion of human technology has been suppressed for political reasons," Dyson said at the time.

Merit, then, is not the only factor that determines which technologies become reality. Whatever we send to space comes from Earth, where there are laws, unburied hatchets, poorly understood physics and unknown unknowns that seem too risky to put on a costly spaceship. These are among the factors that lead to proverbial inertia—the tendency to keep using the same technologies and keep going the same way we have been going. But that outside kick to point the field in a new direction could come at any moment.

The jury is still out on MEGA, and the concept is still a long way from being useful, if it ever will be at all. The current devices provide just a small push—counted in "micro newtons"—an apple exerts orders of magnitude more force on a kitchen counter. And the apple is not going anywhere near Alpha Centauri. But every shove has to start somewhere. With the Phase II grant, Fearn and Woodward hope to increase their thrust and place multiple devices in parallel so that they add up to something usable. And then, with whatever funding they hope to get next, they will launch a mini satellite, equipped with a mini MEGA drive. With it, they will try to change the satellite's orbit, showing that the Mach effect can act on the real world.

When she walked by every day, what Fearn saw resembled a Physics 101 lab experiment more than a futuristic propulsion system.

This year NIAC opened a new funding line—Phase III awards totaling $2 million. The two 2019 awards went to space mining and prospecting projects, helping the agency achieve its solar system exploration goals. In the future, though, awards may look deeper into space and farther into the future—at projects like MEGA, provided its results pan out. But first, Fearn says, "NASA is making sure this isn't some spurious thing that a couple of people in southern California are wasting their time on"—that it is, in fact, the good kind of crazy. SA

MORE TO EXPLORE

On the Origin of Inertia. D. W. Sciama in *Monthly Notices of the Royal Astronomical Society,* Vol. 113, No. 1, pages 34–42; February 1, 1953. https://doi.org/10.1093/mnras/113.1.34
Experimental Null Test of a Mach Effect Thruster. Heidi Fearn and James F. Woodward in *Journal of Space Exploration,* Vol. 2, No. 2, pages 98–105; 2013.
NASA Innovative Advanced Concepts (NIAC) Program: https://www.nasa.gov/directorates/spacetech/niac/index.html

FROM OUR ARCHIVES

Near-Light-Speed Mission to Alpha Centauri. Ann Finkbeiner; March 2017.

scientificamerican.com/magazine/sa

Richard Montgomery is a Distinguished Professor of mathematics at the University of California, Santa Cruz. His research focuses on the *N*-body problem and the geometry of distributions.

MATHEMATICS

The Three-Body Problem

Although mathematicians know they can never fully "solve" this centuries-old quandary, tackling smaller pieces of it has yielded some intriguing discoveries

By Richard Montgomery

Illustration by Chris Buzelli

BY THE SPRING OF 2014 I HAD LARGELY GIVEN UP ON THE THREE-BODY PROBLEM. Out of ideas, I began programming on my laptop to generate and search through approximate solutions.

These attempts would never solve my problem outright, but they might garner evidence toward an answer. My lack of programming expertise and resulting impatience slowed the process, making it an unpleasant experience for a pencil-and-paper mathematician like myself. I sought out my old friend Carles Simó, a professor at the University of Barcelona, to convince him to aid me in my clunky search.

IN BRIEF

One of the oldest quandaries in mathematics and physics is called the three-body problem—the question of how three bodies, mutually attracted by gravity, will move in the future if their current positions and velocities are known.

Isaac Newton first posed this problem, along with the simpler "two-body problem." Later, in the case of three bodies, the question was found to be practically "unsolvable"—it is essentially impossible to find a formula to exactly predict their orbits.

Mathematicians have nonetheless continued to chip away at the question, discovering interesting solutions to specific cases. By studying the three-body problem, researchers have uncovered fascinating new principles of mathematics.

That fall I traveled to Spain to meet with Simó, who had a reputation as one of the most inventive and careful numerical analysts working in celestial mechanics. He is also a direct man who does not waste time or mince words. My first afternoon in his office, after I had explained my question, he looked at me with piercing eyes and asked, "Richard, why do you care?"

The answer goes back to the origins of the three-body problem. Isaac Newton originally posed and solved the two-body problem when he published his *Principia* in 1687. He asked: "How will two masses move in space if the only force on them is their mutual gravitational attraction?" Newton framed the question as a problem of solving a system of differential equations—equations that dictate an object's future motion from its present position and velocity. He completely solved his equations for two bodies. The solutions, also called orbits, have each object moving on a conic—a circle, ellipse, parabola or hyperbola. In finding all the possible orbits, Newton derived Johannes Kepler's laws of planetary motion, empirical laws Kepler published in 1609 that synthesized decades of astronomical observations by his late employer, Tycho Brahe. Kepler's first law says that each planet (or comet) moves on a conic with the sun as its focus. In Newton's solutions, however, the two bodies—the sun and a planet—move on two separate conics. These conics share one focus, which is the center of mass of the two bodies. The sun is more massive than any planet, so much so that the center of the mass of the sun-planet system is inside the sun itself, very close to the sun's center of mass, with the sun's center of mass barely wobbling about the common center on a tiny elliptical path.

In place of the two masses, put three, and you have the three-body problem. Like its predecessor, its orbits are solutions to a system of differential equations. Unlike its predecessor, however, it is difficult to impossible to find explicit formulas for the orbits. To this day, despite modern computers and centuries of work by some of the best physicists and mathematicians, we only have explicit formulas for five families of orbits, three found by Leonhard Euler (in 1767) and two by Joseph-Louis Lagrange (in 1772). In 1890 Henri Poincaré discovered chaotic dynamics within the three-body problem, a finding that implies we can never know all the solutions to the problem at a level of detail remotely approaching Newton's complete solution to the two-body problem. Yet through a process called numerical integration, done efficiently on a computer, we can nonetheless generate finite segments of approximate orbits, a process essential to the planning of space missions. By extending the run-time of the computer, we can make the approximations as accurate as we want.

ECLIPSES

SIMÓ'S WORDS had knocked the breath out of me. "Of course, I care," I thought. "I have been working on this problem for nearly two decades!" In fact, I had been focusing on a particular question within the problem that interested me:

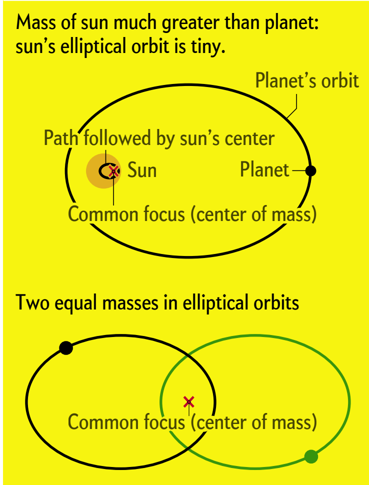
Is every* periodic eclipse *sequence the eclipse sequence of some periodic solution to the planar three-body problem?

Let me explain. Imagine three bodies—think of them as stars or planets—moving about on a plane, pulling at one another with gravity. Number the bodies one, two and three. From time to time all three will align in a single, straight line. Think of these moments as eclipses. (Technically, this "eclipse" is called a syzygy, an unbeatable word to use in hangman.) As time passes, record each eclipse as it occurs, labeling it one, two or three, for whichever star is in the middle. In this way, we get a list of ones, twos and threes called the eclipse sequence.

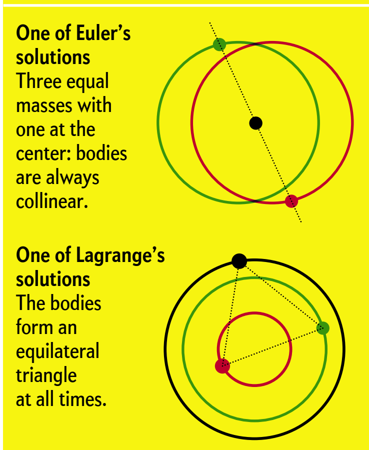
For example, in a simplified version of our sun-Earth-moon system, the moon (which we will label body "3") makes a circle around Earth (body "2") every month, while Earth makes a circle around the sun (body "1") once a year. This movement is repetitive, so it will give us a periodic eclipse sequence. Specifically: 2, 3, 2, 3, 2, 3, 2, 3, 2, 3, 2, 3, 2, 3, 2, 3, 2, 3, 2, 3, 2, 3, 2, 3. There is no 1 in the sequence because the sun never lands between Earth and the moon. In one year, the list is 24 numbers long, with a 2, 3 for each of the 12 months of the year.

There is no reason that the eclipse sequence of a solution must repeat itself. It might go on forever with no discernible pattern. If, however, the solution exactly repeats itself after some period of time, like the Earth-moon-sun system after a year, then the sequence repeats: the same 24 numbers of the Earth-moon-sun system

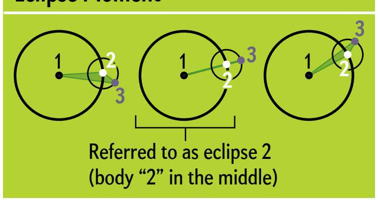
Two Examples of 2-Body Orbits



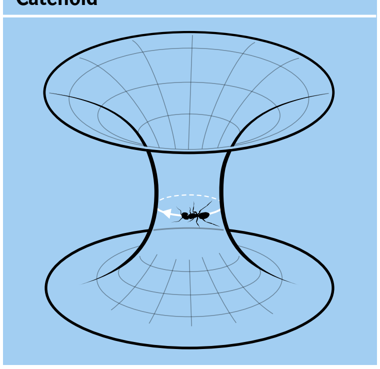
Two Examples of 3-Body Orbits



Eclipse Moment



Catenoid



Illustrations by Nigel Hawtin

replay each year. So, returning to my question: Is every periodic eclipse sequence the eclipse sequence of some periodic solution to the planar three-body problem? I suspected the answer was yes, but I could not prove it.

HOLEY OBJECTS

TO JUSTIFY the importance of my question, I reminded Simó of a basic fact tying together three branches of mathematics: topology, sometimes called rubber-sheet geometry; Riemannian geometry, the study of curved surfaces; and dynamics, the study of how things move. Imagine a bug walking along a curved surface shaped like the "wormhole surface," also called a catenoid. The bug's job is to find the shortest circuit going once around the hole. As far as topology is concerned, the wormhole surface is the same as the x-y-plane with a single hole punctured in it. Indeed, imagine a hole punctured into a flexible rubber sheet. By pushing the hole downward and stretching it outward, you can make the wormhole surface. If the hole has been sufficiently flared outward, then not only does this shortest circuit exist, but it satisfies a differential equation very much like the three-body equations. In this way, our bug has found a periodic solution to an interesting differential equation.

In the three-body problem, the role of the wormhole surface is played by something called configuration space—a space whose points encode the locations of all three bodies simultaneously, so that a curve in configuration space specifies the motions of each of the three bodies. By insisting that our bodies do not collide with one another, we pierce holes in this configuration space. As we will see, as far as topology, or rubber-sheet geometry, is concerned, the resulting collision-free configuration space is the same as an x-y-plane with two holes punctured in it. We will label the holes as "12," meaning bodies 1 and 2 have collided, and "23," meaning that 2 and 3 have collided, and place the holes on the x-axis. We'll also place a third hole at infinity and label it "13" to represent bodies 1 and 3 colliding. These holes break the x-axis into three segments labeled 1, 2 and 3. A curve in this twice-punctured plane represents a motion of all three bodies—which is to say, a potential solution to the three-body problem. When the curve cuts across segment 1, it means an eclipse of type 1 has occurred and likewise for cutting across segment 2 or 3. In this way, an eclipse sequence represents a way of winding around our collision holes.

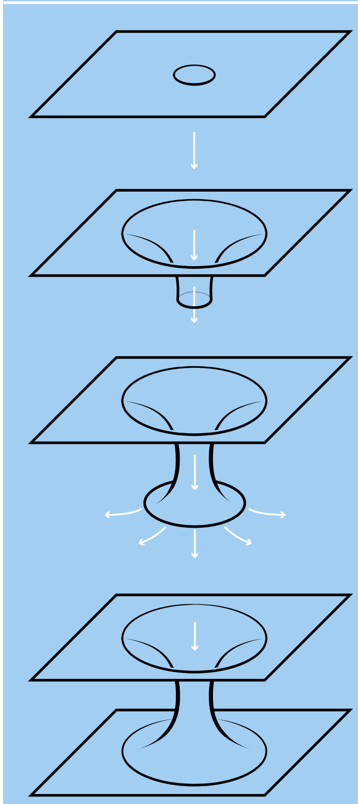
Now, our bug was trying to minimize the length of its path as it circled once around the wormhole. To get the correct analogy between the bug's problem and the three-body problem, we must replace the length of a path by a quantity called the action of a path. (The action is a kind of average of the instantaneous kinetic energy minus the potential energy of the motion represented by the path.) A centuries-old theorem from mechanics states that any curve in configuration space that minimizes the action must be a solution to Newton's three-body problem. We can thus try to solve our eclipse sequence problem by searching, among all closed paths that produce a fixed eclipse sequence, for those closed paths that minimize the action.

This strategy—seeking to minimize the action in configuration space for loops having a particular eclipse sequence—had preoccupied me for most of 17 years and led to many nice results. For instance, in 2000 Alain Chenciner of Paris Diderot University and I rediscovered what seems to be the first known periodic solution to the three-body problem with zero angular momentum. It was a figure-eight-shaped solution first found by Cris Moore of the Santa Fe Institute in 1993. In this case, three equal masses chase one another around a figure-eight shape on the plane. Its eclipse sequence is 123123, repeating forever. Our work popularized the figure eight and gave it a rigorous existence proof. It also led to an explosion of discoveries of many new orbits for the equal-mass N-body problem, orbits christened "choreographies" by Simó, who discovered hundreds of these new families of orbits. Our figure-eight orbit even made it into the best-selling Chinese science-fiction novel by Liu Cixin, whose English translation was entitled *The Three-Body Problem*.

The morning after I shared my ponderings with Simó, he said something that affected me deeply. "Richard, if what you think about your question is true, then there must be a dynamical mechanism." In other words, if I was right that the answer to my question was yes, then there must be something about how these bodies moved that made it so.

Those few words made me question my convictions and led me to abandon my

Rubber-Sheet Geometry



Collision-Free Configuration Space

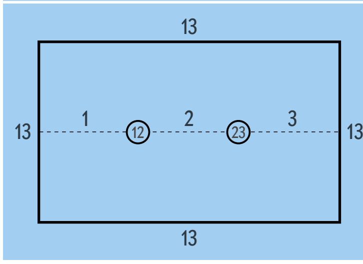
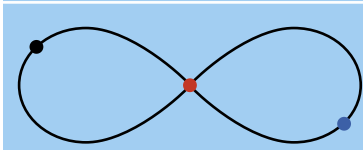


Figure 8 Solution

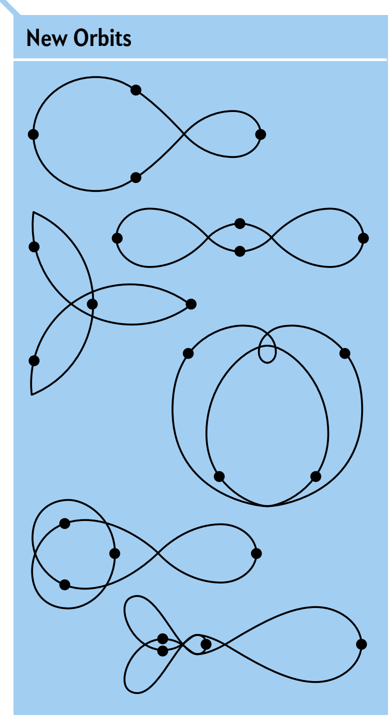


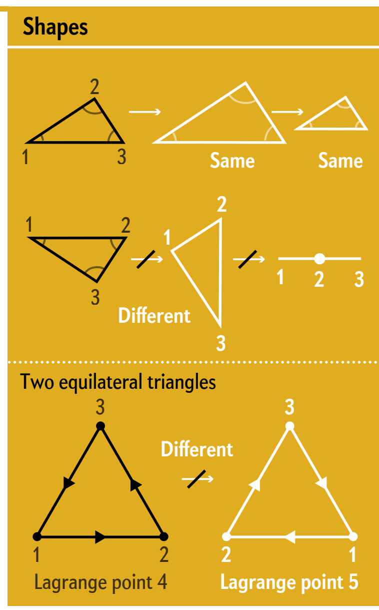
17-year-long attempt to answer my question by minimizing the action of paths. What dynamical mechanisms in this problem did I even understand? I wondered. I could think of two, only one of which held out hope. This mechanism, related to the chaos discovered by Poincaré, led me to reflect on old work of a recent collaborator of mine, Rick Moeckel of the University of Minnesota. In the 1980s he had shown how curves called hyperbolic tangles, born from triple collisions in the three-body problem, can lead to astounding results. As I reread his old papers, it seemed to me that Moeckel had the key to my problem. I got in touch with him, and within a few days Moeckel and I had answered my question! Well, almost. We had answered a question infinitely close.

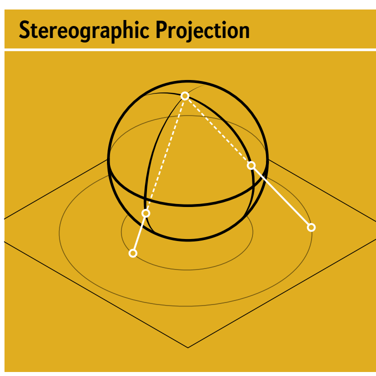
THE SHAPE SPHERE

UNDERSTANDING Moeckel's dynamical mechanism, in conjunction with the relationship between the three-body configuration space and the plane with two holes described above, requires thinking about an object called the shape sphere. As the three bodies move around in the plane, at each instant they form the three vertices of a triangle. Instead of keeping track of the position of each vertex, let us keep track of only the overall shape of the triangle. The result is a curve on the shape sphere, a sphere whose points represent "shapes" of triangles.

What is a "shape"? Two figures in the plane have the same shape if we can change one figure into the other by translating, rotating or scaling it. The operation of passing from the usual three-body configuration space—which is to say, from the knowledge of the locations of all three vertices of a triangle—to a point in the shape sphere, is a process of forgetting—forgetting the size of the triangle, the location of its center of mass, and the orientation of the triangle in the plane. That the shape sphere is two-dimensional is easy to understand from high school geometry: we know the shape of a triangle if we know all three of its angles, but because the sum of the three angles is always 180 degrees, we really only need two of the three angles—hence, two numbers are sufficient to describe the shape of a triangle. That the shape sphere is actually a sphere is harder to understand and requires that we allow triangles to degenerate, which is to say, we allow "triangles" consisting of three vertices that all lie on the same line to be called triangles. These so-called degenerate zero-area triangles form the equator of the shape sphere: they are the eclipses!







The area of a triangle, divided by its size (r) squared, is its distance to the equator. The north and south poles of the sphere represent those triangles of maximum possible area and are the two equilateral triangle shapes. But why are there two equilateral shapes? These two equilateral triangle shapes differ by the cyclic order of their vertices. There is no way to turn one of these equilateral triangles into the other by a rotation, translation or scaling of the plane: they represent different shapes. Yet the operation of reflecting about a line (any line) in the plane will turn one equilateral triangle shape into the other one. This reflection operation acts on all triangles, and so on the shape sphere itself, where it acts by reflection about the equator, keeping the points of the equator (degenerate triangles) fixed while interchanging the north and south hemispheres.

Included among the degenerate triangles are the binary collisions: those "triangles" for which two of the three vertices lie on top of each other. There are exactly three of these binary collision triangles, labeled "12," "23" and "13," according to which two vertices lie on top of each other.

I can now explain how the shape sphere shows us that the three-body configuration space is topologically the same as the usual x-y-plane minus two points. We have to know that the sphere minus a single point is topologically the same object as the usual x-y-plane. One way to see this fact about the sphere is to use stereographic projection, which maps the sphere with a single point removed (the "light source") onto the usual x-y-plane. As a point on the sphere tends toward the light source, its image point on the x-y-plane moves out to infinity, so we can also say that the plane with a point at infinity added is topologically equal to the sphere. Take the light source to be the 13 binary collision point of the shape sphere, so that the point at infinity of the x-y-plane corresponds to the 13 collision point. Orient the sphere so that its equatorial plane intersects the x-axis of the x-y-plane. Then stereographic projection maps the equator of degenerate triangles to the x-axis of the plane and the other two binary collision points get mapped to two points on this x-

axis. In this way, we arrive at exactly the picture described earlier.

The three binary collision points form three special points on the shape sphere. Besides these three there are additional special points on the shape sphere called central configurations. These five central configurations correspond to the five families of solutions discovered by Euler and Lagrange. Their solutions are the only three-body solutions for which the shape of the triangle does not change as the triangle evolves! In the Lagrange solutions, the triangle remains equilateral at each instant; there are two Lagrange configurations, as we have seen, and they form the north and south poles of the shape sphere. We label them "Lagrange point 4" and "Lagrange point 5." The remaining three central configurations are the Euler configurations, labeled "Euler point 1," "Euler point 2" and "Euler point 3." They are collinear (all in a line), degenerate configurations, so they lie on the equator of the shape sphere. They are positioned on the equator between the three binary collision points. (Their spacing along the equator depends on the mass ratios between the three masses of the bodies.) Euler point 1, for example, lies on the equatorial arc marked 1, so is a collinear shape in which body 1 lies between bodies 2 and 3. (Often all five central configuration points are called Lagrange points, with the Euler points labeled "L1," "L2" and "L3.")

One can understand the central configuration solutions by dropping three bodies, by which I mean, by letting the three bodies go from rest, with no initial velocity. Typically when one does this, all kinds of crazy things will happen: close binary collisions, wild dances and perhaps the escape of one body to infinity. But if one drops the three bodies when they are arranged in one of the five central configuration shapes, then the triangle they form simply shrinks to a point, remaining in precisely the same shape as it started, with the three masses uniformly pulling on one another until the solution ends in a simultaneous triple collision.

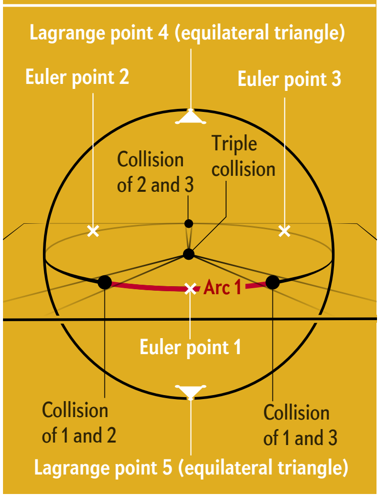
THE FIVE ROADS TO TRIPLE COLLISION

TRIPLE COLLISION is an essential singularity within the three-body problem, something like a big bang at the center of the problem, and it is the source of much of its chaos and difficulty. In the early 1900s Finnish mathematician Karl Sundman proved that the five central configurations, as represented by the dropped solutions just described, are the only roads to triple collision. What this means is that any solution that ends in triple collision must approach it in a manner very close to one of these five dropped central configuration solutions, and as it gets closer and closer to triple collision, the shape of the solution must approach one of the five central configuration shapes.

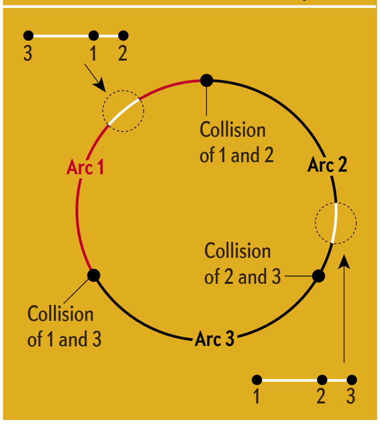
Sundman's work was a complicated feat of algebra and analysis. Then, in the year I graduated from high school (completely oblivious to the three-body problem), American mathematician Richard McGehee invented his so-called blow-up method, which allowed us to understand Sundman's work pictorially and to study dynamics near triple collision in much greater detail. Let r denote the distance to triple collision—a measure of the overall size of a triangle. As r approaches zero, Newton's equations become very badly behaved, with many terms going to infinity. McGehee found a change of configuration space variables and of time that slows down the rate of approach to triple collision and turns the triple collision point, which is $r = 0$, into an entire collection of points: the collision manifold. Surprise! The collision manifold is essentially the shape sphere. McGehee's method extended Newton's equations, originally only valid for r greater than zero, to a system of differential equations that makes sense when $r = 0$.

Newton's equations have no equilibrium points, meaning there are no configurations of the three bodies that stand still: three stars, all attracting one another, cannot just sit there in space without moving. But when Newton's equations are extended to the collision manifold, equilibrium points appear. There are exactly 10 of them, a pair for each of the five central configuration points on the shape sphere. One element of a pair represents the end result of the corresponding dropped central configuration in its approach to triple collision. Newton's equations stay the same even if we run time backward, so we can run any solution in reverse and get another solution. When we run a dropped central configuration solution backward, we get a solution that explodes out of triple collision, reaching its maximum size at the dropped configuration. The other element of the pair represents the initial starting point of

The Shape Sphere



Binary Collision Points and Eclipses



this “exploding” solution. Together these two central configuration solutions—collision and ejection—fit smoothly and form a single ejection-collision solution that leaves the ejection equilibrium point at $r = 0$, enters into the r greater than zero region where it achieves a maximum size, and then shrinks back to end up on the triple collision manifold at the collision equilibrium point there. This complete solution connects one element of an equilibrium pair to the other.

By creating these equilibrium points associated with central configurations, buried deep inside the three-body problem, McGehee gave Moeckel a key that enabled him to apply recently established results from modern dynamical systems—results unavailable to Newton, Lagrange or Sundman—to make some interesting headway on the three-body problem.

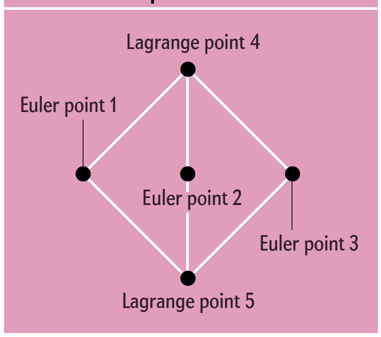
MOECKEL’S WALK

IN MOECKEL’S PAPERS I saw a picture of a graph with five vertices labeled by the central configurations and joined together by edges.

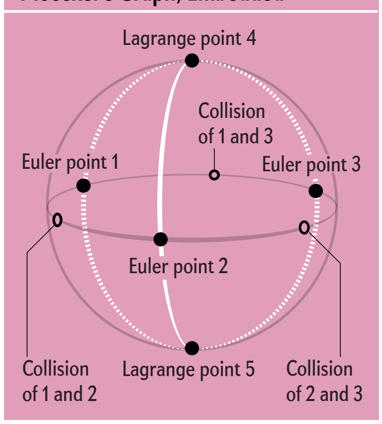
A walk on a graph is a possible circuit through its vertices, traveling the edges from vertex to vertex. Moeckel proved that any possible walk you can take on his graph corresponds to a solution to the three-body problem that comes close for some time to the central configuration solution labeled by the corresponding vertex. For example, the walk E1 L4 E2 L5 corresponds to a solution very close to the Euler ejection-collision solution associated with the Euler point 1, then comes close to triple collision almost along the Lagrange L4 central configuration solution, but before total triple collision is achieved the three bodies shoot out along one of the five “roads” very near to the Euler point 2 central configuration solution. Then, finally, as this Euler solution collapses back toward triple collision, the solution spins out into a Lagrange L5 equilateral shape. Moreover, if we repeat this same walk, making it periodic, the solution following it will be periodic.

Soon after Simó told me there had to be a dynamical mechanism, I realized that Moeckel’s graph embedded into the shape sphere. The important thing about this embedded graph is that it carries all of the topology of the sphere with its three binary collision holes. Indeed, we can deform the thrice-punctured sphere onto the graph and in so doing turn any loop in the punctured sphere to a walk on the graph. To see this deformation, imagine the sphere as the surface of a balloon. Make three pin pricks in it, one at each binary collision hole. The balloon is made of very flexible material, so we can stretch out our three pinpricks, enlarging them until the edges of the three holes almost touch each other and the remaining material forms a ribbon hugging close to the embedded graph. In the process of making this deformation, any closed loop in the thrice-punctured sphere gets deformed into a closed loop in this ribbon structure and, from there, to a walk on Moeckel’s embedded graph.

Moeckel’s Graph



Moeckel’s Graph, Embedded



To turn this picture into a theorem about solutions, I needed to prove that if I project the solutions guaranteed by Moeckel’s theorem onto the shape sphere, then they never stray far from this embedded graph. If they did, they could wind around the binary collisions or even hit one, killing or adding some topologically significant loops and so changing the eclipse sequence. I e-mailed Moeckel to ask for help. He wrote back, “You mean you’re going to force me to read papers I wrote over 20 years ago?” Nevertheless, he dove back into his old research and proved that the projections of the solutions he had encoded symbolically all those years ago never did stray far from the embedded graph. My question was answered—almost.

To make his proof work, Moeckel needed a tiny bit of angular momentum. (Angular momentum, in this context, is a measure of the total amount of “spin” of a system and is constant for each solution.) But for those 17 years before my conversation with Simó I had insisted on solutions having zero angular momentum. This insistence arose because solutions that minimize action among all curves having a given eclipse sequence must have zero angular momentum. On the other hand, Moeckel needed a small bit of angular momentum to get solutions traveling along the edges of his graph. The symbol for a tiny positive quantity in mathematical analysis is an epsilon. We needed an epsilon of angular momentum.

There was another catch to Moeckel’s results: his solutions, when they cross the equator of the shape sphere near the Euler points E1, E2 and E3, will oscillate back and forth there across the equator before traveling up to the north or south pole as

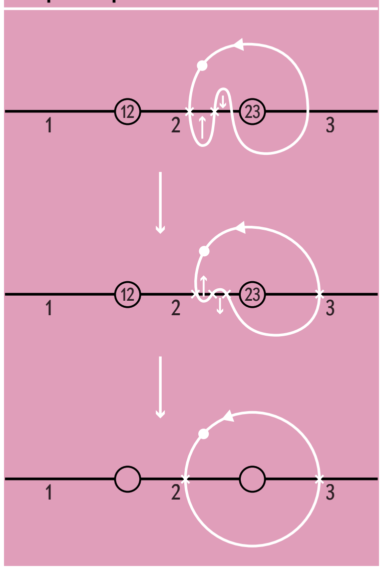
they go in near triple collision along the corresponding Lagrange road, L4 or L5. To account for these oscillations, take a positive integer N and call an eclipse sequence "N-long" if every time a number occurs in the sequence it occurs at least N times in a row. For example, the sequence 1112222333332222 is 3-long, but it is not 4-long, because there are only three 1s in a row.

Here, finally, is our main theorem: Consider the three-body problem with small nonzero angular momentum epsilon and masses within a large open range. Then there is a large positive integer N with the following significance. If we choose any eclipse sequence whatsoever—which is N-long—then there is a corresponding solution to our three-body problem having precisely this eclipse sequence. If that sequence is made to be periodic, then so is the solution realizing it.

What about my original question? There was no large N mentioned there. I had asked about every eclipse sequence. But I did not tell you my real question. What I really wanted to know was whether or not I could realize any "topological type" of periodic curve, not any eclipse sequence. I was using the eclipse sequence as a convenient shorthand or way of encoding topological type, which is to say as a way of encoding the winding pattern of the loop around the three binary collision holes. The eclipse sequence representation of the topological type of a closed curve has redundancies: many different eclipse sequences encode the same topological type of curve. Consider, for example, the topological type "go once around the hole made by excluding the binary collision 23." The eclipse sequence 23 represents this topological type. But so do the eclipse sequences 2223, 222223 and 2333. Whenever we have two consecutive crossings of the arc 2, we can cancel them by straightening out the meanders, making the curve during that part of it stay in one hemisphere or the other without crossing the equator. Indeed, we can cancel any consecutive pair of the same number that occurs in an eclipse sequence without changing the topological type of closed curve represented by the sequence.

To use our main theorem to answer my real question, note that by deleting consecutive pairs I can ensure that the eclipse sequence that encodes a given topological type never has two consecutive numbers of the same type in it: no "11" or "22" or "33." Call such a sequence an admissible sequence. Now, take any admissible sequence, for example, 123232. Allow me to use exponential notation in writing down eclipse sequences, so, for example, $1^3 = 111$. Choose an odd integer n at least as big as the number N of our main theorem. Replace the admissible sequence by the longer sequence $1^n\,2^n\,3^n\,2^n\,3^n\,2^n$ and continue it periodically. This longer sequence represents the same originally chosen topological type because n is odd. Our theorem says that this longer sequence is realized by a periodic solution. This periodic solution represents our original topological type 123232.

Eclipse Sequence



WHAT'S NEXT?

WE STILL HAVE MUCH left to do. When I originally posed my question almost 20 years ago, I only wanted solutions having zero angular momentum. But evidence is mounting that the answer to my question in the case of zero angular momentum is "no." We have some evidence that even the simplest nonempty periodic sequence 23 is never realized by a periodic solution to the equal-mass, zero angular momentum three-body problem.

Our main question as posed here, even for angular momentum epsilon, remains open because our theorem allowed us to realize only sequences that are N-long for some large N. We have no clue, for example, how to realize admissible sequences, that is, sequences with no consecutive numbers of the same type.

At the end of the day, we may be no closer to "solving" the three-body problem in the traditional sense, but we have learned quite a lot. And we will keep at it—this problem will continue bearing fruit for those of us who are drawn to it. It turns out that new insights are still possible from one of the classic quandaries in mathematical history. SA

MORE TO EXPLORE

A Remarkable Periodic Solution of the Three-Body Problem in the Case of Equal Masses. Alain Chenciner and Richard Montgomery in *Annals of Mathematics,* Vol. 152, No. 3 pages 881–901; November 2000.

Realizing All Reduced Syzygy Sequences in the Planar Three-Body Problem. Richard Moeckel and Richard Montgomery in *Nonlinearity,* Vol. 28, No. 6, pages 1919–1935; June 2015.

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Prize Mistake. Christoph Pöppe and Madhusree Mukerjee; Science and the Citizen, February 1997.

The Top 10 Martin Gardner *Scientific American* Articles. Colm Mulcahy; ScientificAmerican.com, October 21, 2014.

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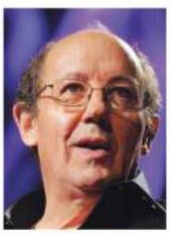

David Christian, Ph.D.
Distinguished Professor
of Modern History
Macquarie University

David Christian began teaching courses in Big History in the 1980s and has been at the forefront of many educational initiatives since, including co-founding The Big History Project with Bill Gates, directing Macquarie University's Big History Institute and co-creating their Big History School for K-12 online courses.

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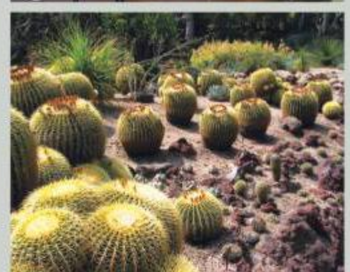

NOTES: Maximum of 40 for our private telescope reservation. Mt. Wilson Observatory is at 5,700 feet of elevation and not ADA compliant.

Millie Hughes-Fulford, Ph.D.

Professor of Medicine University of California Medical Center

Millie Hughes-Fulford was selected as a Scientist-Astronaut on the first Spacelab mission dedicated to biomedical studies in 1991 and has since continued her research into the mechanisms of cell growth and activation in spaceflight, winning an award from NASA in 2012 for discovering why the immune system is weakened in zero gravity.

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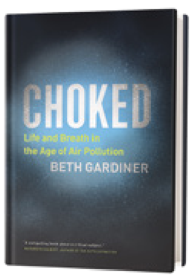
By Andrea Gawrylewski

Choked: Life and Breath in the Age of Air Pollution

by Beth Gardiner. University of Chicago Press, 2019 ($27.50)

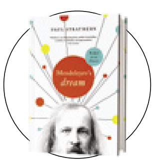


PEDESTRIANS slog through low-hanging smog in the Indian state of Uttar Pradesh.

Breath is life. But pollution-laden air is "quietly poisoning us," Gardiner writes in her arresting account of one of the biggest environmental threats to human health, one that claims seven million premature deaths a year worldwide. Through a world tour of air-pollution hotspots, Gardiner, a journalist, personalizes the damage pollutants do with vivid portraits of residents living alongside dirty ports in Los Angeles, women inhaling acrid smoke from cooking fires in rural India and the "sour taste" left in her mouth by London's diesel-clogged air. She lays out solutions, such as the landmark Clean Air Act and China's concerted move away from coal, although she is clear-eyed about potential hurdles and the recent push to undo critical safeguards. "This is not an insoluble puzzle.… We know how to fix it," Gardiner says. The question is, Will we? —*Andrea Thompson*

Mendeleyev's Dream: The Quest for the Elements

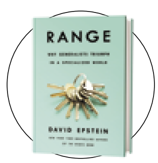
by Paul Strathern. Pegasus Books, 2019 ($27.95)



The structure of the periodic table of elements came to Dmitri Mendeleyev in a dream. The Russian scientist had been struggling for three nights and three days to find a pattern organizing the 63 known chemical elements, when he finally fell into a frustrated doze at his desk. When he awoke, he wrote down what had come to him while sleeping: a table listing the elements according to both their atomic weight and their chemical properties, which repeated at periodic intervals. Writer Strathern tells the story of this monumental discovery, as well as the history of chemistry leading to this point, to show how science has progressed from believing the world was made of the elements earth, air, fire and water to our present-day knowledge of 118 elements and counting. —*Clara Moskowitz*

Range: Why Generalists Triumph in a Specialized World

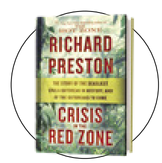
by David Epstein. Riverhead Books, 2019 ($28)



How does someone become the world's greatest chess player, violinist, chemist or pro golfer? Conventional wisdom holds that focusing on one endeavor early in life and pouring thousands of practice hours into it is the only way to excel. Sports journalist Epstein challenges that assumption in a book that studies artists, athletes, scientists and musicians who did not follow a fixed path to success. One surprising example is eight-time Wimbledon champion Roger Federer, who bounced around several sports before settling on tennis. Generalists, Epstein finds, often find their direction later and dabble in many areas rather than homing in on any given pursuit. He argues that approaching a field with an outsider's unfamiliarity may lead to brilliant breakthroughs. —*Jim Daley*

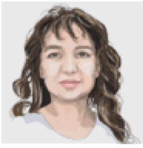
Crisis in the Red Zone: The Story of the Deadliest Ebola Outbreak in History, and of the Outbreaks to Come

by Richard Preston. Random House, 2019 ($28)



In 1976, from somewhere in the rain forest in what is now the Democratic Republic of the Congo, an unknown virus jumped from an animal into a human. That strain of virus quickly spread and infected hundreds of people and then vanished for decades. Writer Preston weaves this thrilling tale of the reemergence of the Ebola virus in 2013, told in the words of those in the thick of the health crisis. It reads like fiction: In one ward in Sierra Leone during the latest outbreak, disease researcher Lina Moses ran in flip-flops among the hospital wings, helping with one emergency after another. At night, shaky and feverish with malaria, she would lie on her bed and cry, looking at the photos of her daughters in the locket around her neck. She lived.

PRASHANTH VISHWANATHAN *Getty Images*



Zeynep Tufekci is an associate professor at the University of North Carolina School of Information and Library Science and a regular contributor to the *New York Times.* Her book, *Twitter and Tear Gas: The Power and Fragility of Networked Protest,* was published by Yale University Press in 2017.

Should Kids Learn to Code?

Not necessarily!

By Zeynep Tufekci

The government is behind it. In his 2016 State of the Union address, President Barack Obama said that the U.S. should offer "every student the hands-on computer science and math classes that make them job-ready on day one." Soon after, he launched a $4-billion Computer Science For All initiative.

Technology companies are enthusiastic. Amazon wants to teach coding to 10 million kids a year through its Amazon Future Engineer program. Facebook, Microsoft, Google and others have similar projects of varying scale and scope. Many parents are eager, too. According to Code.org, a nonprofit aiming to increase computer science education, 90 percent of parents want their children to study computer science in school. That explains the popularity of many kid-oriented tutorials and computer programming languages, such as Scratch and Hour of Code.

So should you sign your kid up for a programming camp? Insist they take computer science classes? Maybe, maybe not. I learned coding as a child, and it has served me very well. I purchased a home computer with money I earned bagging groceries and learned the Basic programming language, as well as some machine language. It was fun, like solving puzzles—and I got my first job as a software developer in my first year in college. Things haven't changed that much: software developers still make good money and are in high demand. So what's with the "maybe not"?

Programming was fun for me. But what about the child who's not so enthusiastic? Should he or she be made to learn programming because it could lead to a job someday? I would hold off: it's unlikely we will be programming computers the same way in the decades ahead that we do now. Machine learning, for example, which is what we mostly mean when we talk about AI, is very different than giving the computer detailed, step-by-step instructions. Instead we feed machine-learning algorithms large amounts of data, and the programs themselves construct the models that do the work.

To give a striking example, Google Translate used to involve 500,000 lines of code. Nowadays it's just about 500 lines in a machine-learning language. The key challenge isn't knowing a programming language: it's having enough data and understanding how the computer-constructed models work mathematically so we can fine-tune and test them.

What matters, then, for the future of this kind of computer work? The technical side is mostly math: statistics, linear algebra, probability, calculus. Math remains a significant skill and is useful for many professions besides programming. It's essential for everyday life, too. And algorithmic thinking doesn't have to come from computer coding. Some math and an appropriate learning experience via cooking, sewing, knitting—all of which involve algorithms of a sort—can be valuable.

More important for the future, though, is the fact that, by itself, computer programming encourages closed-world building. That's partly what made it so much fun for me: it's magical to put together something (tedious) instruction by instruction and then go play in the world one has built. Unfortunately, that is the farthest from what the tech industry does these days. Programmers are now creating tools that interact with the messy, challenging reality of life. If anything, their affinity for building insular worlds might have hindered their understanding of how the tools would actually function. What we need now are people who know history, sociology, psychology, math and computers and who are comfortable analyzing complex, open and chaotic systems.

So should you let an interested child enroll in a coding camp? Of course. Should kids play around with Scratch or do an Hour of Code tutorial to see if that captivates their interest? Absolutely. But no worries if they want instead to learn how to make cupcakes, sew pillows or pajamas, or climb trees.

We need to make sure youngsters do not think of the world as forcing them to choose between math and science on the one hand and social sciences and humanities on the other. The most interesting, and perhaps most challenging, questions facing us will be right at that intersection—not in the tiny, closed worlds we like to build for fun. SA

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Illustration by Jianan Liu

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.

Do the Math

It sure comes in handy for doing physics

By Steve Mirsky

Early in his new book, physics historian Graham Farmelo quotes Nima Arkani-Hamed, a theoretical physicist at the Institute for Advanced Study (IAS) in Princeton, N.J.: "We can eavesdrop on nature not only by paying attention to experiments but also by trying to understand how their results can be explained with the deepest mathematics. You could say that the universe speaks to us in numbers." Relax, he doesn't mean numerology.

That quote provides the book's title: *The Universe Speaks in Numbers*. Of course, there's a subtitle, too: *How Modern Math Reveals Nature's Deepest Secrets*. The book also deals with the thorny question of whether the revelations of math truly are nature's deepest secrets or whether they're merely some secrets that we can glimpse via math. That discussion can lead to physics conference fistfights.

The IAS hosted a symposium on Farmelo's subject on May 29. In brief opening remarks, IAS director Robbert Dijkgraaf said, "There are many anecdotes about the relationship between physics and mathematics." He then quoted Richard Feynman—"not known as a lover of abstract mathematics"—as having said, "'If all mathematics disappeared today, physics would be set back exactly one week.'" After the laughs (possibly from only the physicists and not the mathematicians in the audience) subsided, Dijkgraaf continued: "Sir Michael Atiyah actually gave me the perfect riposte, which was, 'That was the week that God created the world.'"

Atiyah, who died in January at the age of 89, was described in his *New York Times* obituary as a "British mathematician who united mathematics and physics during the 1960s in a way not seen since the days of Isaac Newton." So he was probably one of the few people on the planet who could outfox Feynman.

Atiyah helped to end a period of estrangement between physics and math, which Freeman Dyson (who at 95 is safely referred to as a living legend) talked about at the symposium. Dyson had noticed the falling-out when he joined Einstein (among other luminaries) on the IAS faculty: "When I became a professor, [which] just coincided with the time when [Robert] Oppenheimer [former head of the Manhattan Project] became director..., there was a divorce—largely occasioned by the fact Oppenheimer had no use for pure mathematics, and the pure mathematicians had no use for bombs."

When asked what the most important questions were still to be addressed by physics and math, Dyson said, "The question of what's important is entirely a matter of taste. I like to think of going to the zoo ... you can either admire the architecture of the zoo or you can admire the animals. And so, at the present time, mathematicians are very busy admiring the architecture. The physicists are admiring the animals. Which is actually more important isn't to me the interesting question. The interesting question is, Why do they fit so well?"

Mathematician Karen Uhlenbeck, professor emeritus at the University of Texas at Austin, had a different take: "There's this picture [that] there's a perfect world out there, and it has laws, and we're going to discover these laws. [But we're] just a bunch of human beings muddling along in a world that's very hard to understand. I mean, it's deceptive that the world looks so clear and beautiful and well put together. Because the minute you look at it with a different wavelength, it looks completely different. So our picture of the world as completely made and perfect—and all we need to do is find the rules for it—doesn't fit with my feeling. It's a kind of a muddle-y place, and you look at a piece of it, and we try to straighten it out, and we put together ideas in our mind, and we somehow make rules and order, and we create mathematics as a language in response to external stimuli."

Dyson immediately attempted a reconciliation: "I don't disagree with you. We're exploring a universe which is full of mysteries ... what to me is still amazing is that we understand so much."

These conversations always remind of the very short Robert Frost poem: "We dance round in a ring and suppose,/But the Secret sits in the middle and knows." I would have loved to ask Frost how he knew the secret was sitting. SA

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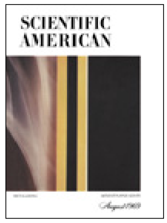
Illustration by Matt Collins

50, 100 & 150 YEARS AGO

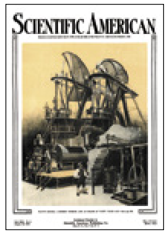
INNOVATION AND DISCOVERY AS CHRONICLED IN *SCIENTIFIC AMERICAN*

Compiled by Daniel C. Schlenoff

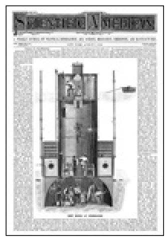
AUGUST



1969



1919


1869

1969 Drifting Genes

"The survival and preferential multiplication of types better adapted to the environment (natural selection) is the basis of evolution. Into this process, however, enters another kind of variation that is so completely independent of natural selection that it can even promote the predominance of genes that oppose adaptation rather than favoring it. Called genetic drift, this type of variation is a random, statistical fluctuation in the frequency of a gene as it appears in a population from one generation to the next. My colleagues and I have for the past 15 years been investigating genetic drift in the populations of the cities and villages in the Parma Valley in Italy. We have examined parish books, studied marriage records in the Vatican archives, made surveys of blood types, developed mathematical theories and finally simulated some of the region's populations on a computer. We have found that genetic drift can affect evolution significantly. —Luigi Luca Cavalli-Sforza"

Drifting Continents

"More evidence has been adduced to support the concept of continental drift. Walter Sproll and Robert S. Dietz of the Atlantic Oceanographic Laboratories of the Environmental Sciences Service Administration report they have succeeded in demonstrating that Antarctica and Australia, now separated by 2,000 miles of ocean, were once a single land mass. Concentrating on the 1,000-fathom isobath (a line around each continent at that depth), which they believe represents the true edge of each land mass, they fed their data into a computer at the University of Miami until it found the best fit between them."

1919 Aerial Mail

"An experiment in delivering mail to a steamer at sea is to be undertaken within a few days by C. J. Zimmerman, a skilled pilot, who will follow the steamer 'Adriatic' two or three hours after she has sailed for England, and overtaking her will drop a mail pouch into the sea just ahead of her bow [*see illustration*]. This experiment will be closely followed by the post office authorities and the steamship men." *The delivery was successful, but the technique was perilous as compared with regular airmail delivery.*

Dead Water

"Mariners who frequent the coast of Peru are familiar with a curious phenomenon that occasionally prevails there—notably in the harbor of Callao near Lima—commonly known as the 'painter.' The water becomes discolored and emits a nauseous smell, apparently due to sulfuretted hydrogen. The white paint of vessels becomes coated with a chocolate-colored slime. In a paper recently presented to the Geographical Society of Lima, Senor J. A. de Lavalle y Garcia concludes that the primary cause is the seasonal shift of ocean currents, at which time the warm equatorial countercurrent displaces the cool Peruvian current. The resulting change in temperature of the ocean water would, he thinks, kill quantities of plankton, and the decay of this organic matter would give rise to the phenomena observed." *The low oxygen content of warmer El Niño waters suffocates many organisms.*


1919: Delivering mail by seaplane to a steamer in transit.

SCIENTIFIC AMERICAN, VOL. CXXI, NO. 8; AUGUST 23, 1919

1869 Solar Furnace

"The materials of our sun are, doubtless, capable of producing greater heat, pound for pound, than the substances usually employed by us for the same purpose. Recent researches in chemistry would seem to point to a more elementary condition of matter in the stars and nebulae than any with which we are acquainted on the earth. Who can say but that the production of our terrestrial elements was accompanied by displays of light and heat similar in intensity to those now witnessed in the sun and stars? This theory has great support in the constantly accumulating facts which the spectroscope is bringing to our attention."

Coal Economics

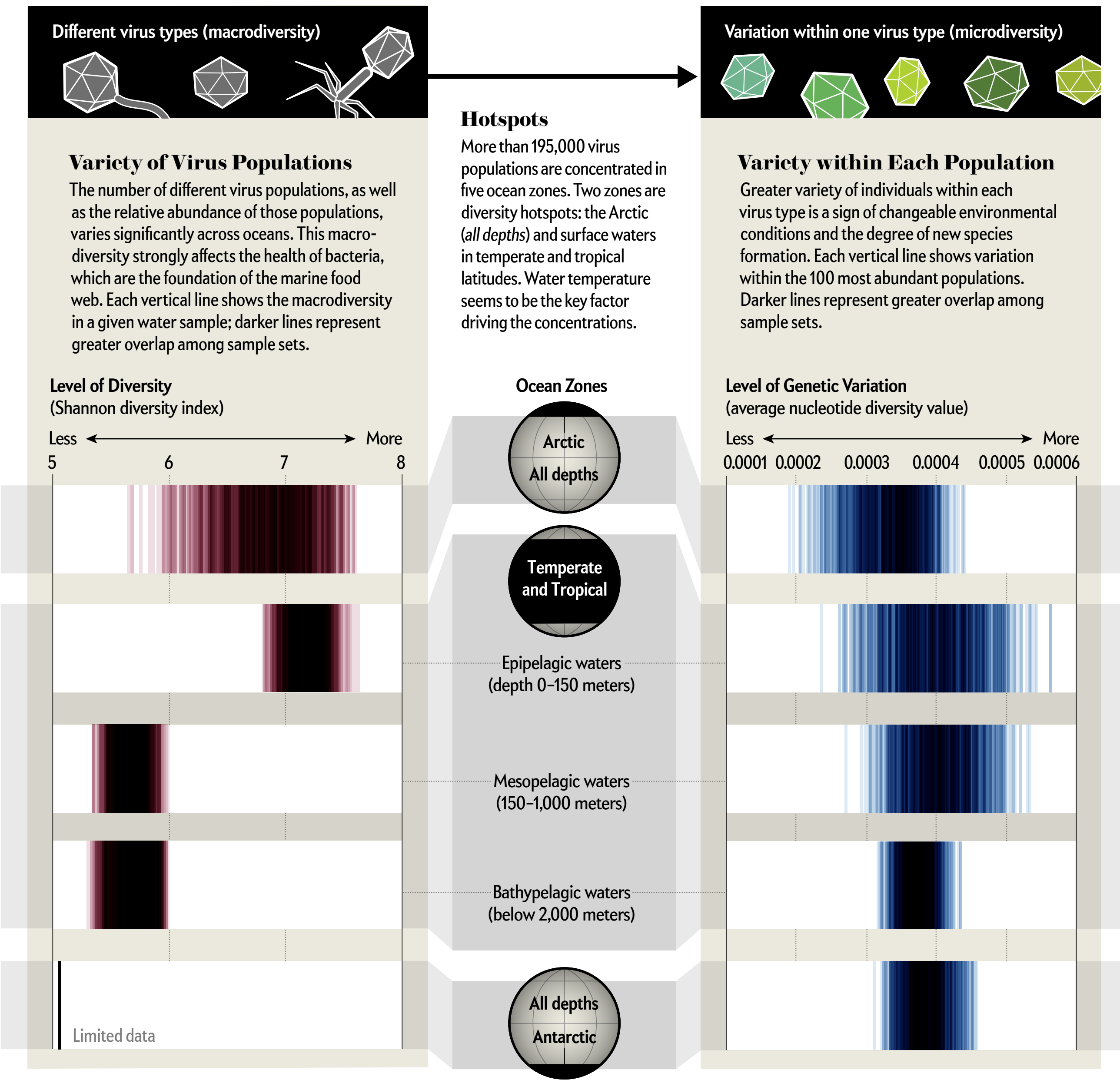
"All agree that coal is absurdly, extortionately, cruelly high; but all do not agree as to the cause of present high prices, or as to how it may be cheapened. The free traders say the high price is dependent on the present tariff, while some protectionists say it is owing to extortionate freights and high prices demanded by miners. We say it is a combination of all the causes assigned. We need additional and competing lines of transit from the great beds of coal to the principal centers of trade, and we need more labor; the want of a proper labor supply being, in our opinion, one of the chief causes of trouble. This labor can be found in abundance in Asia. It only waits to be properly invited."

Text by Mark Fischetti | Graphic by Jen Christiansen

Viruses Thrive in Arctic Seas

A surprising study overturns a common assumption

Even though scientists did not have a thorough record of viruses in the oceans, many of them assumed the number and variety of viruses would diminish from the equator toward the poles. Not so. A new study has vastly expanded the data set and shows the Arctic Ocean has a richer cast of viruses than other major oceans. "It's a hotspot," says study member Matthew Sullivan, a microbiologist at Ohio State University. He thinks the reason is that the Arctic Ocean is a mixing pot of waters from the Atlantic and Pacific Oceans, global ocean conveyor belts and huge rivers that empty there. Also surprising is that viruses are largely concentrated in four other marine zones across the planet (*graphic*). "We just didn't know that before," Sullivan says. "It could have been 20."



SOURCE: "MARINE DNA VIRAL MACRO- AND MICRODIVERSITY FROM POLE TO POLE," BY ANN C. GREGORY ET AL., IN *CELL*, VOL. 177, NO. 5; MAY 16, 2019