IS OCEAN ACIDIFICATION DRIVING SEA CREATURES CRAZY? PAGE 42

SCIENTIFIC AMERICAN

THE QUANTUM MULTIVERSE

A surprising connection between cosmology and quantum mechanics could unveil secrets of space and time

PLUS

ARTIFICIAL INTELLIGENCE GROWS UP

Teaching machines to learn like children PAGE 60

VANISHED VIKINGS

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NEW HOPE FOR ALS

Gene therapies could hold promise PAGE 46

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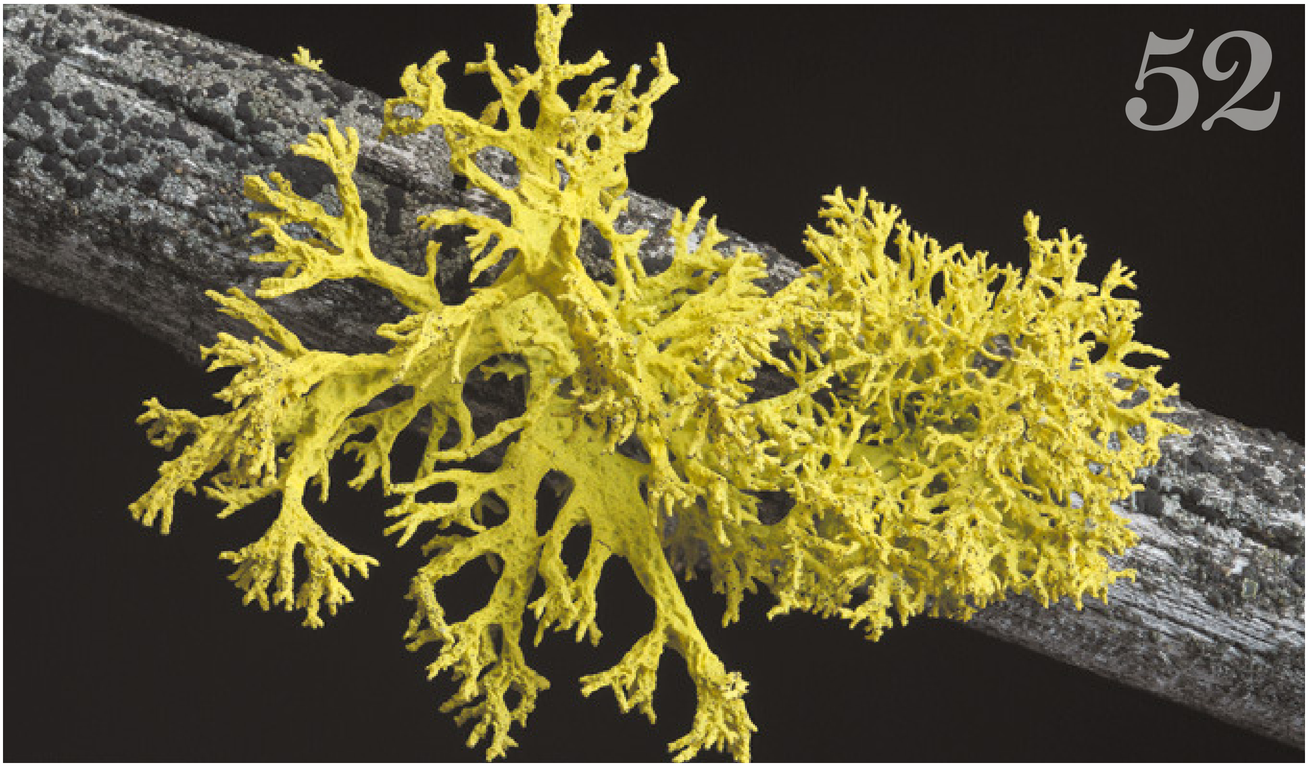

TIM WHEELER (*Letharia vulpina*)

ON THE COVER
If our entire observable universe is only a bubble embedded in an infinitely larger multiverse, cosmologists may be in trouble. In a multiverse, all possible events occur an infinite number of times, stripping theories of predictive power. Ideas from quantum mechanics, however, offer fresh hope for more predictive cosmological theories. Photograph by The Voorhes.

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ON THE WEB

Marching for Science
Watch *Scientific American*'s video coverage of the March for Science, held on April 22 in Washington, D.C.
Go to www.ScientificAmerican.com/jun2017/science-march

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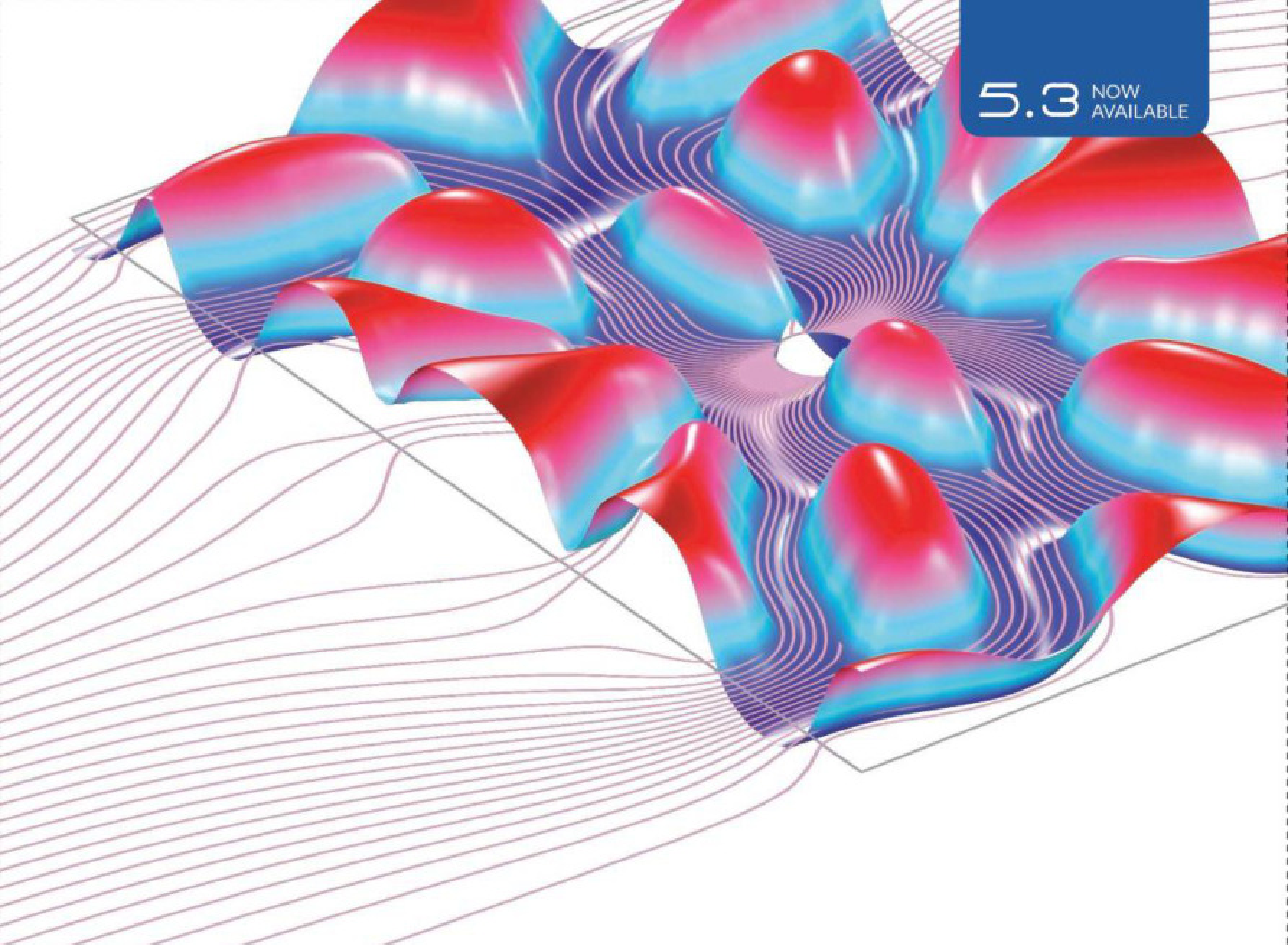
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Mariette DiChristina is editor in chief of *Scientific American.* Follow her on Twitter @mdichristina

From Science to Knowledge to Hope

"CHAINED LIKE A DOG." He gestured at the block letters he had scrawled on a yellow legal pad and then at the ventilator connection on his throat. Gregarious and charming, my father had prized autonomy above all else. A self-made man, as he called himself, he ran his own business; enjoyed "playing" with his "machines" (motorcycle, motorboat, sports car, minivan), which he fixed himself; and raised three daughters alone after our mother died when I was 12. He taught my two younger sisters and me to "learn something new every day" and advised us to get university degrees: "You can do anything you want, but you must do something so you can be independent." At the end, Dad was robbed of his rich voice and his freedom, confined to the ventilator that forced air into his lungs. Francis P. DiChristina died in 1991, after three long years with amyotrophic lateral sclerosis, or ALS. He was 57.

Research has advanced in the past couple of decades since then, and recent findings are providing renewed hope today for patients with Lou Gehrig's disease, as it is commonly known, and for their families. In "Unlocking the Mystery of ALS," beginning on page 46, Leonard Petrucelli of the Mayo Clinic and Aaron D. Gitler of the Stanford University School of Medicine describe newly discovered genetic mutations that play key roles in a person's susceptibility to ALS. More exciting yet, it is possible that a technique called "gene silencing" could lead to promising therapeutics.

My father instilled in me admiration for the process of science as a means to increase knowledge. In addition to developments in medical and other applied fields, he revered its ability to demonstrate, for instance, that the stars were not "reflections from the ocean," as he had once been told by a nun, but fiery powerhouses in a vast cosmos. I like to think he would have enjoyed the new insights offered in this issue's cover story, "The Quantum Multiverse," by Yasunori Nomura of the University of California, Berkeley. Nomura discusses the fantastic-sounding but now widely accepted view that our universe "may actually be only a tiny part of a much larger structure called the multiverse." As Nomura explains, some problems with the multiverse idea, which grew out of the theory of cosmic inflation, may be resolved by seeing it as equivalent to a notion from quantum mechanics called the many-worlds interpretation. To find out how, turn to page 28.

Science may not answer our every question, of course, but it remains humanity's best tool yet for pursuing our greatest challenges. With basic research, we lay down the foundations of understanding. And in doing so, we have the means to continue to build on that underpinning, further lifting our awareness of how the world works. If he were here now, Dad would add emphasis with another of his favorites: "Don't forget," he would say with a knowing smile and a wink, "your father is always right." SA

Illustration by Nick Higgins

February 2017

"Could there not be aspects of the universe our human intelligence is unable to reach at the present time?"

DAVE BOLTON *ESSEX, ENGLAND*

EXERCISING RESTRAINT

In "The Exercise Paradox," Herman Pontzer asserts that greater physical activity does not allow people to control weight. He goes on to describe studies on how the human body burns calories that help to explain why this is so.

But in one of these studies, "couch potatoes" expended an average of around 200 fewer calories a day, compared with moderately active subjects. A difference of 200 fewer calories a day equates to more than 20 fewer pounds a year. Year after year after year, that really adds up.

Ann Azevedo
Tolland, Conn.

Cyclists participating in the Tour de France are said to ingest more than 5,000 calories a day. According to Pontzer's article, this would seem to be way too much. So why do they do it? And why don't they become obese?

Walter Bräu
via e-mail

PONTZER REPLIES: In response to Azevedo: A 200-calorie-a-day difference could certainly affect weight. What we see across studies, though, is that individuals who burn more energy per day are not any less likely to gain weight than those with lower energy expenditures—our bodies do a remarkably good job in matching intake to output. Yet with daily energy expenditure being so difficult to change, it is much easier to overeat than to underexpend, meaning we should probably focus more on diet to prevent obesity.

Regarding Bräu's question: Events such as the Tour de France, the Ironman Triathlon and various marathons are too short and extreme for the body to adapt to them. Athletes in those events eat prodigious amounts and often still lose weight because their bodies burn more than 5,000 calories a day. These feats fall well outside the requirements of daily life for even the most active populations, and thus they are not truly sustainable over the long term. Racers need significant recovery periods, and the metabolic demands of these events may be one reason that some athletes are drawn to performance-enhancing drugs that support high expenditures.

THINKING OF NOTHING

In "Imagine No Universe" [Skeptic], Michael Shermer explores attempts to answer the question of why there is "something rather than nothing" in the universe and the difficulty in defining "nothing."

Why do we assume we have the potential brainpower to ever explain such mysteries? Could there not be aspects of the universe our human intelligence is unable to reach at the present time? Consider this: A dog travels in your car. Can it ever understand motor mechanics or geography? Your cat watches television. Has it any knowledge of electronic communications?

Why do we, just one of the species in existence, assume our brains are capable of knowing why we exist and what there is beyond infinity? This should not inhibit us in striving to understand the purpose of life, and so on. But we should accept that it may take a millennium of human development to know everything. Perhaps then we will become gods!

Dave Bolton
Essex, England

SHERMER REPLIES: I agree that we should not assume we have the cognitive capacity to explain such mysteries, and there are even those who call themselves "mysterians" who believe that hard problems such as consciousness may be inexplicable because of such cognitive limitations, so perhaps "nothingness" and "God" are as well.

As for the coming millennium, in my next book, Heavens on Earth, *I suggest that in the far future, civilizations may become sufficiently advanced to colonize entire galaxies, genetically engineer new lifeforms, terraform planets, and even trigger the birth of stars and new planetary solar systems through massive engineering projects. Civilizations this advanced would have so much knowledge and power as to be essentially omniscient and omnipotent. What would you call such a sentience? If you didn't know the science and technology behind it, you would call it God, which is why I postulate that any sufficiently advanced extraterrestrial intelligence or far future human is indistinguishable from God.*

GRAPHIC LITERATURE

"Novel Math," by Mark Fischetti [Graphic Science], discusses studies of works of fiction that found, respectively, limited variations of emotional arcs and fractal patterns in the lengths of sentences.

I am a high school English teacher who has taught the works of Kurt Vonnegut for about the past 20 years. I am certainly not a brilliant math person, but I am fascinated by the mathematical connections with art and the universe. The second I began reading the article, I started laughing and flashed on my man, Kurt.

In the late 1940s he (probably facetiously) proposed a master's thesis at the University of Chicago on the graphing of stories. His proposal was rejected, but the graphs of stories show up in his work *Palm Sunday,* which is hilarious (though maybe only to English majors). He also discussed the subject in a short lecture segment that can be seen at www.youtube.com/watch?v=oP3c1h8v2ZQ.

Michelle Pell
Daegu High School
Daegu, South Korea

COSMIC CAN-DO

In "Deep-Space Deal Breaker," Charles L. Limoli discusses how new studies show that cosmic radiation might damage astronauts' brains more than we had previously thought.

Although I agree that cosmic radiation is a difficult and challenging issue for deep-space travel, it is by no means a "deal breaker." It is "merely" an engineering problem, albeit a hard one. In the late 1800s some assumed that powered flight for humans would not be possible. Yet given the numerous examples from the natural world, others instead saw human flight as an engineering challenge that could be overcome.

Limoli touches on a couple of strategies in early stages of development for protecting humans in space, but he notes that none of these efforts "has the potential to be a cure-all. The best we can hope is to reduce, rather than eliminate, damage." I can imagine many methods to better shield astronauts: we could invent nanobots that will quickly repair the damage or magnetic fields that will surround spacecraft to deflect the radiation in a manner similar to how Earth's magnetic field protects us on the surface. We don't know which of these or other potential solutions will eventually prove practical, but there is no doubt that with effort and a dose of logical imagination, engineers can indeed solve the issue.

Joseph Kelly
St. Paul, Minn.

EDITORS' NOTE: In "Pop Goes the Universe," Anna Ijjas, Paul J. Steinhardt and Abraham Loeb criticize the inflationary theory of the universe. A response to that article by Alan H. Guth and David Kaiser, both at the Massachusetts Institute of Technology, Andrei Linde of Stanford University and Yasunori Nomura of the University of California, Berkeley, is available at www.ScientificAmerican.com/inflation-response.

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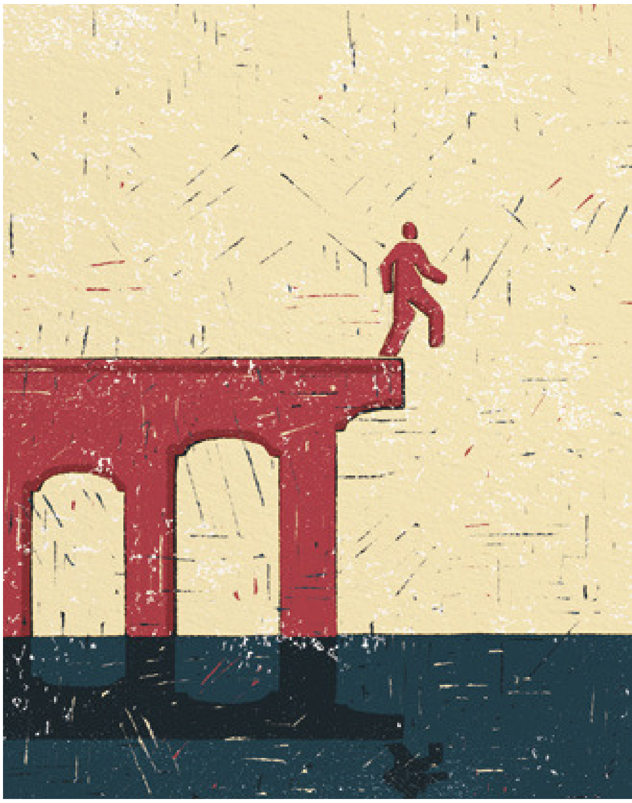

Science without Walls

Partnering across borders means faster discovery and a safer world

By the Editors

The U.S. appears to be plunging headlong into a new era of isolationism. The White House wants to pull out of international agreements, including the Paris climate deal and the North American Free Trade Agreement. It has issued executive orders trying to halt or slow the flow of refugees and immigrants to the nation.

This is bad for the U.S. and terrible for hundreds of thousands of desperate people across the planet. And it will strangle science. The choke hold will leave us more vulnerable to emerging, deadly viruses and will hamper efforts to explore space and control global threats such as climate change.

Research depends on ideas shared across political borders—including among countries in conflict. Even as the cold war was raging, hostility between the U.S. and the Soviet Union was put aside when American medical researcher Albert B. Sabin and his Soviet counterparts tested a live-virus, oral polio vaccine in the U.S.S.R. That successful trial provided the scientific proof needed for the vaccine's use around the world and ultimately helped to eradicate polio in most countries. During the International Polar Years of 1882–1883 and 1932–1933, nations also put aside their differences to study the Arctic and Antarctic.

Louis Pasteur once declared that "science knows no country, because knowledge belongs to humanity, and is the torch which illuminates the world." Nations have repeatedly seen the wisdom of his words.

The Soviets and Americans also worked together to further space exploration in the 1960s and 1970s—exchanging weather data from and launching new meteorologic satellites and jointly mapping the earth's geomagnetic field. Similarly, when the Soviet Union's Cosmos 936 mission launched in 1977, seven U.S. biological experiments were onboard. And in 2014, before the U.S.'s restoration of diplomatic relations with Cuba was in place, the American Association for the Advancement of Science and the Cuban Academy of Sciences pledged to work together to further research on drug resistance, cancer, emerging and infectious diseases, and the brain.

In recent years the U.S. has taken some crucial steps to strengthen our science diplomacy: In 2009 President Barack Obama spoke in Cairo about working with scientists in the Muslim world to develop novel sources of energy, create green jobs, digitize records, provide clean water and grow new crops. That speech led to the U.S. Science Envoy program, an outreach effort that selects top American scientists to promote the nation's commitment to science, technology and innovation as tools of diplomacy and economic growth abroad. One of the researchers in the program, vaccine scientist Peter Hotez, used his envoy position in the Middle East to create a vaccine research partnership between his American institute and a university in Saudi Arabia.

Yet the future of the envoy program under President Donald Trump remains unclear. Trump's travel bans have thrown researchers' plans into disarray—making foreign scientists and scholars question whether they should attempt to come to the U.S. for jobs or conferences and raising doubts about whether foreign scientists working here can risk visiting relatives in Muslim-majority countries, lest they be prevented from returning.

That is unfortunate because better science—and dialogue about science—benefits us all. Detecting and stopping emerging threats such as Zika or Ebola require partnering with countries around the globe. Understanding the extent of Zika damage and testing candidate vaccines among susceptible populations, for instance, will call for international cooperation.

For space exploration, we need Russia's assistance to ferry our astronauts to the International Space Station. To better map the stars and explore the unknown, we must partner with China because it has the world's largest radio telescope. To help limit the effects of climate change, we need all the big emitters, including the U.S., China and India, to take steps to address the issue and to work toward solutions that will help communities build resiliency.

Let's resist the urge to turn inward and isolate ourselves. Instead we must continue to forge strong ties worldwide, using science as a diplomatic wedge. We gain far more from these partnerships than we risk. Weakening them will hurt us all. SA

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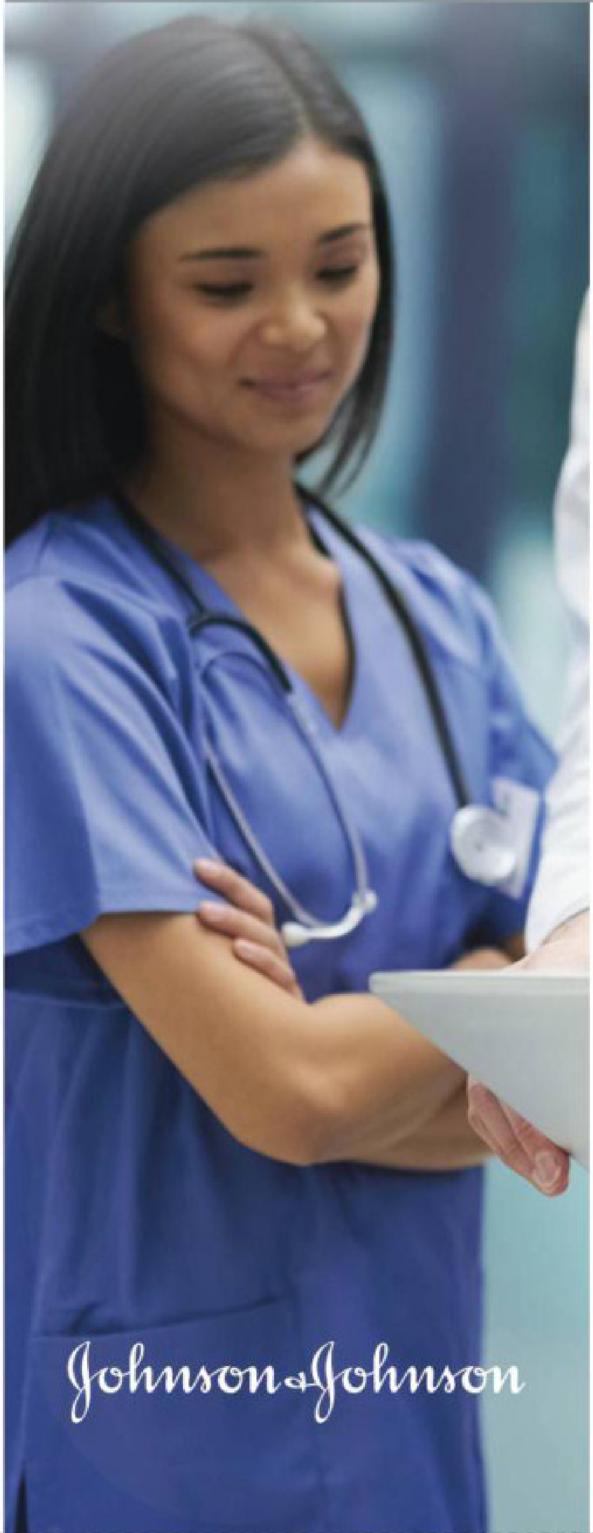
Illustration by Augusto Zambonato

SPARKING INNOVATION; LIGHTING UP BRIGHT MINDS

Johnson & Johnson Innovation and the Johnson & Johnson Office of the Chief Medical Officer (OCMO) are offering up to $200,000 USD in multiple grants, and one year of JLABS space, to the individuals or teams who submit the best ideas on how to educate, inform and provide clarity around healthcare product safety.



Johnson & Johnson INNOVATION | JLABS

QUICKFIRE CHALLENGE

Advancing the Safe Use of Healthcare Products

The new Challenge, the sixth one in the QuickFire series, seeks to identify entrepreneurs, academics, scientists, engineers or startup companies who are advancing potentially game-changing, early stage solutions to advance safety in healthcare products that help inform patients and consumers, simulate surgical procedures, and ensure proper storage and use of prescription, over-the-counter and cosmetic products.

"Dedicated to scientific excellence, bioethics and values-based decision-making, the Johnson & Johnson Office of the Chief Medical Officer has a history of collaborating externally to create innovative solutions for patients and consumers," said Joanne Waldstreicher, M.D., Chief Medical Officer, Johnson & Johnson. "Through our collaboration with Johnson & Johnson Innovation on this challenge, we hope to identify scientifically sound, breakthrough ideas that will advance both the safe use and a greater understanding of the safety of healthcare products to positively impact outcomes."

This initiative represents the Johnson & Johnson Family of Companies' ongoing commitment to patient and consumer safety and independent safety assessments. It is open globally to applicants with solutions across the pharmaceuticals, medical devices and consumer products sectors. QuickFire Challenge winners will receive research grants totaling up to $200,000 USD, entrance to a Johnson & Johnson Innovation – JLABS facility and / or mentoring from Johnson & Johnson Innovation.

A Timely Health Need

With increased dissemination and sharing of health information via social media and online, there is a greater need than ever before for bioethical, transparent and evidence-based information sources that help patients and consumers make more informed healthcare decisions. To help make this possible, the challenge aims to improve safety in healthcare through improving the provision of balanced and factual

information – and development of solutions – to ensure safety across the spectrum of medical devices, pharmaceutical and consumer products.

QuickFire Challenge entries that reflect the overall mission of improving the safety of and safe use of healthcare products will be evaluated by a juried panel comprising senior scientific and medical research staff as well as medical safety experts within Johnson & Johnson who have expertise across pharmaceuticals, medical device and consumer sectors.

A Trifecta of Focal Points

The QuickFire Challenge innovation focus areas are:

- ***Empowering patients and consumers to make more informed healthcare decisions by providing better information and education about the safety of healthcare products (pharmaceuticals, medical devices and consumer products).*** This challenge focus area seeks ways to maximize consumer and patient education and understanding of healthcare products and their safety and efficacy, including medical devices, pharmaceuticals and consumer products.
- ***Improving training and development for surgeons by identifying new models that simulate the operating room environment.*** This focus area seeks new and robust models and methods to evaluate medical devices used by surgeons in a simulated environment representative of operating room procedures, with the goal of helping the surgeon understand how to safely and effectively use a medical device and understand variability in device and performance/outcome.
- ***Empowering patients and consumers to more safely administer and handle healthcare products.*** The third focus area seeks ways to address the challenge of prescription medication errors. "Entrants can submit ideas in one of three focus areas that are critical for ensuring that we make the safest possible products on behalf of patients and consumers," said Melinda Richter, Head of Johnson & Johnson Innovation, JLABS. "In addition to funding, Advancing the Safe Use of Healthcare Products QuickFire Challenge winners will be awarded JLABS support that includes infrastructure, services, educational programs and networks in global hotspots."

LEARN MORE: jlabs.tv/safetyquickfirechallenge
APPLICATION DEADLINE: MAY 24TH, 2017

About Johnson & Johnson Innovation

Johnson & Johnson Innovation LLC focuses on accelerating all stages of innovation worldwide and forming collaborations between entrepreneurs and Johnson & Johnson's global healthcare businesses. Johnson & Johnson Innovation provides scientists, entrepreneurs and emerging companies with one-stop access to science and technology experts who can facilitate collaborations across the pharmaceutical, medical device and consumer companies of Johnson & Johnson.

About Johnson & Johnson Innovation, JLABS

Johnson & Johnson Innovation, JLABS (JLABS) is a global network of open innovation ecosystems, enabling and empowering innovators to create and accelerate the delivery of life-saving, life-enhancing health and wellness solutions to patients around the world. JLABS achieves this by providing the optimal environment for emerging companies to catalyze growth and optimize their research and development by opening them to vital industry connections, delivering entrepreneurial programs and providing a capital-efficient, flexible platform where they can transform the scientific discoveries of today into the breakthrough healthcare solutions of tomorrow.

Robbert Dijkgraaf is director and Leon Levy Professor at the Institute for Advanced Study in Princeton, N.J. He is author of a companion essay in *The Usefulness of Useless Knowledge,* by Abraham Flexner (Princeton University Press, 2017).

Knowledge Is Infrastructure

Curiosity-driven science is just as vital as roads and bridges

By Robbert Dijkgraaf

When we think of infrastructure, we tend to think of the facilities and systems required for a country to function and thrive—roads, bridges, tunnels, airports and railways, as President Donald Trump specified in his February 28 speech to Congress.

Potholes and crumbling edifices clearly indicate that something needs fixing. But knowledge is infrastructure, too, and right now it needs urgent attention. Science and technology are the basis of the modern economy and key to solving many serious environmental, social and security challenges. Basic research, driven by curiosity, freedom and imagination, provides the groundwork for all applied research and technology. And just as we have to break the endless cycle of Band-Aid fixes to roads and rails, long-term investments in knowledge are vital.

Curiosity-driven basic research has brought truly revolutionary transformations, such as the rapid growth of computer-based intelligence and the discovery of the genetic basis of life. Albert Einstein's century-old theory of relativity is used every day in our GPS devices. Perhaps the best U.S. government investment ever was the $4.5-million grant from the National Science Foundation that led to the Google search algorithm—an investment that has multiplied by more than 100,000 times.

Basic research not only radically alters our deep understanding of the world, it also leads to new tools and techniques that spread throughout society, such as the World Wide Web, originally developed for particle physicists to foster scientific collaboration. It trains the sharpest minds on the toughest challenges, and its products are widely used by industry and society. No one can exclusively capture its rewards—it is a truly public good.

The path from exploratory basic research to practical applications is not one-directional and linear, but rather it is complex and cyclic. The resulting technologies enable even more fundamental discoveries, such as quantum mechanics, which has led to computer chips and other inventions that are responsible for a significant portion of the U.S. gross domestic product (GDP).

To tap into the full potential of human intellect and imagination, we need to balance short-term expectations with long-term investment. Just as a financial expert would never recommend forgoing a retirement fund to enrich an already sufficient checking account, we need to advocate for a balanced portfolio of short- and long-term research initiatives. But driven by decreasing funding, against a background of economic uncertainty, global political turmoil and ever shortening time cycles, research is becoming dangerously skewed toward short-term goals that may address current problems but miss out on huge advances in the long term.

It is a worrisome trend that over the past decades both public and private support for basic research have declined as a percentage of GDP. The postwar decades saw an unprecedented worldwide growth of science, including the creation of funding councils such as the National Science Foundation and massive investments in research infrastructure. Recent years have seen a marked retrenchment. Steadily declining public funding is insufficient to keep up with the expanding role of the scientific enterprise in a modern knowledge-based society. The U.S. federal R&D budget, measured as a fraction of GDP, has dropped from a high of 1.92 percent in 1964, at the height of the cold war and the space race, to less than 0.8 percent today. And the budget for the National Institutes of Health has fallen since 2003.

Governments are increasingly directing research funding to tackle important societal challenges, such as transitioning to clean, sustainable energy, battling climate change and preventing worldwide epidemics, all within flat or decreasing budgets. As a consequence, basic research and its budget are given short shrift.

It is human to focus on necessities in times of stress. But investing in basic research, just like saving for retirement, is a prerequisite for ensuring welfare, innovation and societal progress. Long-term investments in basic research are crucial and lead to an even higher goal: the global benefits of embracing the scientific culture of accuracy, truth seeking, critical questioning and dialogue, healthy skepticism, respect for facts and uncertainties, and wonder at the richness of nature and the human spirit. SA

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Illustration by Bernard Lee


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ADVANCES

The U.S. Coast Guard has plans to upgrade its icebreaker fleet. Above, a Russian nuclear icebreaker clears a path to the North Pole.

INSIDE

CLIMATE TECH

Polar Ice Squad

Testing designs for new icebreakers to support science and national security

Sailing in the Arctic and the Antarctic is no easy feat. To help scientific and other craft navigate these frozen waters, the U.S. Coast Guard employs a small fleet of icebreakers—powerful ships with reinforced hulls that clear the way for other vessels. This past spring the Coast Guard, which has not built a heavy polar vessel in four decades, took a preliminary but crucial step toward expanding its fleet by testing ship models at one of the world's largest ice-tank facilities, located in Canada. It hopes to start building the first new heavy icebreaker in 2020, with completion scheduled for 2023.

The Coast Guard now relies largely on just two vessels in the polar seas. The heavy ship *Polar Star* conducts the annual Operation Deep Freeze resupply run to McMurdo Station, the largest U.S. Antarctic research base. The *Healy,* a medium-size ship, has better scientific facilities and operates mostly in the Arctic. A Coast Guard without heavy icebreakers would face huge challenges in performing search-and-rescue missions, responding to oil spills, protecting U.S. fisheries or supporting navy operations in the polar oceans.

In the Coast Guard's spring tests, small-scale models navigated an ice sheet as long as one-and-a-half Olympic-sized swimming pools at the National Research Council's ice-tank test facility in Newfoundland to measure various designs' resistance, power

and maneuverability (*shown in inset*). The ice-tank trials were intended to evaluate potential heavy polar icebreaker designs for the future fleet, says Alana Miller, a Coast Guard representative. The most promising performers will set the design standards for building the full-size ships. Ultimately the Coast Guard aims to grow its fleet to include three heavy and three medium icebreakers.

The current U.S. vessels have mainly been used to support scientific research. But mission priorities will likely shift as a warming climate opens Arctic waters to more tourism, shipping and commercial fishing. And energy companies may once again look to tap Arctic oil and gas reserves if prices rise and drilling rights can be secured.

Melting sea ice does not automatically mean smooth sailing, however. Vessels would still encounter plenty of dangerous conditions, according to a 2017 report by the nonprofit Council on Foreign Relations. Researchers still need icebreaking capability to study global warming's effects on polar environments—and climate change will sharpen this need well beyond scientific missions. "Going forward, the Coast Guard will likely need to be able to conduct a similar set of missions in the Arctic [as] they conduct in the lower-48 states, [such as] fisheries enforcement, search and rescue, and law enforcement," says marine scientist Robert Campbell, chair of the Arctic Icebreaker Coordinating Committee at the University-National Oceanographic Laboratory System.

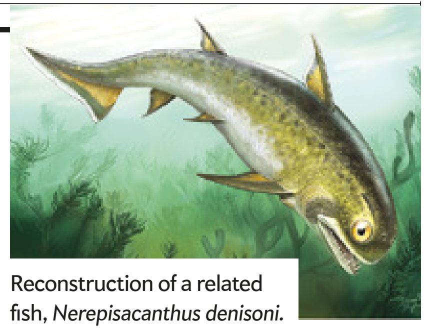
"I don't see how, without an increase in the number of icebreakers, we will be able to maintain a significant presence in the Arctic," Campbell says. "We will by default have to cede leadership on issues in the Arctic—including those that pertain to security—to other nations."

In fact, some experts and members of Congress have warned of an "icebreaker gap," noting that Russia has more than 40 such vessels. But this argument is somewhat misleading because Russia's navy and economy depend more on Arctic routes than the U.S.'s do, says Andreas Kuersten, a law clerk at the U.S. Court of Appeals for the Armed Forces. Still, Kuersten agrees that the U.S. needs new ships: "If someone gets stuck or if someone needs something delivered, [they] don't want to have to call up Russia to steam across the ocean."

Funding for icebreakers has "fallen between bureaucratic cracks" in past years, says public policy expert Sherri Goodman, a senior fellow at the Woodrow Wilson International Center for Scholars and a member of the Arctic Task Force at the Council on Foreign Relations. She says that the Coast Guard has shouldered the burden of building new vessels while government defense spending increases have gone elsewhere. But the icebreaker-acquisition program began grinding forward during the Obama administration and has requested a major funding boost in the fiscal year 2017 budget.

For its current missions the U.S. National Science Foundation charters private research ships such as the *Nathaniel B. Palmer,* which can crunch through three feet of ice at three nautical miles per hour. But such vessels are no match for the Coast Guard's—the *Healy* can breach ice that is eight feet thick by backing up and ramming it, and the *Polar Star* can smash through 21 feet of ice with the same "back and ram" technique. Future icebreakers will also need this ability.

An expanded fleet of six vessels means off-duty ships would have time for maintenance in port, Goodman says. That backup also means rescue capability if a lone icebreaker runs into trouble. As the planet warms and more ships enter Arctic and Antarctic waters, the Coast Guard hopes to finally break the deep freeze on new icebreakers and lead the way. *—Jeremy Hsu*



Reconstruction of a related fish, *Nerepisacanthus denisoni.*

EVOLUTION

Missing Link

An ancient fossil bears features of both bony fish and modern sharks

Science knows very little about shark evolution. This is partly because "cartilage is a funny tissue," says John Maisey, a paleontologist at the American Museum of Natural History in New York City. Shark bodies are largely made of this firm, white connective substance—which does not fossilize well. For hundreds of years scientists have only been able to guess that sharks probably had some bony fish ancestors. But now, using a CT scanner to evaluate the only known fossil of an ancient fish called *Doliodus problematicus,* Maisey and his colleagues may have found a crucial missing piece in the shark origin puzzle.

"Shark skeletons are among the rarest [finds]," Maisey explains. The 400-million-year-old *Doliodus* skeleton was discovered in the mid-1990s in the Canadian province of New Brunswick. Yet it was not until 2014 that advanced CT technology allowed Maisey to see that the specimen had shark-like jaws and tooth arrangements. Earlier this year he and his colleagues reported in *American Museum Novitates* that it also had a row of spines along its back and pelvic fins that match a much older and well-studied class of extinct bony fishes called acanthodians. In other words, *Doliodus* bears features of both the older bony fishes and modern sharks.

"This is a significant discovery," says Michael Coates, an evolutionary biologist at the University of Chicago, who was not involved in the study. The findings support the idea that acanthodians "represent a missing chunk of early shark evolution." Thanks to Maisey's find, researchers will now have to go back and study acanthodians in a whole new light. *—Erin Biba*

PRECEDING PAGES: PER BREIEHAGEN *Getty Images;* THIS PAGE: COURTESY OF NATIONAL RESEARCH COUNCIL OF CANADA (*ice tank*); RECONSTRUCTION BY DANIELLE DUFAULT, FROM "OLDEST NEAR-COMPLETE ACANTHODIAN: THE FIRST VERTEBRATE FROM THE SILURIAN BERTIE FORMATION KONSERVAT-LAGERSTÄTTE, ONTARIO," BY CAROLE J. BURROW AND DAVID RUTKIN, IN *PLOS ONE,* VOL. 9, NO. 8, ARTICLE NO. E104171; AUGUST 5, 2014 *https://doi.org/10.1371/journal.pone.0104171* (*fish*)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NASA's prototype emergency fire shelters.

MATERIALS SCIENCE

Space Age Firefighters

Amid worsening droughts, the U.S. Forest Service tests fire shelters made with NASA heat-shield technology

Despite the most scrupulous planning, wildland firefighters can suddenly find themselves encircled by unpredictable flames reaching nearly 1,500 degrees Fahrenheit. Unable to escape, they have no choice but to hunker down inside fire shelters—reflective, foil-like mini tents—and hope the flames pass over them quickly.

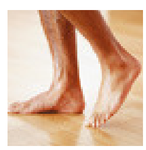
In the summer of 2013, 19 firefighters deployed their standard-issue shelters in Yarnell Hill, Ariz.—but the conflagration proved too much, and none of them survived. After learning of the tragedy, scientists at the NASA Langley Research Center set out to build a better shelter. They used inflatable heat-shield technology designed to withstand the scorching temperatures that spacecraft endure when passing through Earth's atmosphere (2,000 to 5,000

NEUROLOGY

Probing for Parkinson's

Speaking, typing and walking tests hold promise for early detection

People with Parkinson's disease may show hints of motor difficulty years before an official diagnosis, but current methods for catching early symptoms require clinic visits and highly trained personnel. Three recent studies, however, suggest that diagnosis could be as simple as walking, talking and typing. Tests of such activities might eventually enable early intervention if a cure becomes available, which will be crucial for halting progression of the neurodegenerative condition. The findings are exciting, says neurologist Zoltan Mari of Johns Hopkins University. But he cautions that larger studies will be necessary to ensure that these techniques are ready for wider use.



Walking: Data from wearable sensors attached to 93 Parkinson's patients and 73 healthy controls revealed distinctive walking patterns: factors such as step distance and heel force helped to differentiate between the two groups with 87 percent accuracy, according to an analysis by Shyam Perumal and Ravi Sankar of the University of South Florida.

Talking: In a study by Jan Rusz of Czech Technical University and Charles University, both in Prague, and his colleagues, participants read a list of words aloud, and each made a 90-second recording during which they

COURTESY OF IAN GROB *U.S. Forest Service (fire shelters)*; GETTY IMAGES (*feet*); ROY HSU *Getty Images (mouth)* degrees F). In mid-April the U.S. Forest Service blasted the NASA shelters with flames at a research facility at the University of Alberta. Results have not yet been released, but earlier tests were promising. If this space technology proves sturdy enough, firefighters may carry it into the woods this summer.

Traditional fire tents have saved hundreds of lives in the past half-century. But the Yarnell Hill incident showed that "the shelters could not withstand significant, direct-flame heating," explains NASA thermal scientist Josh Fody, who helped to develop the prototype. The heat-shield material can do so, however. Embedded in the thin fabric are bits of graphite the size and shape of pepper flakes. When exposed to flames, the graphite causes a layer of fiberglass insulation to expand, creating "a big, fluffy blanket," Fody says. He calls the material "smart" because it expands only when exposed to high temperatures. Its lightweight design is crucial because wildland firefighters often trek through tough terrain and cannot lug cumbersome gear.

If proved, this technology could not come at a better time. Wildfires now burn twice as much land in the U.S. as they did 20 years ago because of a hotter, drier climate, says Forest Service ecologist W. Matt Jolly. "This means firefighters are exposed to more fire than ever before." —*Mark Kaufman*

described their current interests. Fifty of the participants were at high risk for developing Parkinson's, but only 23 had begun to show symptoms. Simple acoustic features of the short speech samples—including slower talking speed and longer pauses than healthy controls—pinpointed the symptomatic participants with 70 percent accuracy.

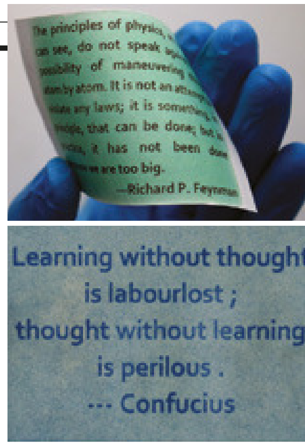
EMMA INNOCENTI *Getty Images*

Typing: People with and without Parkinson's were asked to listen to a folktale and transcribe it by typing. The two groups were matched for age and overall typing speed and excluded people with dementia. Luca Giancardo of the Massachusetts Institute of Technology and his colleagues successfully discriminated between the groups solely by analyzing key hold times (the time required to press and release a key). Their analysis performed comparably or better than motor tests currently used in clinical settings.
—*Anne Pycha*

CHEMISTRY

Print, Wipe, Rewrite

Nanoparticle coating allows paper to be reused more than 80 times



Printed rewritable paper made using Prussian blue nanoparticles.

Despite the ubiquity of tablet computers and e-readers, we simply cannot erase our addiction to paper. An estimated four billion trees are felled every year to make paper or cardboard, an energy-intensive process with a vast environmental footprint. Now chemist Yadong Yin of the University of California, Riverside, and his colleagues have developed "rewritable" paper that could help curb that impact.

The researchers coated conventional paper with nanoparticles of two chemicals: Prussian blue, the pigment that gives blueprints their characteristic color, and titanium dioxide, a substance used in sunscreens. A blast of ultraviolet light makes the titanium dioxide nanoparticles donate electrons to their Prussian blue neighbors. That jolts the pigment into shifting its color from midnight blue to milky white.

By shining that UV light through a transparent screen marked with black text, the researchers "printed" blue text on a white background. The text lasts about five days and then spontaneously fades away: "Every morning I could just push a button, and a printer would give me a fresh newspaper to read over breakfast," Yin says.

The paper can also be reset by heating and reused more than 80 times, a significant improvement over previous types of rewritable paper. "The key advantages are high reversibility and stability, easy handling, low cost and low toxicity," says Sean X. Zhang, a materials scientist at Jilin University in China, who was not involved in the study but has also worked on developing rewritable paper. By comparison, technologies such as electronic ink—used for Amazon's Kindle Paperwhite—involve moving charged black-and-white particles around, which requires electronics.

Since reporting their invention in *Nano Letters* early this year, the scientists have MacGyvered a digital projector to replace their transparent screen. They are now working on increasing the number of times the paper can be reused. Zhang says a key hurdle will be persuading companies to develop the unconventional UV zappers needed for widespread use. Even though commercialization could be a few years away, Yin says, "We've had a lot of discussions with industry investors."

—Mark Peplow

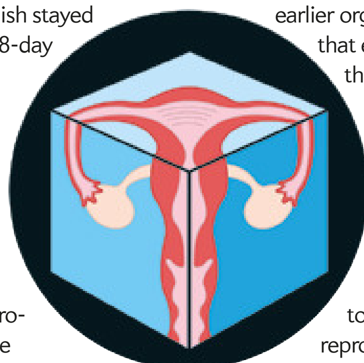
HEALTH

Menstrual Cycle "on a Chip"

Researchers built a lab model that mimics the workings of the human female reproductive system

The exquisite hormonal signaling that drives the female reproductive system cannot be modeled in a flat petri dish. Scrambling to address history's long dearth of research in women's health and physiology, scientists have now created the first "organ on a chip" model that functionally re-creates the female menstrual cycle. This 3-D system may help scientists understand some causes of recurrent miscarriages and could fuel new studies into birth control and drug development in other areas. Fertility experts hope they might eventually be able to place a sample of an individual woman's cells in such a model and thereby determine the best treatment.

A team led by Northwestern University obstetrics and gynecology professor Teresa K. Woodruff grew human and mouse cells from several reproductive organs in a network of tiny, interconnected cubes. Tubes, valves and pumps pushed air and fluids through the system, mimicking the body's natural circulation. Cells that would die in a petri dish stayed alive for a standard 28-day reproductive cycle.



The researchers jump-started the system's chemical communications with an injection of pituitary hormone. In response, the cells secreted levels of estrogen and progesterone found in a typical menstrual cycle—including during ovulation—replicating the signaling that occurs among different female reproductive organs. The team was also able to simulate hormone activity that takes place shortly after conception, creating a tool that could yield insight into maintaining a successful pregnancy. The research was described earlier this year in *Nature Communications.*

The system comprises mouse ovarian cells (which produce the same hormones as human ovaries), along with human cells from the fallopian tube, endometrium and cervix. Human liver cells are also included because the organ breaks down many drugs. The work builds on numerous earlier organ-on-a-chip studies that explored ways to model the human body.

The new system is still far from a perfect stand-in for female anatomy: It lacks both the placenta, which is key to supporting pregnancy, and the inflammatory system. Nor can it address how early toxic exposure may affect reproductive health, says Kevin G. Osteen, a professor of obstetrics and gynecology at the Vanderbilt University School of Medicine, who was not involved in the study. But Woodruff says that her team's work will enable new studies on a wide range of conditions, among them cervical diseases, that cannot be modeled in rodents because of cellular differences.

—Dina Fine Maron

COURTESY OF YADONG YIN *University of California, Riverside*

Illustration by Thomas Fuchs

IN THE NEWS

Quick Hits

GREENLAND

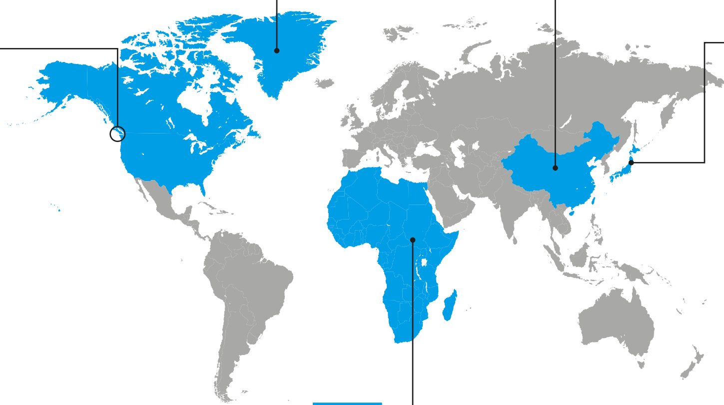
Rising ocean temperatures are melting Greenland's ice caps at three times what the rate was before 1997, according to a recent data analysis of meltwater runoff and ice-cap mass. The island's melting ice caps account for a third of global sea-level rise.

CHINA

Ozone pollution is damaging rice at an important stage of its growth, a new study has shown. China loses more than 1 percent of its rice crop yield for every day that high concentrations of surface ozone occur.

PACIFIC NORTHWEST

Scientists found traces of *Salmonella* and other human-carried pathogens in the breath of orcas in the Pacific Ocean off the coast of North America. Stormwater runoff and sewage may be a source, and researchers worry the parasites could be killing the whales.



JAPAN

This past March a Japanese man became the first human to receive an injection of "reprogrammed" stem cells donated by another person. Mature skin cells were converted to an embryonic state before being transformed into retinal cells to treat the man's eye disease.

AFRICA

University of California, Berkeley, researchers mapped out a plan for developing renewable power and reducing fossil-fuel dependency in Africa. The project would establish wind and solar farms in 21 countries in the continent's densely populated eastern and southern regions.

—Andrea Marks

For more details, visit
www.ScientificAmerican.com/jun2017/advances

HEALTH TECH

Radiation Triage

A new blood test validated in monkeys could speed diagnoses following a nuclear accident

Exclusion zone near the Fukushima Daiichi nuclear power plant, February 26, 2016.

After a nuclear disaster like the one in Fukushima, Japan, in 2011, first responders need to quickly measure radiation exposure en masse and decide who requires urgent treatment. Existing tests are fast and accurate—but they rely on sophisticated laboratories, expensive machinery and meticulous work, says Dipanjan Chowdhury, a radiation oncologist at the Dana-Farber Cancer Institute. "We don't have copious amounts of radiation drugs available" in such a situation, he adds. "So how do we decide who gets them?"

To address this question, Chowdhury and his colleagues are developing a simple assay that responders could deploy in the field with limited expertise or equipment. The test, described in March in *Science Translational Medicine,* detects levels of molecules called microRNAs (miRNAs) in blood and other bodily fluids. The same researchers had previously identified certain miRNAs whose levels rise or fall in mice exposed to radiation.

Chowdhury's team members found that this radiation signature also exists in monkeys (which are the best lab proxies for humans). Their study identifies seven miRNAs that fluctuate in both mice and macaques exposed to radiation. The monkeys were given lethal doses of 5.8, 6.5 or 7.2 grays of whole-body radiation, similar to levels inhaled by Fukushima workers (all the animals received "lethal" doses, but only some resulted in death). Together three of these miRNAs—miR-133b, miR-215 and miR-375—can indicate with 100 percent accuracy whether a macaque has encountered radiation, and two—miR-30a and miR-126—can predict whether the exposure will be fatal. The signature appears within 24 hours of exposure and can be measured using polymerase chain reaction (PCR), a common technique. "Based on the ingredients and the complexity, the miRNA test should be significantly cheaper than any existing test," Chowdhury says.

The findings in nonhuman primates are encouraging, says Nicholas Dainiak, director of the Radiation Emergency Assistance Center/Training Site at the Oak Ridge Institute for Science and Education, who was not involved in the study. Dainiak is skeptical, however, that the test will outperform the gold standard metric for radiation exposure: the dicentric chromosome assay (DCA), which requires technical expertise and carefully calibrated equipment. "Every time a new test comes along, and you compare it with the DCA, it typically fails," Dainiak says.

Chowdhury has held informal talks with companies that are interested in creating a rapid diagnostic kit for radiation. "When we did this in mice, people said, 'We've seen a lot of stuff in mice that never pans out in primates,'" Chowdhury says. "Well, this seems to be panning out in primates."

—*Ann Griswold*

CHRISTOPHER FURLONG *Getty Images*

COURTESY OF GE ENERGY CONNECTIONS

ENGINEERING

Electric Renaissance

A need to convey renewable power sparks a return to direct current

More than 100 years ago scientists and business leaders feuded over the incipient U.S. electrical grid: Should it rely on alternating current (AC) or direct current (DC)? Both are used to transmit electricity—DC flows steadily in one direction, whereas AC varies direction periodically. Thomas Edison championed DC as the better option—and even publicly electrocuted stray animals with AC to convince the public that it posed a danger. By the early 20th century AC prevailed, however, for technical and economic reasons.

Now DC is making a comeback.

In coming years the handful of DC transmission lines scattered across the country today may be joined by at least nine new long-distance, high-voltage DC (HVDC) lines that several companies are planning to build. That is largely a result of one major trend: the Midwest and other regions are now producing a great deal of renewable energy—about 2.8 trillion kilowatt-hours in 2015—and utility companies need a way to deliver it to faraway urban and industrial centers. "You have remote resources, and there's just not enough infrastructure to move that energy to the market," says Wayne Galli, executive vice president of engineering at Clean Line Energy Partners, which plans to build four HVDC lines. The Houston-based company has already sent out field crews to prepare for construction of one of its lines—it will bring wind energy up to 720 miles from Oklahoma and the Texas panhandle to Tennessee and Arkansas and then on to other nearby states.

Technology for power transmission advanced in the 1970s, allowing direct current to return as a viable option—and for lines more than 300 to 500 miles long, DC outcompetes AC. After a certain distance, AC systems become more costly to build than DC and have larger power losses along the line because of issues such as higher resistance. "Using DC lines is a much better solution for moving power from big, remote wind or solar farms," says Gregory Reed, director of the University of Pittsburgh's Center for Energy and the Energy GRID Institute. "It's a rapid change in where we're getting our resources from."

And because renewable energy isn't going away anytime soon, DC likely won't either. But as Galli notes, "DC never totally went away." —*Annie Sneed*

CLIMATE

Swell or High Water

A sobering new report pinpoints potential U.S. sea-level rises with unprecedented resolution

Norfolk, Va., is half a world away from Antarctica's melting ice sheets. Yet this low-lying city on the Chesapeake Bay is one of the places most vulnerable to tidal flooding from rising sea levels in the U.S. As the climate heats up, in the most extreme scenario Norfolk and other East Coast communities can expect waters to climb as much as 11.5 feet—about 3.5 feet more than the global average—by 2100.

This year the National Oceanic and Atmospheric Administration released a report aiming to help local governments such as Norfolk's get ready. It is the first analysis to break down vulnerability into one-degree chunks of latitude and longitude—about 70 miles across—for the entire U.S. coastline, and it lays out possible scenarios for average global sea-level rise from "low" (a rise of 0.3 meter, or about one foot) to "extreme" (2.5 meters, or about eight feet). It also accounts for local factors such as subsidence, or sinking land. In nearly all the scenarios, rises in the Northeast and the western Gulf of Mexico exceed the worldwide average.

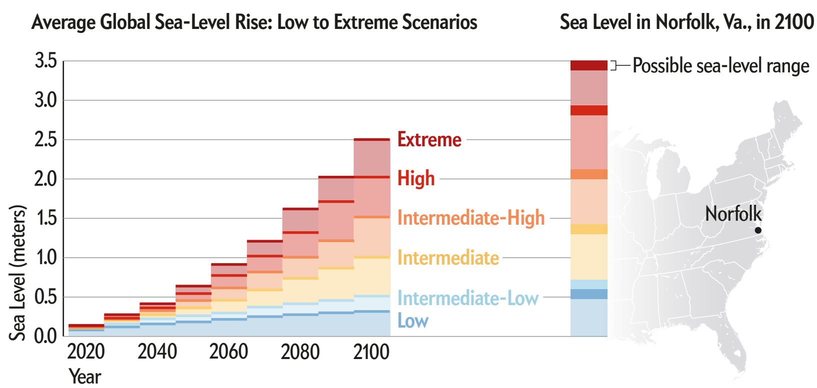
"We wanted to say, 'Listen, here are the main factors, and here's how they could affect you,' so that everyone has the best available data and the same models to use in the same manner across the coastline," says NOAA oceanographer William Sweet, the report's lead author.

To understand why the East Coast is particularly vulnerable, one has to look southward. Antarctica's ice sheets are melting faster than initial models predicted, and ocean currents sweep that water northward. Gravity is also to blame: Antarctica's tremendous mass exerts a huge pull on the oceans, extending all the way to the Atlantic—but as the continent loses ice, its grip will weaken, allowing that closely held water to flow toward the opposite pole. Melting mountain glaciers add more water, and higher global temperatures make the oceans warm and swell in a process called thermal expansion.

So-called sunshine flooding—inundation without storms—now occurs in Norfolk as often as nine days a year, up from two days a year in the mid-1980s, the report says. City officials are employing everything from earthen dikes to water-permeable pavement to tame the rising waters.

Authorities along the entire East Coast would do well to start planning for a waterlogged future now, says Larry Atkinson, a professor of oceanography at Old Dominion University in Norfolk, who was not involved in the NOAA report. "Greenhouse gases can be stopped tomorrow," he says, "and there will still be sea-level rise into the next century."

—April Reese



Researchers projected six scenarios of sea-level rise, putting the global average between 0.3 and 2.5 meters by 2100. Depending on which scenario occurs, Norfolk will experience moderate to large deviations from the mean, all resulting in comparatively high sea levels.

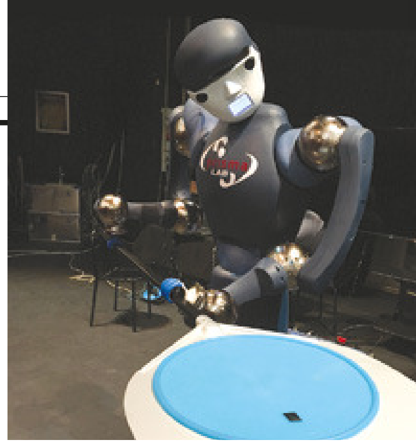
HYUNSOO LEO KIM *AP Photo (flood)*; SOURCE: *GLOBAL AND REGIONAL SEA LEVEL RISE SCENARIOS FOR THE UNITED STATES.* BY WILLIAM V. SWEET ET AL. NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION, JANUARY 2017

Graphic by Amanda Montañez

ROBOTICS

Robo Pizzaiolo

A new generation of dexterous machines could show off in the kitchen



COURTESY OF BRUNO SICILIANO AND PRISMA LAB

Pizza has a proud history of fueling late-night lab work, and scientists in Naples—an Italian city famous for its slice—have easy access to some of the world's tastiest take-out. But what inspires engineer Bruno Siciliano is not just that first bite so much as how the dish is made.

"Preparing a pizza involves an extraordinary level of agility and dexterity," says Siciliano, who directs a robotics research group at the University of Naples Federico II. Stretching a deformable object like a lump of dough requires a precise and gentle touch. It is one of the few things humans can handle, but robots cannot—yet.

Siciliano's team has been developing a robot nimble enough to whip up a pizza pie, from kneading dough to stretching it out, adding ingredients and sliding it into the oven. RoDyMan (short for Robotic Dynamic Manipulation) is a five-year project supported by a €2.5-million grant from the European Research Council. Like a human chef, RoDyMan must toss the dough into the air to stretch it, following it as it spins and anticipating how it will change shape. The bot will debut in May 2018 at the legendary Naples pizza festival.

RoDyMan has been working this spring toward a milestone: stretching the dough without tearing it. To guide the robot, Siciliano's team recruited master pizza chef Enzo Coccia to wear a suit of movement-tracking sensors. "We learn [Coccia's] motions, and we mimic them with RoDyMan," Siciliano says.

This strategy makes a lot of sense, says robotics researcher Nikolaus Correll of the University of Colorado Boulder. He has modeled flexible motion with rubber springs but was not involved in Siciliano's research. "Someone who's learning how to make a pizza would use feedback from their hands," he adds. "You'd just take the dough and start pulling and try to experience it."

RoDyMan uses visual sensors in its head to track the dough in real time. Using software, it can train itself to handle the pizza like a chef would—a task that is challenging because it is unwieldy and messy. The robot maps the dough's position and tracks how it moves. Through practice, the robot can get better—much like humans develop "muscle memory." Researchers hope RoDyMan's technology can lead to a new generation of robots that will perform tasks in ways that are accurate, precise and responsive, if not more lifelike.

Yet Siciliano admits that nothing compares with a traditional chef. "I would never eat a pizza made by a robot," he says. "It would not have the taste a real pizzaiolo, with his soul, would put in it." —*Jeanette Beebe*

Revenge of the Super Lice

Overexposure to insecticides has bred resistance in the parasites, making it harder than ever to treat infestation

By Karen Weintraub

Karen Sokoloff finds a certain satisfaction in picking lice off a person's scalp, smoothing olive oil into the hair strands and carefully pulling a metal comb through them to catch the stragglers. It's a good thing she enjoys it: Sokoloff co-founded LiceDoctors, one of a handful of national chains of lice pickers, and business is booming, in part because conventional treatments have become largely ineffective.

For decades people have turned to special over-the-counter shampoos containing plant-derived insecticides known as pyrethrins or their synthetic counterparts, called pyrethroids, to treat cases of head lice. When they first came to market, these products worked well. But sustained use of these same few chemicals has allowed the blood-sucking parasites to evolve widespread resistance to them. Indeed, a recent study of lice in the U.S. carried out by pesticide toxicologist John Marshall Clark of the University of Massachusetts Amherst and his colleagues found that two thirds to three quarters of them are immune to the effects of these insecticides. They have become "super lice."

This high prevalence of resistance means that most people are wasting their money when they turn to over-the-counter lice shampoos, which range in price from about $6 to more than $30 a bottle and remain the weapon of choice for those doing battle with lice. Use of these shampoos may also prolong the misery of the patients, given that it can take a week or more to determine that the treatment has failed. The problem is particularly disruptive for children, the most common victims of lice, because some schools require students to stay home until their scalps are totally clear of both lice and their eggs, called nits.

This resistance problem has spurred scientists to look for new methods of controlling lice. In Europe, nonpesticide treatments have met with success. In the U.S., doctors have recently added new prescription medications to their arsenal. But scientists warn that those drugs need to be used wisely to keep lice from developing resistance to them, too.

A PERVASIVE PARASITE

Lice are far more common than people want to believe—or may perceive at first glance. In a 2001 study Kosta Mumcuoglu of the Hebrew University of Jerusalem and his colleagues examined the scalps of 280 Israeli children. One group of researchers looked for any lice they could spot with a simple visual inspection. They found that upward of 5 percent were infested. Another group reexamined the same children using lice combs. This more rigorous check turned up insects on the heads of more than four times as many children. Researchers have also reported high rates of infestation in Turkey and England, among other places. The findings suggest that an average of one in five children in developed countries has lice, Mumcuoglu says.

Lice mostly spread when people touch heads; children are particularly susceptible because they come into closer physical contact than adults. Sokoloff, whose LiceDoctors chain has technicians in 40 states, says her business always sees a spike when kids come home from summer camp, as well as after the winter holidays, when they have shared beds with friends and relatives.

Illustration by Sara Gironi Carnevale

Karen Weintraub is a freelance health and science journalist who writes regularly for the *New York Times,* STAT (www.statnews.com) and *USA Today,* among others.

Personal hygiene does not seem to be a determining factor in who gets lice, but long hair hides the parasites more readily than short hair does and makes it harder to comb out nits.

Head lice technically belong to the same species as body lice, *Pediculus humanus*. But whereas body lice can spread diseases, including epidemic typhus, trench fever and even the plague, head lice have never been blamed for any such outbreak. The distinction may have to do with differences in immune response between the two types of lice. Clark and his colleagues found that when they infected both kinds of lice with the bacterium that causes trench fever, the head lice fought off the infection far more aggressively than the body lice did. Perhaps head lice do not transmit disease partly because their immune system eradicates the infection before they can pass it along to humans.

Still, head lice cause plenty of discomfort and distress. And in a really bad infestation, as can happen with homeless people living in crowded shelters, severe scalp itching can open up wounds in the head, allowing bacteria to enter the person's bloodstream and cause systemic infections.

GROWING RESISTANCE

THE ROOTS OF PESTICIDE RESISTANCE in head lice reach back over decades to World War II, when millions of people in Europe and Asia were doused with the insecticide DDT to prevent body lice. Use of DDT to combat lice and other insects continued until the 1980s in Europe and Asia; in the U.S., the insecticide was phased out a decade earlier amid safety concerns. But it left a lasting legacy in the insects.

When pyrethroids were introduced into Israel in the early 1990s, just one treatment would destroy all the adult lice on an individual within a few weeks. The chemicals also lingered on the scalp long enough to kill the eggs, which normally hatch up to 10 days later. Within two to three years, however, these pyrethroid-based treatments ceased to kill the majority of the parasites.

The earlier use of DDT had primed lice to develop this resistance. DDT works by disrupting the nervous system. Nerve cells have tiny pores in their cell membranes that regulate the flow of sodium ions into the cell, which in turn modulates the firing of the cell. DDT holds open the tiny sodium pores, allowing sodium to flow into the cell unabated. The influx causes the nerve cells to fire constantly, leading to convulsion of the insect, paralysis and eventually death. Decades of DDT exposure allowed lice to evolve mutations that block its effects on the sodium pores. These mutations persisted in the lice population. Pyrethrins and pyrethroids also work by interfering with sodium pores. Lice have thus been able to readily evolve resistance to them, by co-opting mutations that fortified them against DDT.

Mutations that confer protection to head lice have spread to high frequency. From 2013 to 2015 Kyong Sup Yoon, an entomologist at Southern Illinois University Edwardsville, gathered lice from 48 U.S. states. He and his colleagues, including Clark, found that 132 out of the 138 populations they tested carry so-called knockdown resistance–type mutations, which desensitize the louse nervous system to pyrethroids.

NEW TACTICS

HUMANS HAVE GIVEN HEAD LICE an advantage by subjecting them to the same treatments again and again. Such repeated exposure builds resistance not only to that treatment but to virtually all others that work according to the same or similar mechanisms, Clark says. At that point, the only way to defeat the lice is to find a completely novel approach, one that the parasites are not pre-adapted to fending off. To that end, in recent years researchers have developed a few treatments that are based on entirely different mechanisms of action than the pyrethroids are. In the U.S., the Food and Drug Administration has approved three prescription treatments since 2009: Ulesfia, which contains high levels of alcohol and kills the lice essentially by suffocating them; Natroba, which overexcites nerve cells by activating their nicotinic acetylcholine receptors; and Sklice, which inhibits nerve impulses by activating their glutamate chloride channels.

For these treatments to work over the long term, health care providers need to rotate them among patients to avoid overexposing lice to any single drug and thus lessen the chances of the lice developing resistance to it. There are no official medical guidelines requiring such a rotation, however. Doctors can prescribe whichever drug they want, and they are usually unaware of the benefits of alternating treatments.

Further confounding matters, the co-pay for visiting a doctor, plus the cost of prescriptions, which may or may not be covered by insurance, can impede patient access to these newer medications. And despite their diminishing efficacy, over-the-counter lice shampoos remain the first response recommended by most doctors, health plans and even the American Academy of Pediatrics. For its part, the combing method used by many parents and professional lice pickers such as LiceDoctors is theoretically effective, Clark and Yoon note, but hard to do well.

The situation is totally different in Europe, where treatment moved on from pyrethroids and virtually all insecticides about a decade ago, says Ian Burgess, president of the International Society of Phthirapterists (people who study lice). Instead most Europeans now rely on silicone and other synthetic oils to eliminate head lice. The oils envelop the lice, preventing them from excreting water. As liquid builds up inside the louse, its internal organs start to shut down from the exhaustion of trying to pump out the water. Either it dies of this exhaustion, Burgess says, or its guts rupture from the liquid.

In Europe, such synthetic oil treatments are considered medical devices rather than drugs and so are subject to fewer regulations; in the U.S., they are viewed as medications and have not passed regulatory hurdles, observes Burgess, who also works for a contract research company that helps to develop anti-lice devices. Overall, Burgess says he thinks Europe's approach to lice is working. When he tests schoolchildren today, he finds the same percentage infested as he did two decades ago, but each child has fewer lice.

Still, despite this progress, lice seem poised to keep researchers—and the rest of us—scratching our heads for quite some time to come. SA

David Pogue is the anchor columnist for Yahoo Tech and host of several *NOVA* miniseries on PBS.

The iOS 11 To-Do List

Here's what Apple should fix before the next operating system update

By David Pogue

Remember when we got a few years off between operating systems? We got a little break between, say, Windows 95 and 98 or between Mac OS 8 and 9.

But in 2011 Apple started releasing new versions of its Mac and iPhone operating systems every single year. Unfortunately, when you pile on new features that often, sooner or later the OS suffers. It gets harder to learn, harder to use and sometimes buggier.

At this moment, Apple is working on iOS 11 for the iPhone. If history is any guide, it will come out in September. As a public service, therefore, I thought I'd helpfully point out a few things in iOS 10 that need fixing. C'mon, Apple—here's your chance to make things right!

(Note: These are design fails, not features I'd like to see. I could offer plenty of those, too.)

■ **Clean up the hard presses.** The screens on the latest iPhone models (the 6s and 7) have what Apple calls 3D Touch, meaning that they're pressure-sensitive. In many spots, touching the screen hard produces one result; pressing lightly delivers another.

But how hard is hard? If you use the wrong pressure, you get a result you didn't intend.

A classic example: To move or delete app icons on the iPhone's home screen, you're supposed to touch any app's icon for a couple of seconds. At that point, they all begin to—what's the technical term?—*wiggle*. Now you can manipulate them.

But if you try that on a 3D Touch model, you're likely to open a shortcut menu instead because you're pressing too hard. You have to cancel out and try again, remembering to press *lightly* but *longer*. No way is that intuitive.

■ **Make hard-press features available to all!** Some useful features are available only to iPhones with 3D Touch. For example, only with a hard press can you adjust the brightness level of the "flashlight" (the LED on the back of the phone) or clear all the notification bubbles at once. There's no reason Apple couldn't make these features available to the millions of people who own older phones. Why couldn't a long press perform the same function as the hard press?

■ **Fix the Control Center swiping.** In iOS 10, Apple reinvented the Control Center—the settings panel that appears when you swipe up from underneath the screen. Specifically, Apple split it into three "panes": one with the traditional controls (brightness, Wi-Fi, Bluetooth, et cetera); one that contained music-playback controls; and a third that controlled accessories in your home.

Until iOS 10, you could adjust the screen brightness by dragging horizontally on the Brightness slider. But now horizontal swiping means: "Switch to the Music controls." If your finger's aim on the Brightness slider isn't absolutely pixel-perfect, you wind up opening the Music page by accident. Happens all the time.

■ **Make a decision about the Genius playlist.** Previous iOS versions offered something called a Genius playlist, which automatically generated lists of songs with similar musical styles. That's gone in iOS 10. But the on/off switch for the feature is still there, in the Music Settings; it does absolutely nothing. Oopsie.

■ **Let us clear our music queue, please.** It's easy to create a "queue" of songs or albums that you want to hear next in the Music app. It's not so easy to *clear* that queue all at once—it's impossible.

■ **Let us choose our preferred apps!** Years ago Microsoft got in trouble for bundling its own apps with Windows, making it harder for independent companies to make inroads with their software. Apple is now doing the same thing with its apps for mail, calendar, browser and maps. For example, if you ask Siri to give you directions somewhere or hit the Get Directions button on an address, the iPhone uses Apple's built-in Maps app to guide you. There's no easy way to direct it to use the far superior Google Maps. That's just 800-pound gorilla-ism.

So there you go, dear Apple: a to-do list for the next release of one of the world's most popular operating systems. Please remember the principle that put you on the map in the first place years ago: simpler is usually better. SA

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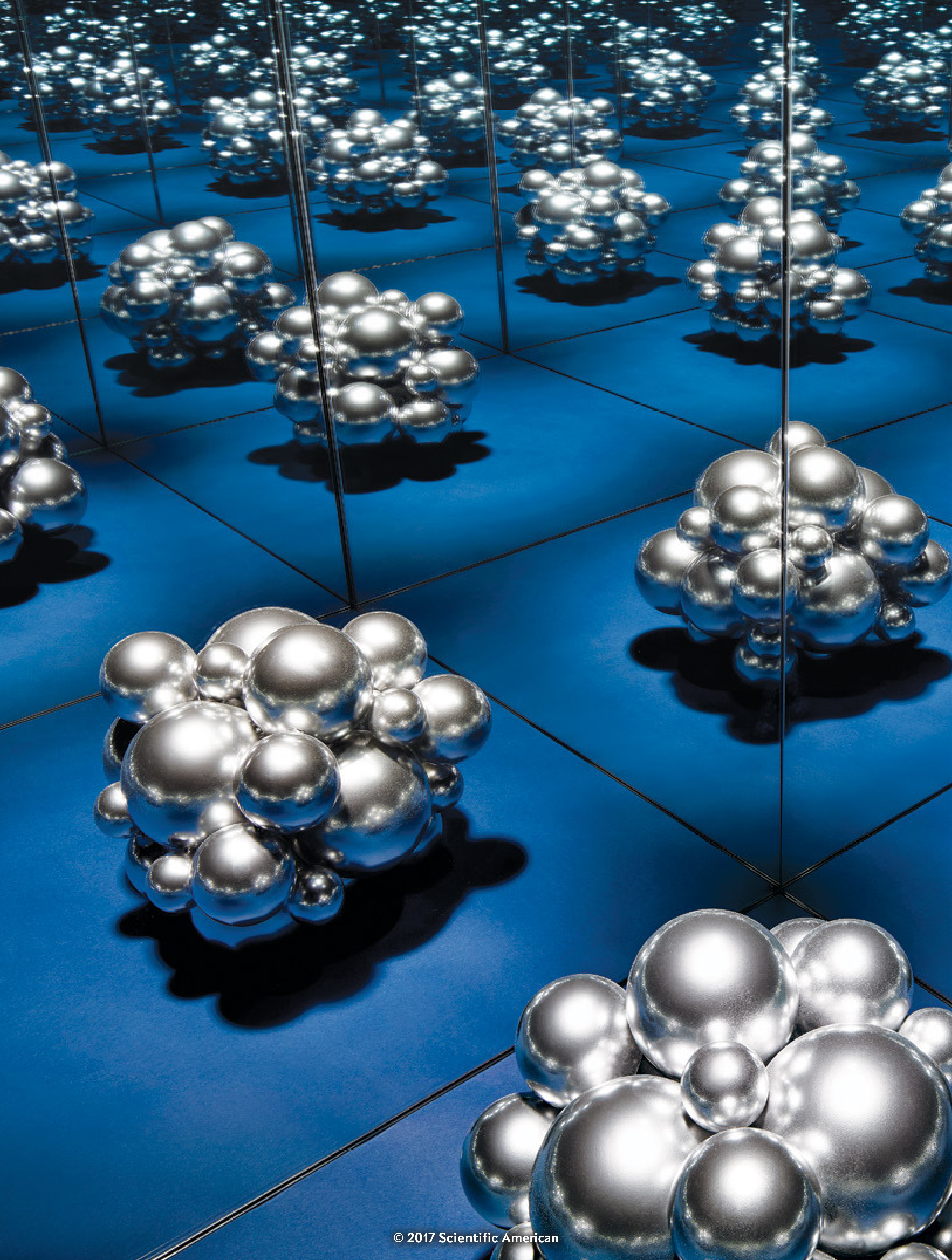
SOME ANDROID PHONES HAVE FEATURES APPLE SHOULD CONSIDER: scientificamerican.com/jun2017/pogue

Illustration by Jay Bendt



COSMOLOGY

THE QUANTUM MULTIVERSE

A surprising connection between cosmology and quantum mechanics could unveil the secrets of space and time

By Yasunori Nomura

Photograph by The Voorhes

Yasunori Nomura is a professor of physics and director of the Berkeley Center for Theoretical Physics at the University of California, Berkeley. He is also a senior faculty scientist at Lawrence Berkeley National Laboratory and a principal investigator at the University of Tokyo's Kavli Institute for the Physics and Mathematics of the Universe.

MANY COSMOLOGISTS NOW ACCEPT THE EXTRAORDINARY IDEA THAT what seems to be the entire universe may actually be only a tiny part of a much larger structure called the multiverse. In this picture, multiple universes exist, and the rules we once assumed were basic laws of nature take different forms in each; for example, the types and properties of elementary particles may differ from one universe to another.

The multiverse idea emerges from a theory that suggests the very early cosmos expanded exponentially. During this period of "inflation," some regions would have halted their rapid expansion sooner than others, forming what are called bubble universes, much like bubbles in boiling water. Our universe would be just one of these bubbles, and beyond it would lie infinitely more.

The idea that our entire universe is only a part of a much larger structure is, by itself, not as outlandish as it sounds. Throughout history scientists have learned many times over that the visible world is far from all there is. Yet the multiverse notion, with its unlimited number of bubble universes, does present a major theoretical problem: it seems to erase the ability of the theory to make predictions—a central requirement of any useful theory. In the words of Alan Guth of the Massachusetts Institute of Technology, one of the creators of inflation theory, "in an eternally inflating universe, anything that can happen will happen; in fact, it will happen an infinite number of times."

In a single universe where events occur a finite number of times, scientists can calculate the relative probability of one event occurring versus another by comparing the number of times these events happen. Yet in a multiverse where everything happens an infinite number of times, such counting is not possible, and nothing is more likely to occur than anything else. One can make any prediction one wants, and it is bound to come true in some universe, but that fact tells you nothing about what will go on in our specific world.

This apparent loss of predictive power has long troubled physicists. Some researchers, including me, have now realized that quantum theory—which, in contrast to the multiverse notion, is concerned with the very smallest particles in existence—may, ironically, point the way to a solution. Specifically, the cosmological picture of the eternally inflating multiverse may be mathematically equivalent to the "many worlds" interpretation of quantum mechanics, which attempts to explain how particles can seem to be in many places at once. As we will see, such a connection between the theories not only solves the prediction problem, it may also reveal surprising truths about space and time.

QUANTUM MANY WORLDS

I CAME TO THE IDEA of a correspondence between the two theories after I revisited the tenets of the many-worlds interpretation of quantum mechanics. This concept arose to make sense of some of the stranger aspects of quantum physics. In the quantum world—a nonintuitive place—cause and effect work differently than they do in the macro world, and the outcome of any process is always probabilistic. Whereas in our macroscopic experience, we can predict where a ball will land when it is thrown based on its starting point, speed and other factors, if that ball were a quantum particle, we could only ever say it has a certain chance of ending up here and another chance of ending up there. This probabilistic nature cannot be avoided by knowing more about the ball, the air currents or such details; it is an intrinsic property of the quantum realm. The same exact ball thrown under the same exact conditions will sometimes land at

IN BRIEF

The theory of cosmic inflation, which implies that the early cosmos expanded exponentially, suggests that we live not in a universe but a vast multiverse.

The problem with the multiverse idea, however, is that all events that can occur will occur infinitely many times, ruining the theory's predictive ability.

Physicists realized they can resolve the issue by viewing the multiverse as equivalent to a notion from quantum mechanics called the many-worlds interpretation, which suggests that our universe is one of many that coexist in "probability space" rather than in a single real space.

HUBBLE SPACE TELESCOPE'S Ultra Deep Field shows galaxies as far as 13 billion light-years away. Objects much farther out will forever be beyond reach because the expansion of space causes them to recede faster than the speed of light. This so-called cosmological horizon has important implications for the theory of the multiverse.

point A and other times at point B. This conclusion may seem strange, but the laws of quantum mechanics have been confirmed by innumerable experiments and truly describe how nature works at the scale of subatomic particles and forces.

In the quantum world, we say that after the ball is thrown, but before we look for its landing spot, it is in a so-called superposition state of outcomes A and B—that is, it is neither at point A nor point B but located in a probabilistic haze of *both* points A and B (and many other locations as well). Once we look, however, and find the ball in a certain place—say, point A—then anyone else who examines the ball will also confirm that it sits at A. In other words, before any quantum system is measured, its outcome is uncertain, but afterward all subsequent measurements will find the same result as the first.

In the conventional understanding of quantum mechanics, called the Copenhagen interpretation, scientists explain this shift by saying that the first measurement changed the state of the system from a superposition state to the state A. But although the Copenhagen interpretation does predict the outcomes of laboratory experiments, it leads to serious difficulties at the conceptual level. What does the "measurement" really mean, and why does it change the state of the system from a superposition of possibilities to a single certainty? Does the change of state occur when a dog or even a fly observes the system? What about when a molecule in the air interacts with the system, which we expect to be occurring all the time yet which we do not usually treat as a measurement that can interfere with the outcome? Or is there some special physical significance in a human consciously learning the state of the system?

In 1957 Hugh Everett, then a graduate student at Princeton University, developed the many-worlds interpretation of quantum mechanics that beautifully addresses this issue—although at the time many received it with ridicule, and the idea is still less favored than the Copenhagen interpretation. Everett's key insight was that the state of a quantum system reflects the state of the *whole* universe around it, so that we must include the observer in a complete description of the measurement. In other words, we cannot consider the ball, the wind and the hand that throws it in isolation—we must also include in the fundamental description the person who comes along to inspect its landing spot, as well as everything else in the cosmos at that time. In this picture, the quantum state after the measurement is still a superposition—not just a superposition of two landing spots but of two entire worlds! In the first world, the observer finds that the state of the system has changed to A, and therefore any observer in this particular world will obtain result A in all subsequent measurements. But when the measurement was made, another universe split off from the first in which the observer finds, and keeps finding, that the ball landed at point B. This feature explains why the observer—let us say it is a man—thinks that his measurement changes the state of the system; what actually happens is that when he makes a measurement (interacts with the system), he himself divides into two different people who live in two different parallel worlds corresponding to two separate outcomes, A and B.

According to this picture, humans making measurements have no special significance. The state of the entire world continuously branches into many possible parallel worlds that co-

COURTESY OF NASA, ESA, S. BECKWITH *STScI* AND HUBBLE DEEP FIELD TEAM

Inflation Meets Many Worlds

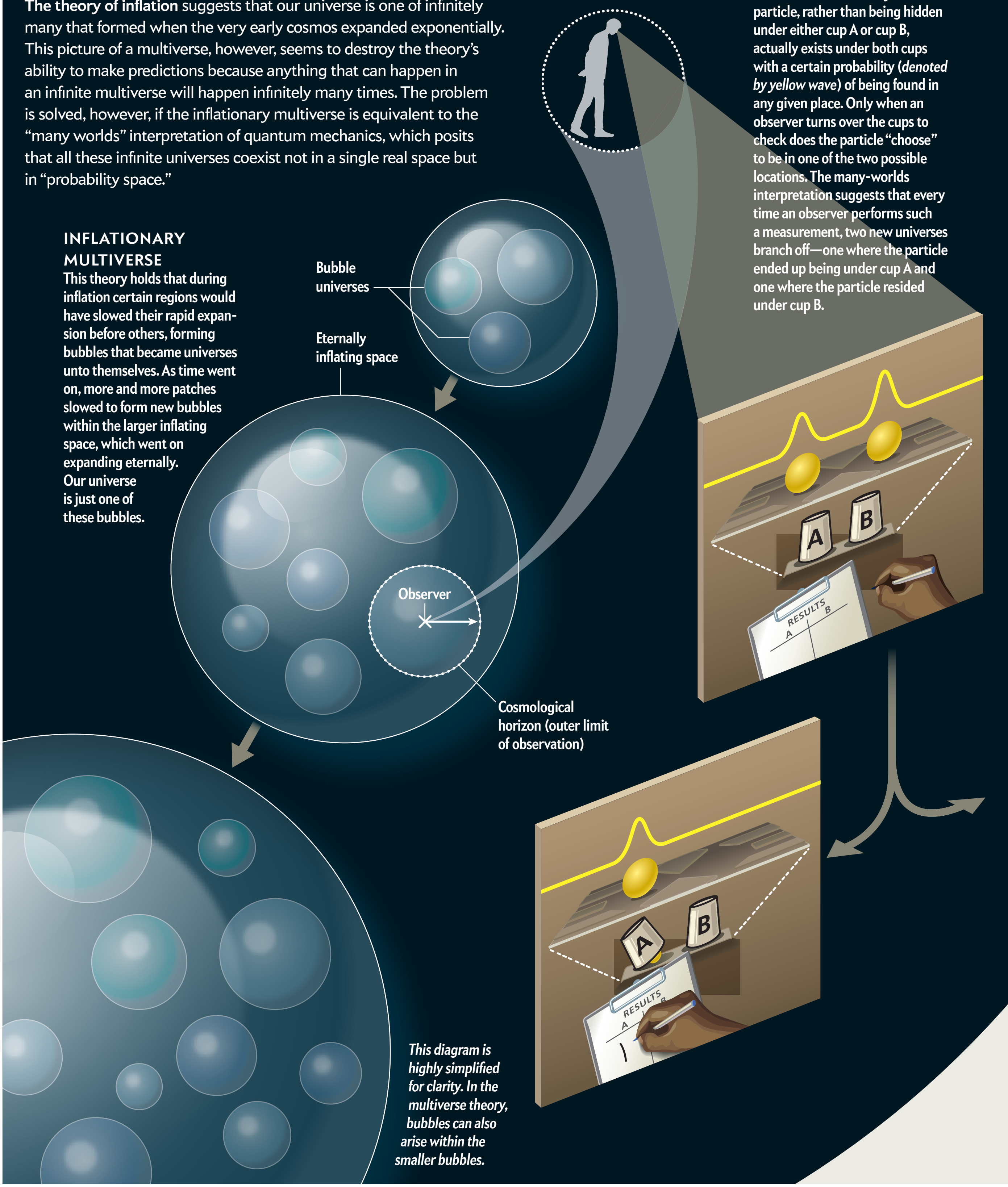
The theory of inflation suggests that our universe is one of infinitely many that formed when the very early cosmos expanded exponentially. This picture of a multiverse, however, seems to destroy the theory's ability to make predictions because anything that can happen in an infinite multiverse will happen infinitely many times. The problem is solved, however, if the inflationary multiverse is equivalent to the "many worlds" interpretation of quantum mechanics, which posits that all these infinite universes coexist not in a single real space but in "probability space."

MANY WORLDS

Quantum mechanics says that a particle, rather than being hidden under either cup A or cup B, actually exists under both cups with a certain probability (*denoted by yellow wave*) of being found in any given place. Only when an observer turns over the cups to check does the particle "choose" to be in one of the two possible locations. The many-worlds interpretation suggests that every time an observer performs such a measurement, two new universes branch off—one where the particle ended up being under cup A and one where the particle resided under cup B.

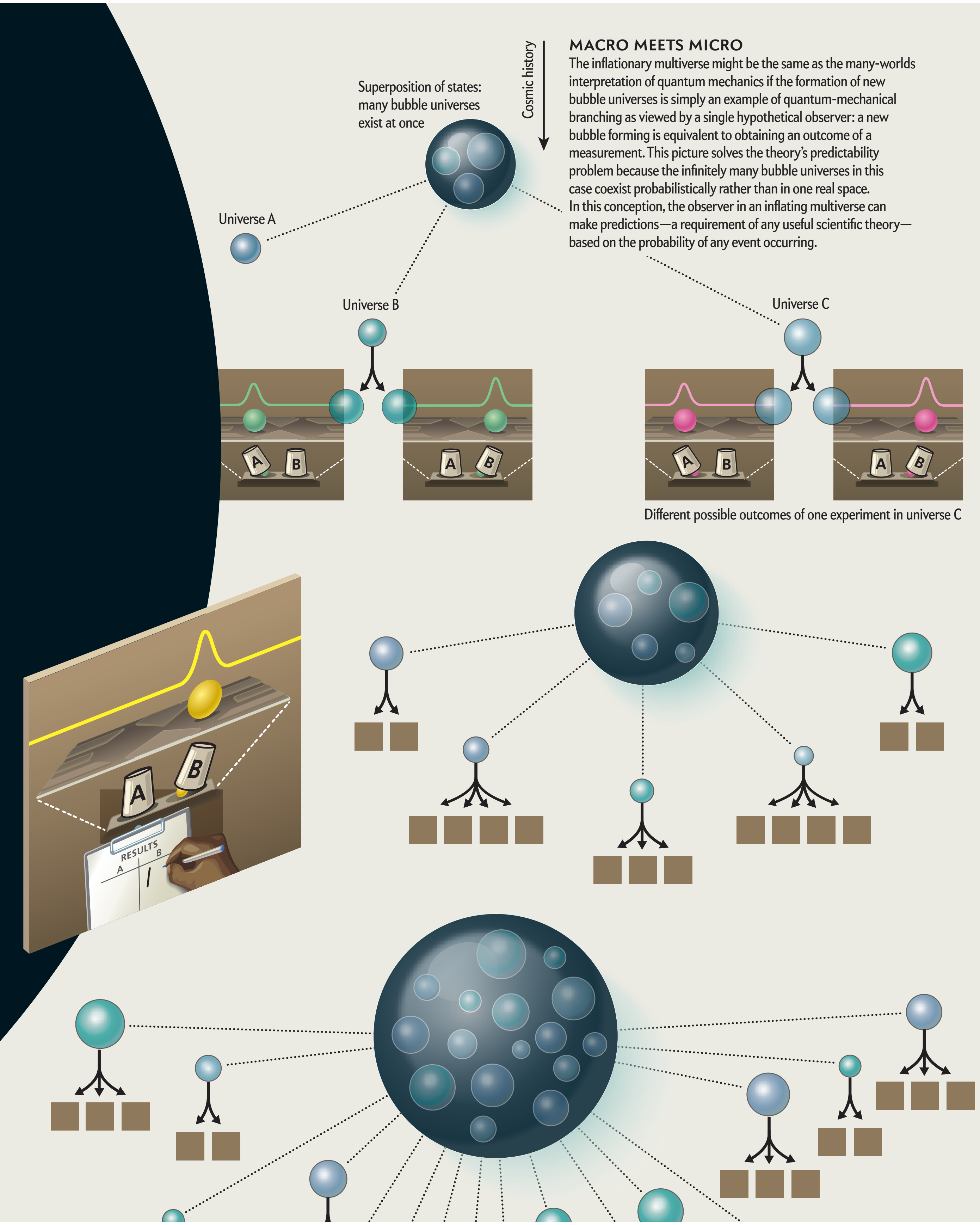
INFLATIONARY MULTIVERSE

This theory holds that during inflation certain regions would have slowed their rapid expansion before others, forming bubbles that became universes unto themselves. As time went on, more and more patches slowed to form new bubbles within the larger inflating space, which went on expanding eternally. Our universe is just one of these bubbles.



This diagram is highly simplified for clarity. In the multiverse theory, bubbles can also arise within the smaller bubbles.

Illustration by Jen Christiansen



MACRO MEETS MICRO

The inflationary multiverse might be the same as the many-worlds interpretation of quantum mechanics if the formation of new bubble universes is simply an example of quantum-mechanical branching as viewed by a single hypothetical observer: a new bubble forming is equivalent to obtaining an outcome of a measurement. This picture solves the theory's predictability problem because the infinitely many bubble universes in this case coexist probabilistically rather than in one real space. In this conception, the observer in an inflating multiverse can make predictions—a requirement of any useful scientific theory—based on the probability of any event occurring.

exist as a superposition. A human observer, being a part of nature, cannot escape from this cycle—the observer keeps splitting into many observers living in many possible parallel worlds, and all are equally "real." An obvious but important implication of this picture is that everything in nature obeys the laws of quantum mechanics, whether small or large.

What does this interpretation of quantum mechanics have to do with the multiverse discussed earlier, which seems to exist in a continuous real space rather than as parallel realities? In 2011 I argued that the eternally inflating multiverse and quantum-mechanical many worlds à la Everett are the same concept in a specific sense. In this understanding, the infinitely large space associated with eternal inflation is a kind of "illusion"—the many bubble universes of inflation do not all exist in a single real space but represent the possible different branches on the probabilistic tree. Around the same time that I made this proposal, Raphael Bousso of the University of California, Berkeley, and Leonard Susskind of Stanford University put forth a similar idea. If true, the many-worlds interpretation of the multiverse would mean that the laws of quantum mechanics do not operate solely in the microscopic realm—they also play a crucial role in determining the global structure of the multiverse even at the largest distance scales.

> I and other physicists are also pursuing the quantum multiverse idea further. How can we determine the quantum state of the entire multiverse? What is time, and how does it emerge?

BLACK HOLE QUANDARY

TO BETTER EXPLAIN how the many-worlds interpretation of quantum mechanics could describe the inflationary multiverse, I must digress briefly to talk about black holes. Black holes are extreme warps in spacetime whose powerful gravity prevents objects that fall into them from escaping. As such, they provide an ideal testing ground for physics involving strong quantum and gravitational effects. A particular thought experiment about these entities reveals where the traditional way of thinking about the multiverse goes off track, thereby making prediction impossible.

Suppose we drop a book into a black hole and observe from the outside what happens. Whereas the book itself can never escape the black hole, theory predicts that the information in the book will not be lost. After the book has been shredded by the black hole's gravity and after the black hole itself has gradually evaporated by emitting faint radiation (a phenomenon known as Hawking radiation, discovered by physicist Stephen Hawking of the University of Cambridge), outside observers can reconstruct all the information contained in the initial book by closely examining the radiation released. Even before the black hole has completely evaporated, the book's information starts to slowly leak out via each piece of Hawking radiation.

Yet a puzzling thing occurs if we think about the same situation from the viewpoint of someone who is falling into the black hole along with the book. In this case, the book seems to simply pass through the boundary of the black hole and stay inside. Thus, to this inside observer, the information in the book is also contained within the black hole forever. On the other hand, we have just argued that from a distant observer's point of view, the information will be *outside*. Which is correct? You might think that the information is simply duplicated: one copy inside and the other outside. Such a solution, however, is impossible. In quantum mechanics, the so-called no-cloning theorem prohibits faithful, full copying of information. Therefore, it seems that the two pictures seen by the two observers cannot both be true.

Physicists Gerard 't Hooft of Utrecht University in the Netherlands, Susskind and their collaborators have proposed the following solution: the two pictures can both be valid but not at the same time. If you are a distant observer, then the information is outside. You need not describe the interior of the black hole, because you can never access it even in principle; in fact, to avoid cloning information, you must think of the interior spacetime as nonexistent. On the other hand, if you are an observer falling into the hole, then the interior is all you have, and it contains the book and its information. This view, however, is possible only at the cost of ignoring the Hawking radiation being emitted from the black hole—but such a conceit is allowed because you yourself have crossed the black hole boundary and accordingly are trapped inside, cut off from the radiation emitted from the boundary. There is no inconsistency in either of these two viewpoints; only if you artificially "patch" the two, which you can never physically do, given that you cannot be both a distant and a falling observer at the same time, does the apparent inconsistency of information cloning occur.

COSMOLOGICAL HORIZONS

THIS BLACK HOLE CONUNDRUM may seem unrelated to the issue of how the many-worlds notion of quantum mechanics and the multiverse can be connected, but it turns out that the boundary of a black hole is similar in important ways to the so-called cosmological horizon—the boundary of the spacetime region within which we can receive signals from deep space. The horizon exists because space is expanding exponentially, and objects farther than this cutoff are receding faster than the speed of light, so any message from them can never reach us. The situation, therefore, is akin to a black hole viewed by a distant observer. Also, as in the case of the black hole, quantum mechanics requires an observer inside the horizon to view spacetime on the other side of the boundary—in this case, the exterior of the cosmological horizon—as nonexistent. If we consider such spacetime in addition to the information that can be retrieved from the horizon later (analogous to Hawking radiation in the black hole case), then we are overcounting the information. This prob-

SCIENTIFIC AMERICAN ONLINE Read more about the many-worlds interpretation of quantum mechanics at ScientificAmerican.com/jun2017/multiverse

lem implies that any description of the quantum state of the universe should include only the region within (and on) the horizon—in particular, there can be no infinite space in any single, consistent description of the cosmos.

If a quantum state reflects only the region within the horizon, then where is the multiverse, which we thought existed in an eternally inflating infinite space? The answer is that the creation of bubble universes is probabilistic, like any other process in quantum mechanics. Just as a quantum measurement could spawn many different results distinguished by their probability of occurring, inflation could produce many different universes, each with a different probability of coming into being. In other words, the quantum state representing eternally inflating space is a superposition of worlds—or branches—representing different universes, with each of these branches including only the region within its own horizon.

Because each of these universes is finite, we avoid the problem of predictability that was raised by the prospect of an infinitely large space that encompasses all possible outcomes. The multiple universes in this case do not all exist simultaneously in real space—they coexist only in "probability space," that is, as possible outcomes of observations made by people living inside each world. Thus, each universe—each possible outcome—retains a specific probability of coming into being.

This picture unifies the eternally inflating multiverse of cosmology and Everett's many worlds. Cosmic history then unfolds like this: the multiverse starts from some initial state and evolves into a superposition of many bubble universes. As time passes, the states representing each of these bubbles further branch into more superpositions of states representing the various possible outcomes of "experiments" performed within those universes (these need not be scientific experiments—they can be any physical processes). Eventually the state representing the whole multiverse will thus contain an enormous number of branches, each of which represents a possible world that may arise from the initial state. Quantum-mechanical probabilities therefore determine outcomes in cosmology and in microscopic processes. The multiverse and quantum many worlds are really the same thing; they simply refer to the same phenomenon—superposition—occurring at vastly different scales.

In this new picture, our world is only one of all possible worlds that are allowed by the fundamental principles of quantum physics and that exist simultaneously in probability space.

THE REALM BEYOND

TO KNOW IF THIS IDEA is correct, we would want to test it experimentally. But is that feasible? It turns out that discovery of one particular phenomenon would lend support to the new thinking. The multiverse could lead to a small amount of negative spatial curvature in our universe—in other words, objects would travel through space not along straight lines as in a flat cosmos but along curves, even in the absence of gravity. Such curvature could happen because, even though the bubble universes are finite as seen from the perspective of the entire multiverse, observers inside a bubble would perceive their universe to be infinitely large, which would make space seem negatively curved (an example of negative curvature is the surface of a saddle, whereas the surface of a sphere is positively curved). If we were inside one such bubble, space should likewise appear to us to be bent.

Evidence so far indicates that the cosmos is flat, but experiments studying how distant light bends as it travels through the cosmos are likely to improve measures of the curvature of our universe by about two orders of magnitude in the next few decades. If these experiments find any amount of negative curvature, they will support the multiverse concept because, although such curvature is technically possible in a single universe, it is implausible there. Specifically, a discovery supports the quantum multiverse picture described here because it can naturally lead to curvature large enough to be detected, whereas the traditional inflationary picture of the multiverse tends to produce negative curvature many orders of magnitude smaller than we can hope to measure.

Interestingly, the discovery of positive curvature would falsify the multiverse notion discussed here because inflation theory suggests that bubble universes could produce only negative curvature. On the other hand, if we are lucky, we may even see dramatic signs of a multiverse—such as a remnant from a "collision" of bubble universes in the sky, which may be formed in a single branch in the quantum multiverse. Scientists are, however, far from certain if we will ever detect such signals.

I and other physicists are also pursuing the quantum multiverse idea further on a theoretical level. We can ask fundamental questions such as, How can we determine the quantum state of the entire multiverse? What is time, and how does it emerge? The quantum multiverse picture does not immediately answer these questions, but it does provide a framework to address them. Lately, for instance, I have found that constraints imposed by the mathematical requirement that our theory must include rigorously defined probabilities may enable us to determine the unique quantum state of the entire multiverse. These constraints also suggest that the overall quantum state stays constant even though a physical observer, who is a part of the multiverse state, will see that new bubbles constantly form. This implies that our sense of the universe changing over time and, indeed, the concept of time itself may be an illusion. Time, according to this notion, is an "emergent concept" that arises from a more fundamental reality and seems to exist only within local branches of the multiverse.

Many of the ideas I have discussed are still quite speculative, but it is thrilling that physicists can talk about such big and deep questions based on theoretical progress. Who knows where these explorations will finally lead us? It seems clear, though, that we live in an exciting era in which our scientific explorations reach beyond what we thought to be the entire physical world—our universe—into a potentially limitless realm. SA

MORE TO EXPLORE

Physical Theories, Eternal Inflation, and the Quantum Universe. Yasunori Nomura in *Journal of High Energy Physics,* Vol. 2011, No. 11, Article No. 063; November 2011. Preprint available at **https://arxiv.org/abs/1104.2324**

Multiverse Interpretation of Quantum Mechanics. Raphael Bousso and Leonard Susskind in *Physical Review D,* Vol. 85, No. 4, Article No. 045007. Published online February 6, 2012. Preprint available at **https://arxiv.org/abs/1105.3796**

FROM OUR ARCHIVES

The Many Worlds of Hugh Everett. Peter Byrne; December 2007.

scientificamerican.com/magazine/sa

THE MESSY TRUTH ABOUT WEIGHT LOSS

HEALTH

Two decades of research confirm that weight loss is about burning more calories than you consume—but what you eat is more important than how much you exercise

By Susan B. Roberts and Sai Krupa Das

Photograph by Dan Saelinger

THE GLOBAL OBESITY epidemic is one of the greatest health challenges facing humanity. Some 600 million, or 13 percent, of the world's adults were obese in 2014—a figure that had more than doubled around the globe since 1980. At present, 37 percent of American adults are obese, and an additional 34 percent are overweight. If current trends continue, health experts predict that half of all Americans will be obese by 2030.

If fad diets, reality television programs and willpower could make a dent in the problem, we would have seen a change by now. Obesity (characterized by excess body fat and measured as 120 percent or more of ideal weight) is much too complex to be solved with quick fixes, however. Figuring out why we eat what we eat, how the body controls weight and how best to get people to change unhealthy habits is not easy. Our laboratory has spent the past two decades trying to develop, with all the rigor that science allows, more effective methods for treating obesity and maintaining a healthy weight.

Much of our work has challenged common dogmas and opened doors for new approaches. We have shown, for example, that exercise is not the most important thing to focus on when you want to lose weight—although it has numerous other health benefits, including maintaining a healthy weight. As many experts have suspected and as we and others have now proved, what you eat and how much you eat play a substantially greater role in determining whether you shed kilograms. But our research has gone much deeper, showing that different people lose weight more effectively with different foods. This realization allows us to create personalized weight-loss plans for individuals that work better than any one-size-fits-all advice.

We believe this new understanding could improve the health of millions of people around the world. Obesity increases the risk of all the major noncommunicable diseases, including type 2 diabetes, heart disease, stroke and several types of cancers—enough to decrease a person's potential life span by as much as 14 years. Research shows that excessive weight also interferes with our body's ability to fight off infections, sleep deeply and age well, among other problems. It is long past time for us to understand how to combat this epidemic.

Susan B. Roberts is a senior scientist and director of the Energy Metabolism Laboratory at the Jean Mayer USDA Human Nutrition Research Center on Aging at Tufts University. She is also a professor of nutrition at the Gerald J. and Dorothy R. Friedman School of Nutrition Science and Policy at Tufts and a professor of psychiatry and staff member in pediatrics at the Tufts School of Medicine.

Sai Krupa Das is a scientist at the Energy Metabolism Laboratory at the Human Nutrition Research Center on Aging and is a faculty member at the Friedman School of Nutrition Science and Policy at Tufts.

FUEL-EFFICIENT

LOSING WEIGHT can be reduced to a simple mathematical formula: burn more calories than you consume. For decades health experts figured that it did not matter too much how you created that deficit: as long as you got the right nutrients, you could safely lose weight with any combination of increased exercise and reduced consumption of food. But this assumption does not take into account the complexities of human physiology and psychology and so quickly falls apart when tested against real-world experience. As it happens, sorting out the details and putting weight management on a more scientific footing have taken much longer and have required a wider range of expertise than anyone had expected.

Our first step, beginning in the 1990s, was to determine a base requirement: How much energy does it take to fuel the average human body? This straightforward question is not easy to answer. People get their energy from food, of course. But for individuals to use that energy, the food must be broken down or metabolized to become the equivalent of gasoline for a car. The oxygen we breathe helps to burn that fuel, and whatever is not used right away is stored in the liver as glycogen (a form of carbohydrate) or fat. When no more space is available in the liver, the excess is stored elsewhere in fat cells. In addition, metabolism creates carbon dioxide, which we exhale, as well as other waste products that are excreted as urine and feces. The process runs at different levels of efficiency in different individuals and under different circumstances in the same individual.

For a long time the best way to measure people's energy expenditure was to have them live for two weeks in a specialized lab, such as ours, where researchers could measure everything subjects eat and track their weight. Another way was to put volunteers in a sealed room (called a calorimeter) and measure the oxygen they breathe and the carbon dioxide they exhale. From these measurements we could assess the body's basic energy requirements. Neither method is terribly convenient, and neither does a good job of replicating the conditions of everyday life.

A much easier approach uses so-called doubly labeled water, which contains tiny amounts of deuterium (^2H) and oxygen 18 (^{18}O), both harmless, nonradioactive isotopes. For one to two weeks after a person drinks doubly labeled water, the body excretes the deuterium and some of the oxygen 18 in urine. (The rest of the oxygen 18 is exhaled as carbon dioxide.) Investigators take urine samples and compare how quickly these two isotopes disappear from the body during that time. With these data, they can calculate the number of calories an individual burns without interrupting his or her daily routine.

The method was developed in the 1950s, but for decades doubly labeled water was too expensive to use in people. By the 1980s prices had dropped, and the technique had become more efficient, although there were times when our lab had to spend as much as $2,000 to perform a single measurement. As a result, it took more than 20 years to accumulate enough data to figure out how much energy the body needs to avoid weight gain or loss.

These experiments—conducted by our group and others—helped us determine that humans do not need a lot of calories to stay healthy and active. And any excess consumption quickly results in weight gain. In this respect, we are much like other primates, including chimpanzees and orangutans. An adult male of healthy weight and typical height living in the U.S. today requires about 2,500 calories per day to maintain his weight, whereas the average nonobese adult female requires around 2,000 calories. (Men tend to use more calories because, on average, they have larger bodies and greater muscle mass.)

In contrast, studies show that species as diverse as red deer (*Cervus elapus,* average weight 100 kilograms for the six-year-old females in one experiment) and gray seals (*Halichoerus grypus,* average weight 120 kilograms for three adult females) re-

IN BRIEF

For years nutritionists have assumed that all calories are basically the same when it comes to gaining or losing weight and that diet and exercise are equally effective in preventing obesity.

New evidence, which researchers have painstakingly accumulated over the past two decades, has confirmed some important exceptions to this general understanding.

The composition of food—how much protein, how much fiber—turns out to be almost as important as the quantity consumed. Exercise has less of a practical effect than many had anticipated.

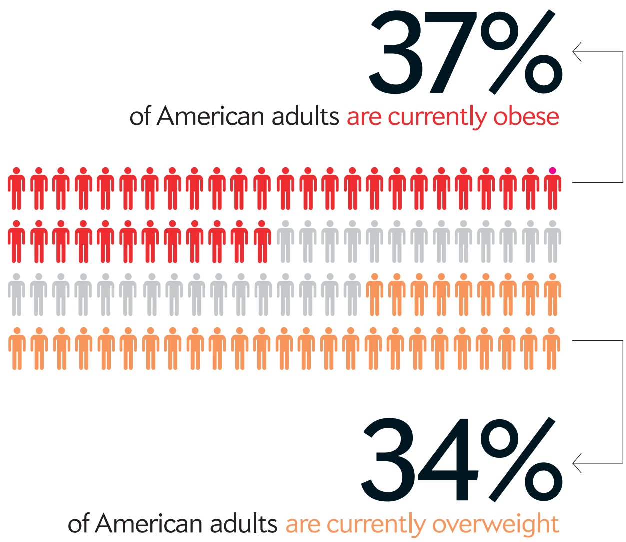
This more detailed, scientific understanding of why we put on weight and how best to lose it could make a significant difference in the battle of the bulge.

quire two to three times more calories, kilogram per kilogram, than primates to maintain their size.

It is tempting to assume that Americans have low calorie requirements because they lead sedentary lives, but researchers have documented similar calorie needs even in indigenous populations leading very active lives. Herman Pontzer of Hunter College and his colleagues measured the calorie requirements of the Hadza people in northern Tanzania, a group of hunter-gatherers, and found that the men needed 2,649 calories on average per day. The women, who—like the men—tend to be smaller than counterparts in other regions, needed just 1,877. Another study of the indigenous Yakut people of Siberia found requirements of 3,103 calories for men and 2,299 for women. And members of the Aymara living in the Andean altiplano were found to require 2,653 calories for men and 2,342 calories for women.

Although our calorie requirements have not changed, government data show that, on average, Americans consume 500 more calories (the equivalent of a grilled chicken sandwich or two beef tacos at a fast-food restaurant) each day than they did in the 1970s. An excess of as little as 50 to 100 calories a day—the equivalent of one or two small cookies—can lead to a gain of one to three kilograms a year. That easily becomes 10 to 30 kilograms after a decade. Is it any wonder, then, that so many of us have become overweight or obese?

SCALE UP



COMPLICATED CALORIES

THE FORMULA for maintaining a stable weight—consume no more calories than the body needs for warmth, basic functioning and physical activity—is just another way of saying that the first law of thermodynamics still holds for biological systems: the total amount of energy taken into a closed system (in this case, the body) must equal the total amount expended or stored. But there is nothing in that law that requires the body to use all sources of food with the same efficiency. Which brings us to the issue of whether all calories contribute equally to weight gain.

Research in this area is evolving, and understanding why it has taken so long to get definitive answers requires a trip back in history to the late 1890s and the tiny community of Storrs, Conn. There a chemist by the name of Wilbur O. Atwater built the first research station in the U.S. designed to study the production and consumption of food. In fact, Atwater was the first to prove that the first law of thermodynamics holds for humans as well as animals. (Some scientists of his day thought people might be an exception to the rule.)

The experimental design of metabolic labs has changed remarkably little since Atwater's day. To determine how much energy the body can derive from the three major components of food—proteins, fats and carbohydrates—he asked a few male volunteers to live, one at a time, inside a calorimeter for several days. Meanwhile Atwater and his colleagues measured everything each human guinea pig ate, as well as what became of that food, from the carbon dioxide the volunteer exhaled to the amounts of nitrogen, carbon and other components in his urine and feces. Eventually the researchers determined that the body can extract about four calories of energy per gram from proteins and carbohydrates and nine calories per gram from fat. (These numbers are now known as Atwater factors.)

Food does not come to us as pure protein, carbohydrate or fat, of course. Salmon consists of protein and fat. Apples contain carbohydrates and fiber. Milk contains fat, protein, carbohydrates and a lot of water. It turns out that a food's physical properties and composition play a greater role in how completely the body can digest and absorb calories than investigators had anticipated.

In 2012, for example, David Baer of the U.S. Department of Agriculture's Beltsville Human Nutrition Research Center in Maryland proved that the body is unable to extract all the calories that are indicated on a nutritional label from some nuts, depending on how they are processed. Raw whole almonds, for example, are harder to digest than Atwater would have predicted, so we get about a third fewer calories from them, whereas we can metabolize all the calories found in almond butter.

Whole grains, oats and high-fiber cereals are also digested less efficiently than we used to think. A recent study by our team looked at what happened when volunteers consumed a whole-grain diet that included 30 grams of dietary fiber versus more typical American fare that contained half as much fiber. We detected an increase in the number of calories lost to the feces, as well as a bump in metabolism. Together these changes amounted to a net benefit of nearly 100 calories a day—which can have a substantial effect on weight over a period of years.

And so we and others have proved that not all calories are equal—at least for nuts and high-fiber cereals. As scientists learn more about how efficiently different foods are digested and how they affect the body's metabolic rate, we will likely see some other examples of such disparities that are just large enough to influence how easy—or hard—individuals find managing their weight.

ENERGY EXPENDITURE

SO MUCH FOR what we put in our mouth. What our body does with the food we eat brings us to the other side of the energy balance equation—energy expenditure. Researchers are discovering a surprising deal of variability here as well.

SOURCE: CENTERS FOR DISEASE CONTROL AND PREVENTION

One of the most common pieces of advice that people get when they are trying to lose weight is that they should exercise more. And physical activity certainly helps to keep your heart, brain, bones and other body parts in good working order. But detailed measurements conducted in our lab and others show that physical activity is responsible for only about one third of total energy expenditure (assuming a stable body weight). The body's basal metabolism—that is, the energy it needs to maintain itself while at rest—makes up the other two thirds. Intriguingly, the areas of the body with the greatest energy requirement are the brain and certain internal organs, such as the heart and kidneys—not the skeletal muscle, although strength training can boost basal metabolism modestly.

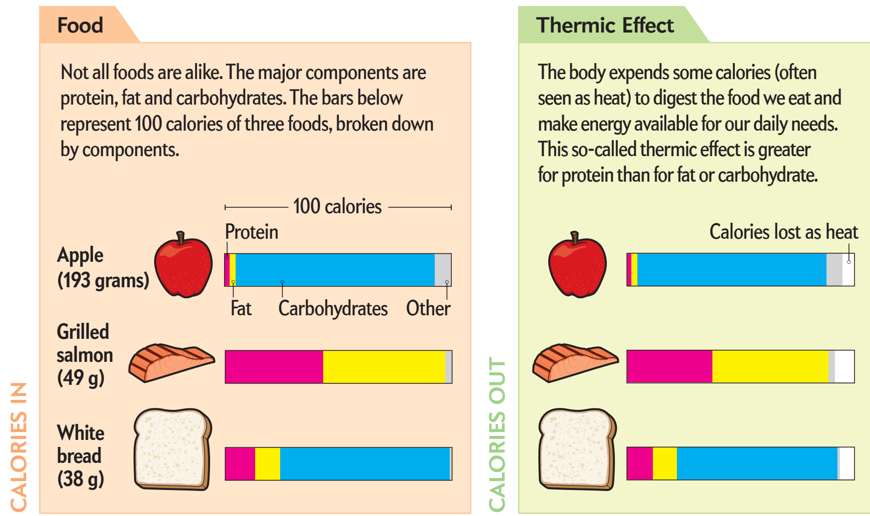
In addition, as anyone who has ever reached middle age understands all too well, metabolism changes over time. Older people need fewer calories to keep their body running than they did in their youth. Metabolic rate also differs among individuals. One study published in 1986 measured the metabolic rates of 130 people from 54 families. After accounting for differences in age, gender and body composition, investigators reported variability among families of around 500 calories a day. The inescapable conclusion: when it comes to metabolic rate—and your ability to lose or maintain your weight—parentage makes a difference.

But let us suppose that you have started to lose some weight. Naturally, your metabolic rate and calorie requirements must fall as your body becomes smaller, meaning that weight loss will slow down. That is just a matter of physics: the first law of thermodynamics still applies. But the human body is also subject to the pressures of evolution, which would have favored those who could hold on to their energy stores by becoming even more fuel-efficient. And indeed, studies show that metabolic rate drops somewhat more than expected during active weight loss. Once a person's weight has stabilized at a new, lower level, exercise can help in weight management by compensating for the reduced energy requirement of a smaller body.

FINDINGS

The Energy Equation

The laws of thermodynamics apply to biological organisms just as much as anything else in the universe. The number of calories that we absorb from food has to equal the number of calories our body either expends or stores. But the simplest methods for balancing this equation are not necessarily the most true to life. Individuals do not, for example, process all foods equally effectively. And different people require different amounts of energy just to keep their body humming. The graphic illustrates a few of the known complexities.



Graphic by Brown Bird Design (food illustrations) and Amanda Montañez (graphs)

SOURCES: U.S. DEPARTMENT OF AGRICULTURE FOOD COMPOSITION DATABASES (*food data*); "HIGH-PROTEIN WEIGHT-LOSS DIETS: ARE THEY SAFE AND DO THEY WORK? A REVIEW OF THE EXPERIMENTAL AND EPIDEMIOLOGIC DATA," BY JULIE EISENSTEIN ET AL., IN *NUTRITION REVIEWS*, VOL. 60, NO. 7; JULY 2002 (*thermic effect data*)

HUNGRY BRAINS

VARIATIONS IN Atwater factors and metabolic rates are not the end of the story. A growing body of research has demonstrated that our brain plays a central role, coordinating incoming signals from a wide range of physiological sensors in the body while alerting us to the presence of food. The brain then creates sensations of hunger and temptation to make sure that we eat.

In other words, the role of hunger has long been to keep us alive. Thus, there is no point in fighting it directly. Instead one of the keys to successful weight management is to prevent hunger and temptation from happening in the first place.

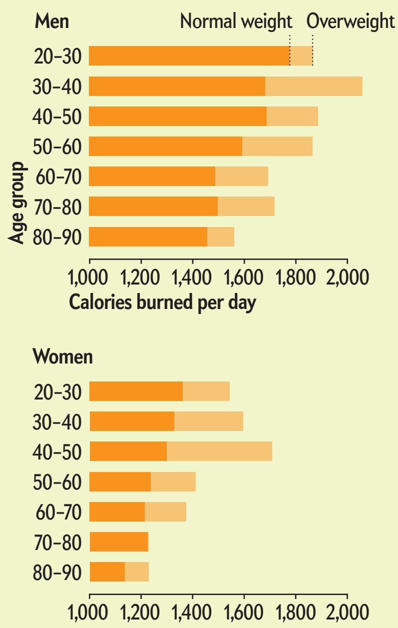
Single-meal feeding tests by several labs, including our own, show that meals higher in protein or fiber or those that do not cause a sudden spike in blood sugar (glucose) levels are generally more satisfying and better at suppressing hunger. (Carbohydrates are the most common source of glucose in the blood, but proteins can generate it as well.) A summary one of us (Roberts) published in 2000 indicated that calorie consumption in the hours following a breakfast with a so-called high glycemic index (think highly processed breakfast cereals) was 29 percent greater than after a morning meal with a low glycemic index (steel-cut oatmeal or scrambled eggs).

In fact, our team recently obtained the first preliminary data showing that it is possible to reduce hunger during weight loss by choosing the right foods. Before assigning 133 volunteers to one of two groups, we asked them to answer a detailed questionnaire about how often, when and how intensely they were hungry. Then we randomly assigned subjects to either a weight-loss program that emphasized foods high in protein and fiber and low in glycemic index (fish, beans, apples, vegetables, grilled chicken and wheat berries, for example) or to a "waiting list," which served as the control group.

Remarkably, over the course of six months members of the experimental group reported hunger levels that decreased to below the values measured before the program began. We noticed a difference on the scales as well. By the end of the study,

Basal Metabolism

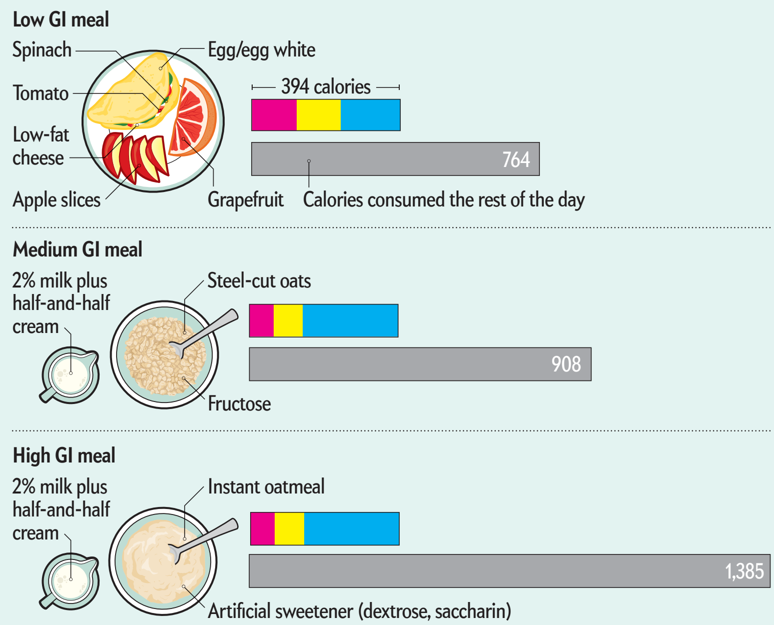
The body needs a certain amount of energy at rest (dubbed basal metabolism) to stay alive. Data from adults in the U.S. show how much basal metabolism varies based on gender, age and weight.



SATIETY

Glycemic Index

How quickly the body converts various foods into glucose (a sugar) is measured by the glycemic index (GI). Foods with a lot of protein and fiber have a lower GI, which helps to create a feeling of fullness. Foods with easily digested carbohydrates tend to have a high GI. A study of a dozen boys with obesity showed that eating meals with a high glycemic index leads to greater calorie consumption overall.



SOURCES: *HUMAN ENERGY REQUIREMENTS: REPORT OF A JOINT FAO/WHO/UNU EXPERT CONSULTATION.* WORLD HEALTH ORGANIZATION, FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS AND UNITED NATIONS UNIVERSITY. FAO, 2001 *(basal metabolism data)*; "HIGH GLYCEMIC INDEX FOODS, OVEREATING, AND OBESITY," BY DAVID S. LUDWIG ET AL., IN *PEDIATRICS,* VOL. 103, NO. 3; MARCH 1999 *(glycemic index data)*

they had also lost an average of eight kilograms, whereas the control group had gained 0.9 kilogram.

Just as interesting, the intervention group experienced fewer food cravings as well, which suggests that what their brains perceived as pleasurable had changed. We then scanned the brains of 15 volunteers as they viewed pictures of a wide range of foods. The results showed that the reward center of the brain became more active over time in the intervention group in response to pictures of grilled chicken, whole-wheat sandwiches and fiber cereal. Meanwhile that group's brains became less responsive to images of french fries, fried chicken, chocolate candies and other fattening foods.

PERSONALIZED DIETS

DIFFERENCES IN the hunger-reducing properties of foods, the efficiency with which they are absorbed and the real, though limited, ability of our metabolism to adapt to changes in energy intake make weight management a complex system. We keep finding special circumstances that affect various people differently. For example, it has been well established that the majority of individuals who are obese secrete proportionately higher levels of insulin, the hormone that helps the body to metabolize glucose. This so-called insulin resistance leads to a host of other metabolic problems, such as increased risk of heart attack or developing type 2 diabetes. When we placed such people on a six-month weight-loss program featuring more protein and fiber, fewer carbohydrates and a low glycemic index, we found that they lost more weight than they could on a high-carbohydrate diet with a high glycemic index. People with low insulin levels, in contrast, did equally well on diets that were higher or lower in the ratio of proteins and carbohydrates, as well as in glycemic index.

Today we regularly help our study volunteers lose weight and keep it off. Despite the fact that our 133-volunteer investigation, described earlier, was six months long and required participants to attend weekly meetings and reply to e-mails during most of that time, only 11 percent dropped out. Some even cried at the research team's final visit because they did not want to say goodbye. Not only had they lost weight, but they had been so much more successful than they expected that they felt transformed psychologically as well as physically. In the words of one participant, "the science worked." SA

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MARINE SCIENCE

LOST AT SEA

Ocean acidification may alter the behaviors of underwater creatures in disastrous ways

By Danielle L. Dixson

CLOWN FISHES LIVE THEIR ENTIRE ADULT LIVES nestled in the protective arms of a single sea anemone on a coral reef. Between birth and adulthood, however, the fishes have to complete a treacherous journey. After hatching, a larva—a tiny, partially formed version of an adult fish—swims out of the reef to the open sea to finish developing, presumably away from predators. After maturing for 11 to 14 days, the juvenile is ready to swim back to the reef and select an anemone to call home. But as it swims close, it has to cross a "wall of mouths"—all kinds of creatures, such as wrasses and lionfish, that lurk along the reef ready to gobble up the tiny fishes. Most successfully navigate the gauntlet by recognizing the smells of the predators and avoiding their grasp.

The sense of smell is really chemistry in action: detecting, understanding and responding to molecules in the water. Even a small shift in ocean chemistry could throw off this delicate survival mechanism. Scientists began to wonder what might happen when the water becomes more acidic, a trend that is occurring worldwide as the oceans absorb ever more carbon dioxide from the atmosphere. In 2010 my colleagues and I put 300 recently hatched clown fish larvae in a seawater tank in our laboratory and monitored them for 11 days. When we injected the scent of a friendly fish, they did not react. But when we injected the scent of a predator (a rock cod), they swam away.

We then repeated the experiment with 300 new hatchlings from the same parents, but this time the water was more acidic—adjusted to a level we can expect in certain parts of the world's oceans by 2100 if current trends continue. The young fish developed normally, yet not one avoided the predator odor. In fact, they preferred to swim toward the dangerous smell rather than plain seawater. When we introduced predator and nonpredator odors simultaneously, the fish seemed unable to make up their minds, spending equal time swimming toward one smell and the other. They were able to sense chemical signals but were unable to recognize the *meaning* of the signals. The reversal of behavior was surprising and concerning. We thought acidification might affect the chemical signaling slightly but never enough to prompt a fish to swim toward imminent death.

Creatures everywhere have three basic tasks in their lifetime: find food, reproduce and avoid becoming food in the process. In places such as coral reefs, where predators and prey densely pack a limited, complex habitat, natural selection strongly favors species that evade predators. Any disruption to this ability could have catastrophic consequences for the entire ecosystem.

If increasingly acidic water interferes with clown fish's sense of smell, it might also interfere with other senses and behaviors. And although we studied only one species of clown fish, smell is critical for a vast array of marine organisms. At a minimum, confusion and disorientation could place yet another stressor on fish already challenged by rising water temperatures, overfishing and changing food supplies. Further, if many ocean dwellers start to behave strangely, entire food webs, migration patterns and ecosystems could come crashing down. Although the science is still new, the results appear to be lining up: ocean acidification is messing with fish's minds.

THE ACID CHALLENGE

SINCE THE INDUSTRIAL REVOLUTION the atmospheric concentration of carbon dioxide has risen from 280 parts per million (ppm)

Illustration by Pascal Campion

to just more than 400 ppm today. That number would be much higher without oceans, which absorb 30 to 40 percent of the CO_2 sent into our air. More CO_2 in seawater causes chemical reactions that increase acidity—measured as lower pH. Surface waters are roughly 30 percent more acidic today than in the late 1800s, and if current carbon emissions trends continue to the end of the century, they could be nearly 150 percent more acidic than back then.

Additional CO_2 in the water column breaks down calcite and aragonite—two minerals that are essential building blocks of the shells and exterior skeletons of certain sea creatures. Shellfish, urchins and plankton raised by other researchers in tanks with water that had high CO_2 levels developed incomplete or deformed shells and exoskeletons. Yet scientists thought that fish and other nonshelled organisms might escape the wrath of ocean acidification, in part because early research done in the 1980s showed that certain animals had an astonishing ability to regulate their internal chemistry by increasing or decreasing the amounts of bicarbonate and chlorine in their body. These studies, however, only looked at physiology—whether an animal could survive acidified water. Maintaining normal functions such as finding food and avoiding danger is a different challenge. Our research group was among the first to tackle the next logical question: Could acidification change behavior?

CONFUSING SMELLS AND SOUNDS

OUR CLOWN FISH EXPERIMENTS strongly suggested that acidification was indeed altering the animals' behavior. Other tests since then have been equally troubling. Because many reef predators commonly feed during the day, juvenile clown fishes that are returning to a reef to find an anemone tend to approach at night, when the predators are sluggish or sleeping, preferably under low moonlight. But navigation for a fish smaller than a dime in a dark, relatively featureless open ocean is not easy, so they use sounds produced by the reef and its inhabitants for guidance. A year after our smell experiment, we looked at whether acidifying water might interfere with hearing as well.

We tested young clown fish by putting them inside a box in a tank filled with seawater. When we pumped in daytime reef noise (which they would naturally avoid) through one side of the box, the fish spent almost three quarters of their time near the opposing wall, away from the sound source. But when we tested new fish that had spent their brief lives in water that was 60 percent more acidic—a level that we can expect in shallow oceans by 2030—they were not nearly as wary. More than half were actually attracted to the daytime sound.

We repeated the experiment twice more, with water that was 100 percent more acidic and 150 percent more acidic—levels that might arise by 2050 and 2100, respectively. In both situations, the clown fish spent around 60 percent of their time near the speaker playing daytime reef noise. We also ran separate tests to make sure none of them lacked a sense of hearing (they did not). Under the high acidity conditions, the clown fish were unable to recognize the meaning of auditory signals.

Danielle L. Dixson is an assistant professor of marine science and policy at the University of Delaware. She studies how climate change and habitat degradation affect the behavior of marine organisms.

Ocean dwellers that have skewed senses may not avoid predators well. But the opposite effect could also occur: they might not be able to find food effectively.

Sharks have an infamously keen sense of smell, which they rely on to navigate, locate mates and track prey. Given the sensory confusion we found in clown fish, we wondered how sharks might react to acidified waters. We collected 24 adult smooth dogfish—small sharks that migrate in temperate waters between the Carolinas and southern New England—from the coast near Woods Hole, Mass. We split them into three groups and held each group in small, round swimming pools. The sharks in group 1 simply swam around in water taken from the ocean near Woods Hole. We put group 2 sharks in water treated to mimic ocean acidity in 2050 and group 3 sharks in water simulated for 2100. Meanwhile we created a concentrated "squid rinse" by soaking squid in seawater and straining the water through a cheesecloth. (Sharks love squid.)

After five days we let each shark swim in a flume tank 10 meters long and two meters wide. The acidity matched that of the pool in which they had been held. The flume tank had two nozzles that each pushed a mild plume of water from front to back. One plume flowed along the left side of the tank, and the other plume did so along the right. After the sharks started swimming, we infused some of the squid water through one of the nozzles. We later reversed the plumes in case the sharks had a natural preference to swim along one side.

Overhead cameras and tracking software recorded what happened next. Sharks in group 1—regular seawater—spent over 60 percent of their time swimming in the plume that smelled like their lunchtime squid. Sharks in group 2 did the same. But sharks in group 3 actively avoided the scent of prey, spending less than 15 percent of their time in the squid-treated water. We saw other differences. Group 1 sharks repeatedly bumped and bit at a brick held in front of the nozzle emitting the squid water. They hit it more than twice as many times as the sharks in group 2 and more than three times as often as sharks in group 3.

It is surprising to see a predator lose interest in, and even avoid the smell of, its food. Reef fishes tested in other experiments seem to exhibit similarly odd behavior. Given the importance of sharks as top predators to ecosystems and their known vulnerability to environmental changes, ocean acidification could be a major threat to these animals and the ecosystems where they live.

IN BRIEF

Increasingly acidic ocean water created by climate change might be undermining important behaviors that sea creatures need for survival.

Experiments show that damselfishes, sharks and crabs raised in or exposed to highly acidic water may fail to smell predators or to find food or may uncharacteristically wander into dangerous places.

It is unclear whether ocean dwellers can adapt to increasing acidity if the rise is slow or if they can pass along adaptive traits to their offspring. Tests at volcanic reefs that are naturally more acidic might provide some answers.

BOLD IS BAD

IT IS ALWAYS TRICKY to say that behaviors seen in a lab would also be seen in the wild. So we went to a sandy lagoon near one of the Great Barrier Reef's northern islands to examine another trait: boldness. There we tested how wild-caught juvenile damselfishes would react to predator smells after exposing them to acidic water for four days. In a flume tank, about half of them held in water with acidity expected by 2050 were attracted to a predator plume and half were not, but 100 percent of them held in water anticipated by 2100 were attracted to the predator odor.

We tattooed the damselfishes so we could identify them and then let them loose on a small reef we made in the lagoon. The fishes that had been held in the most acidic water demonstrated risky behavior: instead of staying close to a protective coral, they wandered farther away and did so more often than the fishes that had been held in untreated seawater. After a research diver scared them back into the coral, those that had been held in the higher CO_2 levels came back out quicker than the other fishes did. And sure enough, the bold ones exposed to the seawater for 2100 were nine times more likely to be eaten by a predator. Fishes exposed to the seawater for 2050 were not quite as bold but still wandered and were five times more likely to die.

Scientists like to use reef fishes for experiments because their behaviors are consistent and easy to observe. But experiments on other sea creatures have shown disturbing behaviors as well. Researchers at the Monterey Bay Aquarium Research Institute raised hermit crabs in highly acidic conditions. The crabs did not show the significant increase in boldness that damselfishes did, but they took much longer than normal to reemerge from their shells when they were attacked by a simulated predator (a toy octopus).

Investigators in Chile worked with the Chilean abalone, a mollusk that adheres to rocks along wave-swept shores. Typically when rough waves dislodge the abalones from their perches, they quickly reattach themselves so they do not drift around, making them an easy catch for predators. When CO_2 levels were raised by about 50 percent, some abalones took less time than usual to right themselves. Some held in more acidic water took wrong turns while trying to avoid crab predators lurking nearby, and some actually turned *toward* the crabs' claws instead of away from them.

Clearly, ocean acidification is meddling with sea creatures' minds. But how? A few researchers wonder if the cues themselves—the smells and sounds—are altered by the changing pH. But experiments show that fish can readily identify chemical cues in high-CO_2 water. Other scientists hypothesize that the altered behavior could be a stress response in fish that are trying to regulate changing acidity in their body, but that requires further investigation.

On a different hunch, Philip L. Munday of James Cook University in Australia and I decided to collaborate with Göran E. Nilsson of the University of Oslo. Nilsson suspected that acidification interferes with a neurotransmitter called $GABA_A$, which modulates signals in the brains and nervous systems of many animals, including humans. Among other tasks, $GABA_A$ inhibits signals by conducting chlorine and bicarbonate across nerve cell membranes. When fish are exposed to elevated CO_2 levels, they excrete chlorine from their body to accumulate more bicarbonate—an attempt to minimize pH change inside their body. This shift in chemistry, however, causes $GABA_A$ receptors to become excited, impairing signals. When fish exposed to high CO_2 are later placed in water with gabazine, a chemical that reduces the excitation, normal behavior resumes after only 30 minutes. Yet $GABA_A$ sensitivity may differ among species, so it is not clear if this is the primary cause for behavioral changes.

CAN FISH ADAPT?

THE MAIN QUESTION I receive when speaking about ocean acidification is, What are the chances that marine life can adapt? Nature has an astounding capacity to heal itself. Predicting how an organism might adapt is difficult, and predicting how well complex ecosystems can adapt is nearly impossible.

Experiments do indicate some common trends. For example, smell was altered for adult sharks as well as juvenile clown fish. There also seems to be a tipping point for coral-reef fishes: about half exhibited troubling behavior when acidity was raised to levels expected by 2050, but virtually all showed the behaviors at levels anticipated for 2100.

We have to ask, however, if the rate of acidification in experiments is a complicating factor. Most studies have bred or habituated fish to elevated CO_2 conditions over a few days or months—an extremely short time frame. The animals are not given a realistic opportunity to acclimate or adapt. We will have to investigate fish in the wild as the ocean gradually becomes more acidic.

To gain insight, scientists have turned to reefs near volcanic gas seeps, where CO_2 comes up through the reef floor at spots, naturally acidifying the water there to levels anticipated by 2100. When we visited volcanic reefs in Papua New Guinea, we found that juvenile damselfishes at a seep site were attracted to a predator odor, did not distinguish between predator and nonpredator odors, and exhibited bolder behavior—the same oddities shown by our lab fishes. At nonseep reefs, the same damselfish species did detect and avoid predators and was less bold.

We also do not know if the behaviors might be passed on to future generations. Researchers are just beginning to investigate. In one study, the offspring of coral-reef fishes raised under high-CO_2 conditions showed no advantage in adapting to higher levels.

Ocean acidification is one of many stressors. Overfishing, increased water temperature, greater pollution, the removal of top predators such as sharks, and habitat destruction all hurt the sea. Although local issues such as shark finning can be stopped by authorities, broader insults such as increased temperature and acidification could be the straws that break the backs of many species. As we examine how stressors physically affect ocean dwellers, we should also investigate how they might affect cognitive abilities, which are just as important to survival. SA

MORE TO EXPLORE

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GENETICS

UNLOCKIN THE MYSTE OF ALS

Newly discovered genetic mutations are providing clues about how this disorder relentlessly destroys motor neurons and robs people of their mobility. The findings may lead to drug therapies for a condition that has long defied treatment

By Leonard Petrucelli and Aaron D. Gitler

Illustration by Jeremy Wilson

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Leonard Petrucelli is a professor and chair of the department of neuroscience at the Mayo Clinic in Jacksonville, Fla.


Aaron D. Gitler is an associate professor of genetics at the Stanford University School of Medicine.

AMYOTROPHIC LATERAL SCLEROSIS (ALS) STRIKES WITHOUT WARNING. THE condition, which strips nerve cells of their ability to interact with the body's muscles, starts painlessly, with subtle initial symptoms—such as stumbling, increased clumsiness and slurred speech—that are often overlooked. The disease itself attracted little public attention until legendary New York Yankees first baseman Lou Gehrig began dropping balls and collapsing on the field for no apparent reason. Known as the Iron Horse for playing in 2,130 consecutive games over 14 years, Gehrig was diagnosed with ALS in June 1939 and delivered a poignant farewell at Yankee Stadium the next month. Gehrig's loss of muscle control progressed so rapidly that by December he was too weak to attend his National Baseball Hall of Fame induction. Creeping paralysis eventually left him bedridden. He died in June 1941 at the age of 37.

Today more than 6,000 people a year in the U.S. receive a diagnosis of ALS, now commonly known as Lou Gehrig's disease in the States and as motor neuron disease in Europe. It usually afflicts people between the ages of 50 and 60 but can start much earlier or even as late as one's 80s. At its onset, nerve cells in the brain and spinal cord called motor neurons begin to die. Because these cells send signals from the brain through the spinal cord to muscles, their death causes a loss of mobility, dexterity, speech and even swallowing. In most cases, the higher functions of the brain remain undamaged: people stricken with ALS are obliged to watch the demise of their own body as the disease advances unrelentingly. They soon become wheelchair-bound and, eventually, bedridden. Left with no capacity to communicate, eat or breathe on their own, most die from respiratory failure within three to five years. The sole Food and Drug Administration–approved drug for ALS is the glutamate blocker riluzole, which prolongs survival by an average of three months. There is no cure.

Pioneering French neurologist Jean-Martin Charcot, who identified the disease in 1869, encapsulated a description of it in its name: "amyotrophic" means no muscle nourishment; "lateral" refers to an area of the spinal cord where portions of the dying motor neuron cells are located; and "sclerosis" is the hardening or scarring that occurs as the process of neural degeneration unfolds. Despite Charcot's straightforward characterization, nearly a century and a half later the complexity of ALS continues to confound researchers. Although the disorder is invariably fatal, for unknown reasons roughly 10 percent of patients survive for more than 10 years, and some do so even longer. That minority includes physicist Stephen Hawking, who has famously lived with ALS for more than five decades. Current research suggests that environmental factors play only a small role in triggering ALS, probably by increasing the vulnerability of individuals who are already genetically susceptible. Most puzzling is that the disorder occurs largely at random. Fewer than 10 percent of cases arise from genetic traits passed down from one generation to the next within a family. The remaining cases are classified as uninherited, or sporadic.

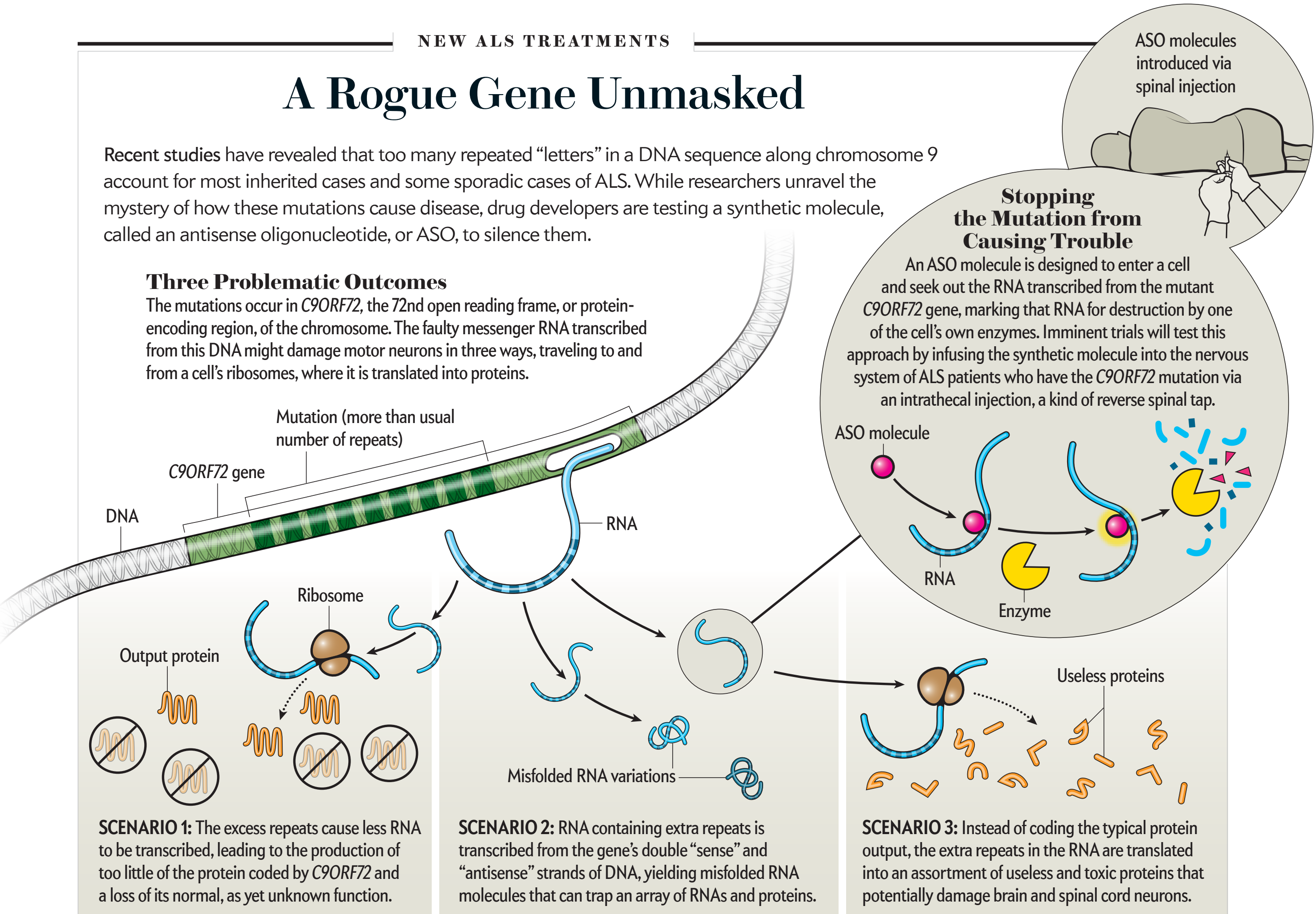
During the past decade sophisticated sequencing technologies have led to exponential growth in our understanding of the disorder's underlying biology. Ongoing research indicates that many different genes, acting alone or in concert, can increase an individual's susceptibility. Specific mutations have been tied to almost 70 percent of familial cases and approximately 10 percent of sporadic ALS. In turn, this wealth of new genetic data is opening up many promising avenues for better therapy. Gene silencing has emerged as a potential treatment for some forms of ALS, with two drugs that target separate rogue genes slated for clinical trials this year. Meanwhile researchers are identifying telltale biomarkers, including measurable substances in bodily fluids or electrical activ-

IN BRIEF

Amyotrophic lateral sclerosis (ALS), a neurodegenerative disorder commonly known as Lou Gehrig's disease, attacks nerve cells that lead from the brain and the spinal cord to muscles throughout the body.

Sophisticated gene-sequencing technologies have led to a flurry of discoveries revealing the genetic underpinnings of ALS. Ongoing research indicates that changes in any of many different genes increase an individual's susceptibility to the disease.

Gene silencing using a synthetic molecule called an antisense oligonucleotide has emerged as a potential treatment for some types of ALS. Researchers are also seeking ways of measuring the disease as it progresses to help with early detection and the development of drug therapies.



ity in the brain, that could help clinicians make early diagnoses and better gauge the progress of the disease. Such biomarkers may also be useful in the development of other drug treatments.

EARLY GENETIC CLUES

ALTHOUGH PEOPLE WITH FAMILIAL ALS, most of whom have a 50 percent chance of passing it to the next generation, make up a small portion of ALS sufferers, they have played an outsize role in helping to unravel the genetic underpinnings of the disease. The first genetic link to ALS came in 1993 from studies that identified a mutation in a gene called *SOD1* in approximately 20 percent of familial ALS cases. *SOD1* codes for the antioxidant enzyme superoxide dismutase, which converts the highly reactive molecule superoxide—an oxygen free radical—into less damaging forms.

Researchers initially theorized that the mutation in *SOD1* might weaken the enzyme's antioxidizing capabilities and thus allow oxygen free radicals to wreak havoc on motor neurons. A quarter of a century later we have learned with near certainty that that is not the case. Rather it seems that this mutation triggers what scientists call a toxic gain of function, in which the enzyme does something beyond what it is normally supposed to do.

In particular, the new function leads to changes in the shape of certain proteins in neurons. Most autopsies of people with ALS reveal a typical pattern of brain pathology: clumps of proteins accumulated within motor neurons. For these neurons to function optimally, the protein building blocks inside the cells must be recycled efficiently; with ALS, that recycling system breaks down. All proteins, including enzymes, need to adopt precise three-dimensional shapes as they are synthesized in cells if they are to work properly. Researchers eventually discovered that mutations seem to cause individual proteins to fold improperly and then clump together. Cells tag these misshapen proteins with ubiquitin, a molecular marker, which signals that they need to be removed. When this cellular disposal system becomes overwhelmed, the trash builds up. In people with certain types of familial ALS, motor neurons are littered with clumps of aberrant SOD1 proteins tagged with ubiquitin.

A major breakthrough in ALS research occurred in 2006, when scientists looked at cases of ALS without *SOD1* mutations. In virtually every one, they discovered that another protein, called TDP-43, also clumps within motor neurons. TDP-43 belongs to a class of proteins that regulate the activity of messenger RNAs—mobile copies of DNA that serve as templates for making the proteins encoded by a gene's DNA "letters." TDP-43 binds to a messenger RNA, guides its processing in the nucleus, transports it to where it needs to go in the cell and performs other functions important for "translating" the RNA into a protein. Somehow in ALS, the TDP-43 protein gets pulled out of the nucleus and starts accumulating in the

Illustration by Jen Christiansen

surrounding cytoplasm. It might even act as a kind of sink to pull additional copies of itself into that cytoplasm. Scientists have yet to determine whether TDP-43 displays a loss of function (because it is pulled from the nucleus) or a toxic gain of function (because it builds up in the cytoplasm), or both.

Identification of TDP-43 as the key clumping protein in most cases of ALS helped geneticists home in on the specific gene encoding it, *TARDBP,* and they found rare mutations among some families with an inherited form of the disease. The main game changer in this work was the conceptual discovery that alterations in an RNA-binding protein could cause ALS. Researchers subsequently identified several additional ALS-causing genes that give rise to proteins involved in regulating RNA and anticipate that there may be many more. The late 2000s saw an explosion in ALS genetics discoveries, with one or two new ALS genes surfacing each year. But the most exciting discovery was yet to come.

ALS ICE BUCKET CHALLENGE videos made by millions of people, including Formula One driver Daniel Ricciardo, helped to raise awareness and money for research.

DNA REPEATS RUN AMOK

THE FINDINGS EMERGED from studies of several families with an inherited form of ALS. In 2011 two scientific teams independently reported that they had found a peculiar type of mutation in a gene with an equally peculiar name—*C9ORF72,* which stands for the 72nd open reading frame, or the part of a gene that codes for a protein, on chromosome 9. In healthy people, this gene includes a short sequence of DNA—GGGGCC—that is repeated two to 23 times. In people with the *C9ORF72* mutation, this segment is repeated hundreds or sometimes thousands of times.

Subsequent research revealed that these excessive repeats could explain 40 to 50 percent of familial ALS cases and 5 to 10 percent of seemingly sporadic cases. Intriguingly, the discovery of the mutations provided a genetic connection between ALS and another disease, a form of dementia called frontotemporal degeneration (FTD). FTD is marked by changes in personality and decision making. *C9ORF72* mutations can cause ALS or FTD, or even a combination of both called ALS-FTD. And clumps of that ever present TDP-43 protein build up in the neurons of people with *C9ORF72* mutations, providing yet another connection between the two disorders. This association implies that ALS and FTD might be part of a spectrum of related conditions, although how mutations in the same gene would lead to such divergent symptoms is unclear.

Researchers are investigating three cellular mechanisms that might explain how the mutations in this mysterious gene cause ALS. The repeating DNA segment could interfere with the way the genetic code is normally copied into messenger RNA and then translated into C9ORF72 protein, decreasing the amount of protein synthesized. This decrease could diminish the protein's effects, although its exact function is still unknown. Alternatively, there could be a toxic gain of function: perhaps the repeating sequence causes the RNA itself to form clumps that build up in the nuclei of neurons and act like a sink, trapping RNA-binding proteins and preventing them from going about their usual business. Or there could be a toxic gain of function because of a bizarre twist of molecular biology in which the expanded repeat sequence gets translated into small rogue proteins that are themselves prone to clumping in the neurons of people with *C9ORF72* mutations.

So far the evidence suggests *C9ORF72* mutations cause ALS through a toxic gain of function, although the relative contributions of clumps of RNA and clumps of protein are still unclear. Ultimately the distinction may not matter, because therapeutic strategies are being developed that could shut off the production of both RNAs and proteins from the mutant gene in one fell swoop.

REPEAT POLICE TO THE RESCUE?

GENE SILENCING using a synthetic molecule called an antisense oligonucleotide (ASO) represents one of the most exciting new therapeutic advances in neurodegenerative disease. An ASO molecule is designed to locate and bind itself to the messenger RNA molecule produced from a specific gene, which in turn prompts an enzyme to snap into action and attack the RNA-ASO hybrid. ASOs can lead to the selective destruction of virtually any RNA produced from a mutant gene. In the case of *C9ORF72,* rodent studies indicate that antisense molecules engineered to destroy RNA clumps in motor neurons can also destroy clumps of aberrant repeat proteins and prevent new protein clumps from forming.

Antisense drugs designed to target the mutant *C9ORF72* gene are expected to enter clinical trials in humans this year. Meanwhile researchers have also designed an antisense agent for the familial form of ALS caused by *SOD1,* and results of an initial clinical trial indicate it is safe to inject into the fluid-filled space of the spinal column, a site chosen to allow the drug to travel through the cerebrospinal fluid that flows around the brain and to find its way into motor neurons.

The success of an ASO developed for another neurodegenerative disease, called spinal muscular atrophy, gives researchers cause for cautious optimism. This genetic motor neuron disease in infants is similar to ALS. Very few children who suffer from it live past their third birthday. In two recent clinical trials of an antisense drug designed to correct a gene defect that leads to abnormal messenger RNA, children with spinal muscular atrophy showed such dramatic improvement in their motor skills that the FDA fast-tracked those trials and gave formal approval for the drug in late December 2016.

SOLVING SPORADIC ALS

STUDIES OF RARE FORMS of ALS with a clear familial inheritance pattern have paved the way for a better understanding of the underlying biology of the disease. The biggest challenge going forward is to identify mutations in the genomes of individuals with sporadic ALS that make them susceptible to the disease. Efforts are under way around the world to collect DNA samples from people with ALS and to scour their genomes for data.

MARK THOMPSON *Getty Images*

SCIENTIFIC AMERICAN ONLINE Read about how Stephen Hawking lives with ALS at ScientificAmerican.com/jun2017/als-genes

To expedite this task, geneticists have developed a microchip that lets them conduct so-called genome-wide association studies (GWASs) to readily compare the genomes of people with ALS with those of healthy people. The chip focuses on genome regions known to have variants called single nucleotide polymorphisms—places where a DNA letter, or nucleotide, can vary from one person to another. GWASs are correlational and thus cannot reveal whether something is causing ALS, but they can identify suspect discrepancies that warrant closer examination. Several recent international efforts to perform GWASs of more than 10,000 people with ALS and more than 20,000 healthy people uncovered a number of genomic differences that are now under investigation. New technologies have also simplified the process of collecting genetic data, making it possible to sequence an individual's entire genome in one day for less than $1,000. It takes even less time and money if you sequence only the exome, the part of the genome that codes proteins.

Once researchers have assembled a comprehensive catalog of genetic variants associated with a predisposition for ALS, they will attempt to decipher the complex ways in which ALS-related genetic mutations increase the risk of disease. That attempt will include studying how various genes interact and investigating whether multiple mutant genes might be involved in some forms of ALS, as well as considering how environmental factors might help trigger the disease in some people. Some new studies suggest that ALS may even result in part from the reawakening of a dormant retrovirus—a viral DNA sequence that long ago inserted itself into the genome and normally would have sat quietly. It may be that a retrovirus in some people with ALS jumps from neuron to neuron in the brain, potentially causing damage and initiating the disorder in its wake.

PROMISING NEW LEADS

A GROWING BODY of research suggests that ALS is not merely a disease of dying motor neurons. So-called glial cells, which are even more abundant in the brain and the central nervous system than neurons, may also play an important role. Glial cells perform a variety of functions: some provide physical support for neurons; others regulate the internal environment of the brain, especially the fluid surrounding neurons and their synapses. Recent studies of mice with the *SOD1* gene mutation produced a surprise. Shutting off synthesis of the mutant gene in glial cells prolonged life despite the continued presence of toxic SOD1 protein in the animals' motor neurons. It appears that ALS may originate in the motor neurons but that communication with glial cells helps to drive the progression of the disease. Glial cells might also contribute to ALS by producing a toxic factor, although scientists are not exactly sure of what that factor is or how it works. Once the factor (or factors) is identified, ways to block its production or hinder its ability to transmit its bad signal to motor neurons could be developed to slow or halt ALS.

Amid the quest to unravel the myriad causes of ALS, researchers have also been scrambling to identify biomarkers that can help doctors assess the progress of the disease. For example, ongoing efforts aim to detect the abnormal repeat proteins made from that *C9ORF72* DNA expansion in easily accessible body fluids, such as the blood or spinal fluid. In March one of us (Petrucelli) reported that he had detected these proteins in the cerebrospinal fluid of people with ALS and ALS-FTD—as well as in asymptomatic carriers of the mutated gene. Such measurements could potentially aid in early diagnosis. Other biomarker research is focusing on developing imaging techniques to help detect the TDP-43 protein clumps that build up in the brains of people with ALS before these aggregates start to kill motor neurons. All these biomarkers could also serve as useful benchmarks to judge the success of possible therapies in clinical trials.

The rapid advances taking place in genetics and genomics, as well as the development of new and improved biomarkers, will usher in an era of precision medicine for ALS. In the near future, patients will be grouped together based on the type of ALS they have and will then receive a treatment or preventive tailored to them.

THE POWER OF SOCIAL MEDIA

MUCH OF THE PROGRESS in ALS research during the past decade can be attributed to the willingness of large numbers of individuals afflicted with the disease to volunteer both their time and their DNA to participate in large-scale genomics studies. People with ALS and their families have also helped increase public awareness and canvas funds to support ongoing research and patient services through the power of social media.

The "ALS Ice Bucket Challenge" took the Internet by storm in 2014. Pete Frates, a former captain of Boston College's baseball team who was diagnosed with ALS two years earlier, at age 27, helped to get things rolling when he posted a video on Facebook challenging his friends to dump buckets of ice water over their heads to raise money for the ALS Association. The campaign quickly went viral as a host of celebrities, including Mark Zuckerberg, Bill Gates, Oprah Winfrey, Leonardo DiCaprio and LeBron James, took the challenge. During an eight-week period, Facebook users posted more than 17 million videos of themselves getting drenched for the cause. Supporters ended up raising more than $115 million, of which 67 percent went to research, 20 percent went to patient and community services, and 9 percent went to public and professional education.

ALS is a relentlessly cruel disease. Before Gehrig's stirring retirement speech at Yankee Stadium—in which he famously referred to himself as "the luckiest man on the face of the earth"—and news of his diagnosis spread, most people who contracted the disease suffered in silence. But now public awareness continues to grow, in part because of people like Frates. The social media campaign he helped to spark revitalized the ALS Association, which has since tripled its annual budget for research. Scientists are optimistic that the explosive growth in our understanding of ALS biology will continue and that casting an ever widening dragnet for rogue genes will lead to better therapies for holding this stealth killer at bay. SA

MORE TO EXPLORE

State of Play in Amyotrophic Lateral Sclerosis Genetics. Alan E. Renton, Adriano Chiò and Bryan J. Traynor in *Nature Neuroscience,* Vol. 17, No. 1, pages 17–23; January 2014.

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FROM OUR ARCHIVES

Playing Defense against Lou Gehrig's Disease. Patrick Aebischer and Ann C. Kato; November 2007.

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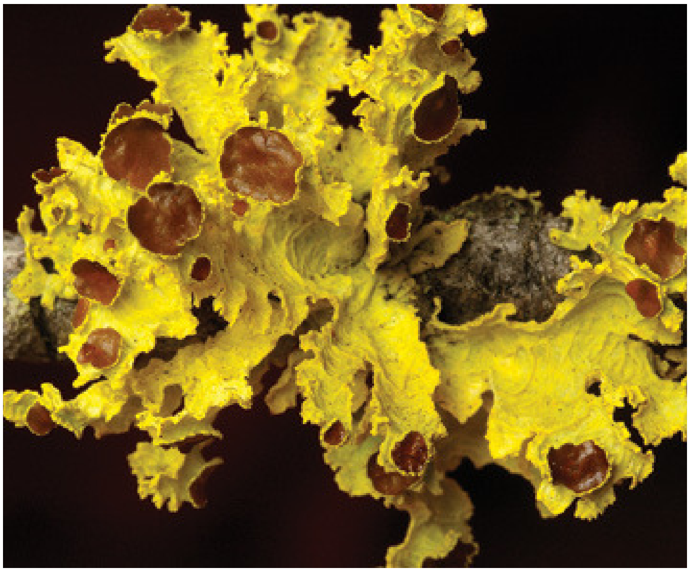
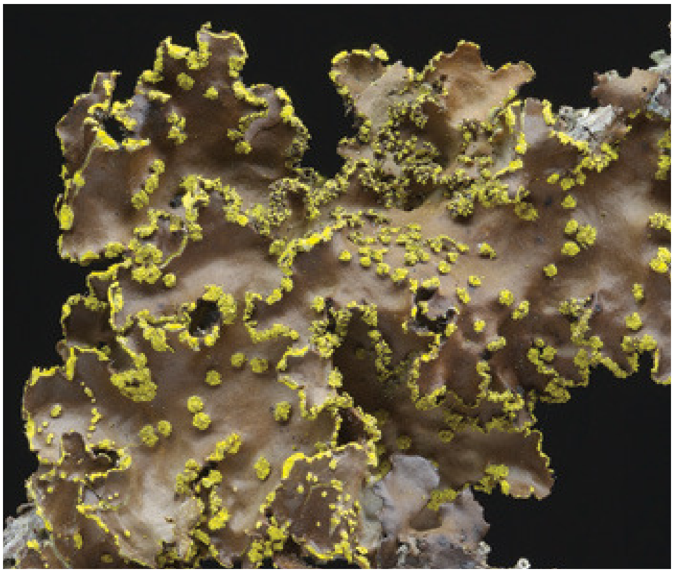


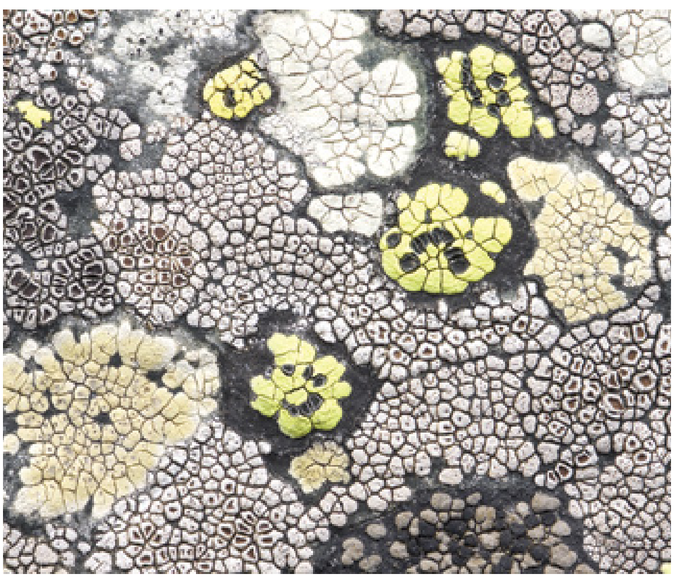
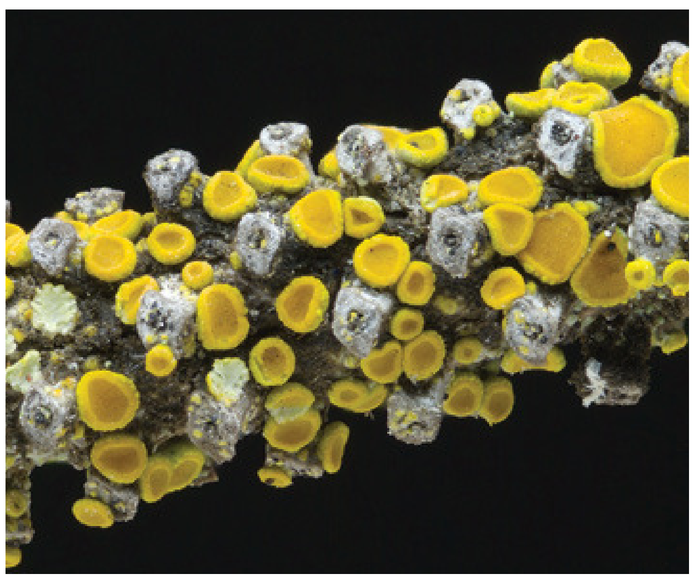




BIOLOGY

The Meaning of Lichen

How a self-taught naturalist unearthed hidden symbioses in the wilds of British Columbia—and helped to overturn 150 years of accepted scientific wisdom

By Erica Gies

Erica Gies writes about science and the environment from Victoria, British Columbia, and San Francisco. Her work appears in the *New York Times*, the *Guardian*, the *Economist*, *Ensia*, *National Geographic* and elsewhere.

TREVOR GOWARD LETS ME LEAD, SO WE TRAVEL THROUGH the mixed forest at my pace. This is a nod to his rangy 6'5" figure and the rapid strides he makes across barely discernible deer and bear paths on his land adjacent to Wells Gray Provincial Park in British Columbia. But mostly he is making space for my observations, my innate way of experiencing the landscape. What engages me? How do I see? I brake in front of a small, white-green growth on the trunk of an aspen. “Look there!” he says excitedly, inviting me to peer into the ragbag lichen through a magnifying lens. Suddenly I am in another world, looking down whorls studded with black dots into little caverns sprinkled with superfine dust.

Goward, white hair sticking up haphazardly, is wearing three flannel shirts on this crisp fall day. A hand lens hangs on a string around his neck, as an Australian shepherd named Purple trots along with him. He seems more mountain man than scientist, a naturalist in the tradition of Charles Darwin or Henry David Thoreau. Goward’s scientific love is lichens—those growths that look like little mosses or colored crusts stuck to trees and rocks everywhere. He is inseparable from this place, where he has spent most of his adult life after growing up in a city south of the park. Now 64, he rarely leaves. “It has become my center of spiritual gravity,” he tells me. It’s not hard to see why. Most of the park has no road access and is rarely seen by humans. Wells Gray’s 1.3 million acres were formed by volcanoes and glaciers; its river valleys, sheer rock mountains, alpine meadows and waterfall spray zones foster rich biodiversity. “I came to understand that the lichens here are pretty special,” among the world’s most diverse, Goward beams. There are hundreds of species and counting. His careful attention to this one place, like conservationist Aldo Leopold’s beloved Sauk County, Wisconsin, allows him to see connections that others might miss.

Goward stumbled upon lichenology when he was educating himself about different branches of nature. “I made a point each year of learning as much as I could about a different taxonomic group. One year it was birds, then plants, then mushrooms, then insects.” When he got to lichens, he was smitten. Since then, despite being self-taught, he has become the go-to expert in central British Columbia for everyone from atmo-

PRECEDING PAGES: TIM WHEELER

IN BRIEF

Trevor Goward, who has no scientific degree, has helped upend the understanding of lichens and perhaps all life-forms by closely observing nature.

His insights, praised by some academics and discounted by others, are a strong reminder that biology, and science, may be getting too removed from the natural world, that mavericks can be brilliant, and that networks may be the most enduring life-form, not individuals.

ERICA GIES

TREVOR GOWARD examines a ragbag lichen on an aspen. His deep observations of nature have upset biology, like those of his predecessors Charles Darwin and Henry David Thoreau.

spheric scientists to gold prospectors to caribou biologists. Several lichen species have been named after him. He has published three taxonomic guides to lichens and has earned a spot as an associate member of the University of British Columbia botany department.

And yet Trevor Goward is a maverick in the scientific world. His radical thought experiments about lichens, published in 12 provocative essays, available on his Web site, Ways of Enlichenment, have been both ridiculed and lauded—but largely ignored by most researchers because he holds no scientific degrees and because many of his ideas are not supported by rigorous data. Still, Goward's astute observations and deep thinking follow in the footsteps of Darwin's and Thoreau's approaches—which, much more than laboratory science, formed the basis of the theories of evolution and ecology. People who are open to considering his ideas say they come away with mind-expanding food for thought about lichens, biology and all life. Goward's longtime friend and sometimes co-author Toby Spribille, a lichenologist at the University of Alberta, says Goward's essays contain many gold nuggets: "Frankly, I think they are brilliant."

In the forest, Goward exudes a quiet, ebullient joy, the yang to his yin: a dark, realistic assessment of humanity's folly. When we stop, he leans on a sturdy walking stick and delivers extended soliloquies about how elements of the ecosystem interact. Reading the lichens informs him about soil chemistry, rain patterns and plant nutrients. He shows me a species growing on a hemlock, unusual because conifer bark is usually too acidic to support these kinds of lichens. So why are they there? In a 2000 paper Goward and his co-author André Arsenault found that the answer lies in a mature trembling aspen nearby. Water dripping from its branches becomes a leachate, which, when it falls onto the conifer's bark, lessens the acidity, allowing the lichen to thrive. They dubbed this interaction the drip-zone effect.

Goward learns from every life-form, including Purple, who waits on us patiently when she is not conducting her own observations: Scat from a pine marten. Red squirrel chatter! Although Goward knows French, Latin, and some conversational German and Swedish, he remarks that "mostly these days I speak lichen and maybe a bit of dog." He says he can learn from Purple's way of seeing. That may seem eccentric, but Goward respects First Nations peoples' ways of knowing, and learning from animals is a storied human tradition.

Modern science tends to ignore outsiders. But reductionist science is not the only way of knowing things. Naturalists were the forebears of science. Humans once lived much closer to the land and were keen observers who had a deep understanding of nature's interactions. Today biology tends to be focused on molecules, and failure to look up from instruments in the lab and actually observe how pieces interact in the natural world sometimes undermines discovery. A clinical focus can lead scientists to miss big-picture connections, such as an emerging understanding that networks may be a more enduring life-form than individuals. Indeed, it was an idea from Goward that inspired Spribille's lab work while he was a postdoc at the University of Montana. That work paid off with a major advance: a July 2016 cover story in *Science* that rocked the ossified world of lichenology. The discovery called into question the very nature of the lichen symbiosis, shedding fresh light on how symbioses across biology work, how natural selection proceeds and even how to define life-forms.

LICHENS ARE BOTH UBIQUITOUS AND FASCINATING. PERHAPS more than 500 million years old, they occur on every continent and can thrive in some of the most inhospitable places on earth. They even survived for a year and a half in space, fully exposed to cosmic radiation, ultraviolet irradiation and vacuum conditions. The approximately 14,000 species of lichen come in a variety of forms: flat rounds on stones, scalloped leaves nestled among mosses, crusts clinging to tree bark, flowing strands hanging from branches, tiny trumpets tipped in red.

For centuries people thought they were plants (and then fungi). Then, in the 1860s, Swiss botanist Simon Schwendener discovered that they were a partnership between a fungus (an organism classified in its own kingdom because, unlike plants, it cannot make its own food) and an alga, an organism that feeds itself with photosynthesis but lacks the roots and stems of plants. The fungus apparently provided the structure of the lichen, and the alga provided food for the fungus via photosynthesis. (Later it was discovered that in some lichens, a cyanobacterium provided the food—and a handful of species contained both an alga and a cyanobacterium, along with the fungus.) Schwendener's discovery, at first resisted by the scientific community, ultimately made lichens the poster children for symbiosis, a mutually beneficial interaction among organisms. Since then, science has found symbioses across nature, including among the trillions of nonhuman microbes that cling to the scaffold of our bodies.

Science over the past two centuries has largely viewed molecules, cells and species as individuals. Symbiosis challenges that notion. "Within a lichen," Spribille says, "algal cells and fungal cells may experience each other as individuals, but together they form a lichen that the feeding caribou sees as an individual: tasty." Natural selection happens on both scales simultaneously. Just as light is both a wave and a particle, the fungus and alga are both individuals and parts of a whole. Science's reductionist focus has made it nearly impossible to fully understand symbiosis, Spribille says. "Ecology was supposed to be the science of natural process and synthesis, but its backbone is severely strained under the mathematics of individuality."

In July 2016 Spribille and his co-authors took a major step forward in that understanding. Their big reveal in *Science:* many lichens have a second fungus in the house.

At the heart of their study is a pair of lichens to which Goward had drawn Spribille's attention: *Bryoria fremontii,* which is hairlike and often brown and eaten by northwestern indigenous peoples, and a similar lichen, *Bryoria tortuosa,* which is often a yellowish green and is toxic, with high levels of vulpinic acid. The two posed a fascinating conundrum. Despite their differences, a genetic analysis published in 2009 by Saara Velmala of the University of Helsinki and her colleagues, on which Goward was a co-author, showed that the two species consisted of the same fungus and same alga. Spribille recalled how this perplexing finding infected them both. "[Goward] took the question of how could these two different lichens—one of which is toxic, for God's sake—be identical." The question would not let go of Goward. And when Goward wrote about it, "by extension, it wouldn't let go of me."

Aside from their different appearances and levels of vulpinic acid, Goward observed that the two lichens also had slightly different ecologies. Although they grew in some of the same places, *B. tortuosa* was found only on the summer-dry fringes of *B. fremontii's* larger territory. In 2009 he proposed that lichens are formed not by the shape of their fungal partner but by a series of decisions made during the developmental dance between fungus and alga. One lichen can look different from another that is composed of the same partners because it took different turns during development. Goward suggested that the difference between the two species of *Bryoria* might stem from each of them having a different relationship with a third life-form, a bacterium.

After five years of work in the lab, Spribille and his colleagues discovered that both *Bryoria* species did include a third partner. But it was not a bacterium; it was another fungus, known as a basidiomycete yeast. The toxic *Bryoria* contained a lot more of the yeast than the edible one. The team also demonstrated that the yeast was not a contaminant but had evolved with the other partners for more than 200 million years. Expanding their search to lichens across the globe, they found the yeast in 52 other sets (genera) of lichen. The finding dramat-

CLOSE EXAMINATION has revealed that *Bryoria fremontii* is not simply a partnership between a fungus and an alga, as long thought; a yeast is also involved.

TIM WHEELER

ically expanded the world's understanding of lichens, opening the door to other insights. "Only now are we beginning to see that lichens really have pulled off a rare feat in evolution: a large multicellular organism but built entirely of microbes—and here's the amazing thing—without a scaffold," Spribille says. "Self-assembling, self-replicating, generation after symbiotic generation."

Goward first became interested in *B. fremontii* and *B. tortuosa* when he read ethnobotanist Nancy Turner's 1977 paper about *B. fremontii*'s importance to First Nations peoples. She said that women elders could easily distinguish the edible from the nonedible lichens. Although the two can have different coloring and a slightly different shape, they can also look quite alike. Elders use clues such as location, color and the types of neighboring lichens to tell them apart. When Stuart Crawford, a friend of Goward's with a degree in ethnobotany, showed bundles of the two lichens to an elder and conservationist from the Neskonlith band, the late Mary Thomas, she correctly identified the edible one every time.

BRYORIA TORTUOSA hosts the same fungus and alga as the edible *B. fremontii,* but it has a much higher concentration of yeast, and it is poisonous.

TIM WHEELER

Local people's wisdom does not always jibe with scientific explanations, Crawford says, but the result, based on observation, is correct. The locals told Crawford that they wait for *B. fremontii* to "ripen" on the tree. In fact, lichens do not ripen as do fruits and vegetables, but the darker color and its growth pattern on trees help the people distinguish it from its poisonous twin. These other realms of knowledge about *Bryoria* would have added interesting context to the *Science* paper, Spribille says, but "it didn't fit the word limit."

Three months after the paper was published, Crawford, who knows Spribille through Goward, got around to telling him something amazing. For years Crawford had been collecting writings from around the world—ancient Egypt, modern Mexico, medieval Russia, the Biblical Middle East, a European cookbook from the 1950s—of people using lichens to make bread and alcoholic beverages. In some cases, they were using them explicitly for leavening and fermentation. On some level, Crawford realized, people knew that lichens contained yeast or functioned like yeast. When he was working on his master's degree in Victoria, B.C., Crawford discussed the notion with a local microbrewer, who told him, "If you can figure out the recipe, I'll do a batch of beer" with it.

SPRIBILLE'S OPENNESS TO GOWARD'S UNCONVENTIONAL WAYS of thinking is perhaps a reflection of his hard-won path to science. He grew up in a fundamentalist Christian family in northwestern Montana, where his parents pulled him out of school after fourth grade to protect him from "the influences of the world." Spribille is telling me this via Skype from Austria, where it is late at night and his wife and young daughter are sleeping. His rectangular glasses frame blue eyes that frequently squeeze shut while he is talking, as if communicating with me is a little painful.

Circumstance could not restrain Spribille's intellectual curiosity. Intrigued about organisms he saw in the wild, he sought answers from biologists at a local U.S. Forest Service outpost. Eventually they recommended him for a job surveying vascular plants, and he could call up professors and authors with his burning questions. Goward was on Spribille's call list. "Trevor kept me on for two and a half hours," Spribille says fondly. That was more than 20 years ago. They have co-written several papers, and "we still haven't run out of things to talk about." Early on, Goward told Spribille that he had ideas that would turn lichenology upside down. "He said I was delusional," Goward recalls. "But he wanted to hear the ideas."

Ultimately Spribille felt a keen desire for a formal education. He took the high school equivalency examination and found an opportunity to go to college in Germany. He later earned a Ph.D. in lichenology at the University of Graz in Austria and this past March began his new appointment as assistant professor of the ecology and evolution of symbiosis at the University of Alberta. During his postdoc at the University of Montana, he met John McCutcheon, one of the co-authors on the *Science* paper and head of the lab in which the work was done. McCutcheon credits the breakthrough to technological advances that allowed the researchers to find the tiny yeast and to cooperation among diverse co-workers. But also critical, he says, was Spribille's ability to look beyond what was assumed to be true. The human mind's tendency to restrict itself is part of what kept this yeast hidden for so long, he says: "When you're used to thinking there's just one fungus there, that's what you see."

Spribille, in turn, credits Goward with having "a huge influence on my thinking. [His essays] gave me license to think about lichens in a way that was not orthodox and freed me to see the patterns I worked out in *Bryoria* with my co-authors." Yet even with that, Spribille says, "one of the most difficult things was allowing myself to have an open mind to the idea that 150 years of literature may have entirely missed the theoretical possibility that there would be more than one fungal partner in the lichen symbiosis."

While he appreciates his education, Spribille maintains that academia's emphasis on the canon of what others have established as important is inherently limiting. "You have this culture of prepared minds that makes it extremely difficult to think outside the box," Spribille says. "It creates the box."

That sounds plausible to Jonathan Foley, executive director of the California Academy of Sciences in San Francisco, who has a Ph.D. and had an acclaimed academic career. (Foley serves on *Scientific American*'s board of advisers.) When it comes to ideas, "the ivory tower is now an ivory fortress," he says. Academic culture's incentives to publish in accepted journals, get funding and obtain tenure are "not aligned with being wildly creative." After Sputnik, science became hyperprofessionalized, Foley says—"kind of Science, Inc. I think we lost part of our souls." The extreme specialization required for the biotech-heavy, molecule-focused world of biology today eliminates time to study taxonomy or epistemology. "There are people getting degrees in biological sciences at the best universities in America today who don't know the names of anything outdoors, who have never studied anything larger than a cell," Foley notes. That means a lot of biologists are lab-bound and rely on people like Goward to find the species they would like to study or even to suggest ideas for studies.

Also worrisome to Spribille is that his own students are petrified of being wrong, a psychological state incompatible with breakthroughs. For a counterexample, he points to Goward. In the case of *Bryoria,* Goward surmised that a third partner was present, although he incorrectly thought it was a bacterium. But being correct "is not the criterion of a brilliant mind," Spribille says. Rather, brilliant minds are characterized by indefatigable curiosity and questioning, traits Spribille tries to encourage in his students. "I tell them, 'Just put all the ideas out there. Nobody here is going to make you feel bad about throwing out an idea that we may then not use.' I live by that."

The unit of life may not be an individual but a network, whether among the organisms making up a lichen or the microbes of the human microbiome.

LICHENS GROW on every continent, and they survived a year and a half on the outside of the International Space Station, fully exposed to cosmic radiation.

ERICA GIES

SOME OF THE MOST SERIOUS PROBLEMS SCIENCE IS TRYING TO solve today—climate change, loss of biodiversity, food and water security—require big, integrated views from multiple perspectives. Stepping out of the lab and back into nature to observe how natural systems actually work is a critical first move. One biologist at the University of the South challenged himself to try it. David George Haskell spent a year sitting in a square yard of old-growth forest in Tennessee, just observing, and wrote a Pulitzer-nominated book about it, *The Forest Unseen*. The experience was profoundly humbling, he says. "You wake up to the extent of your own ignorance. I'd been through decades of training and teaching as a biologist and had published scientific papers and so on, and sitting down in the woods, I realized I know so, so little about this place." From that humility sprouted seeds of curiosity and dozens of questions about relationships among plants and animals, their ecological history, and how that related to climate and geology. Haskell is now an adviser to the New York City–based Open Space Institute, helping it to identify lands for conservation that are most likely to be climate-resilient.

If knowledge comes mostly through reading scientific literature, "we're several steps removed from the actual phenomena we're discovering," Haskell explains. And while instruments are important to help scientists understand the world, "our bodies come preinstalled with all these amazing apps, and they connect directly into our consciousness," he says. "Through literally coming back to our senses, we can learn so much about the world."

Goward has turned this ethic into a way of life. His house, named Edgewood Blue, on 10 acres abutting Wells Gray, has running water for a shower and sinks but no toilet. As I put on my coat and shoes one evening to head to the outhouse, Goward's partner, Curtis Björk, a botanist, encourages me to look up and admire the Milky Way, vivid in the lack of light pollution. When I ask why he and Björk have no toilet, Goward says they appreciate being forced to go outside every day, even

SCIENTIFIC AMERICAN ONLINE Listen to a podcast about yeast's surprising role in lichens at ScientificAmerican.com/jun2017/gies

ERICA GIES

AT HIS WOODLAND HOME, Goward hosts an ongoing parade of biologists, poets and astrophysicists who explore ideas about exotic life-forms and the pitfalls of humans separating from the natural world.

in the depths of winter. On trips to the loo he has seen the Northern Lights and passing moose. When I jokingly whimper about getting wet or cold or chomped by summer mosquitoes, or even stalked by the cougar that recently swiped a neighbor's pigs, Goward is unapologetic: "That's real. Life isn't always comfortable."

To Goward, the real danger lies in separating ourselves from the natural world, living ensconced in cities, ignorant of how badly we are degrading nature. Haskell agrees and points out that this separation has ethical implications. "Trees, fungi, salamanders ... these are our blood kin, if you believe Darwin." When we do not know the world, we have an imperfect sense of right and wrong in how our own behavior impacts ecosystems, he says.

But for scientists who may not have a year, or 30, to spend contemplating the wild, collaborations or friendships with people outside the academy or from different disciplines can open space for new discoveries, as they did for Spribille.

THE DECOR AT EDGEWOOD IS DOMINATED BY BOOKS, WHICH serve as de facto wallpaper, lining homemade shelves in most rooms. The kitchen is Björk's fiefdom, and when dinner is ready, he sends Purple to fetch the humans. Purple eats at the table with us, displaying excellent manners.

Also served at the table are wide-ranging discussions. "We try to make this a place where anyone can express their ideas," Goward pronounces. The strengths and failings of modern science are a frequent theme, driven primarily by deep affection for it. Life and human relationships also take the spotlight, sometimes with quirky analogies to lichens. Although Goward is confident—sometimes bordering on arrogant—about his own ideas, he is eager to consider new information. His dialogue is peppered with references to authors. When I mentioned Haskell's book and an essay by Ursula K. Le Guin, he had read them by the next time we talked.

With the scientific world often reluctant to publish him, Goward spreads his ideas one person at a time. He and Björk host an ongoing parade of biologists, aspiring naturalists, poets, geographers, ecologists, astrophysicists and journalists who stay for a day or a week or longer in return for doing a bit of work at Edgewood. Both Spribille and Crawford are regular guests. "I've done a lot of landscaping on his place," Crawford says proudly. "We have great and intellectually stimulating conversations."

Goward would like to create a more formal venue for learning, to increase "biological literacy" in the next generation, and has offered half of his land as a research center to Thompson Rivers University in nearby Kamloops, where he grew up. He also periodically invites people from various disciplines to meet for a few days of discourse.

On my visit Goward delves into one of his pet lines of inquiry: What are lichens, really? Are they organisms? Fungal greenhouses? Algal farmsteads? Ecosystems? Networks?

What you think lichens are might depend on your perspective. Because lichens have the scientific names of their fungi, that can create an implicit bias that the fungus is in charge, a limited perspective that Goward admits to having once upon a time. Today he sees lichens as a kind of koan. "The lichen by its very nature exists at a portal, a doorway," he says. "If you look in one direction, it's an organism. If you look in the other direction, it's an ecosystem." Goward's essays argue for seeing lichens not as their fungal or algal parts or even as ecosystems or organisms. Rather they are all these things, biological systems encapsulated in a membrane: lichens as emergent property. After all, the lichens that were sent into space survived when their algae alone did not.

Thinking of lichens as systems fits with a larger shift in biology from viewing the fundamental unit of life as the individual to that of community or partnerships. "Whether it is the microbiome within the human body or trees interacting with fungal partners belowground or lichens … we're seeing that networked relationships are more fundamental and persist longer within biological systems than individuals do," Haskell says.

To Goward, lichens are the organisms that are most obviously about relationships. As such, they provide insights into all of life. "Lichens are my window," he says, "but it's the act of looking at the world that's the interesting thing." Systems only hold together in the long term if the parts consider themselves integral to the whole and if the whole protects the parts, as lichens do. "That's what's going wrong with us," he says. "As individuals, we're not concerned with the whole." SA

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MACHINE LEARNING

MAKING AI MORE HUMAN

Illustration by Simon Prades

Artificial intelligence has staged a revival by starting to incorporate what we know about how children learn

By Alison Gopnik

Alison Gopnik is a professor of psychology and an affiliate professor of philosophy at the University of California, Berkeley. Her research focuses on how young children learn about the world around them.

IF YOU SPEND MUCH TIME WITH CHILDREN, YOU'RE BOUND TO WONDER HOW young human beings can possibly learn so much so quickly. Philosophers, going all the way back to Plato, have wondered, too, but they've never found a satisfying answer. My five-year-old grandson, Augie, has learned about plants, animals and clocks, not to mention dinosaurs and spaceships. He also can figure out what other people want and how they think and feel. He can use that knowledge to classify what he sees and hears and make new predictions. He recently proclaimed, for example, that the newly discovered species of titanosaur on display at the American Museum of Natural History in New York City is a plant eater, so that means it really isn't that scary.

Yet all that reaches Augie from his environment is a stream of photons hitting his retina and disturbances of air contacting his eardrums. The neural computer that sits behind his blue eyes manages somehow to start with that limited information from his senses and to end up making predictions about plant-eating titanosaurs. One lingering question is whether electronic computers can do the same.

During the past 15 years or so computer scientists and psychologists have been trying to find an answer. Children acquire a great deal of knowledge with little input from teachers or parents. Despite enormous strides in machine intelligence, even the most powerful computers still cannot learn as well as a five-year-old does.

Figuring out how the child brain actually functions—and then creating a digital version that will work as effectively—will challenge computer scientists for decades to come. But in the meantime, they are beginning to develop artificial intelligence that incorporates some of what we know about how humans learn.

THIS WAY UP

AFTER THE FIRST BURST of enthusiasm in the 1950s and 1960s, the quest for AI languished for decades. In the past few years, though, there have been striking advances, especially in the field of machine learning, and AI has become one of the hottest developments in technology. Many utopian or apocalyptic predictions have emerged about what those advances mean. They have, quite literally, been taken to presage either immortality or the end of the world, and a lot has been written about both these possibilities.

I suspect that developments in AI lead to such strong feelings because of our deep-seated fear of the almost human. The idea that creatures might bridge the gap between the human and the artificial has always been deeply disturbing, from the medieval golem to Frankenstein's monster to Ava, the sexy robot fatale in the movie *Ex Machina*.

But do computers really learn as well as humans? How much of the heated rhetoric points to revolutionary change, and how much is just hype? The details of how computers learn to recognize, say, a cat, a spoken word or a Japanese character can be hard to follow. But on closer inspection, the basic ideas behind machine learning are not as baffling as they first seem.

One approach tries to solve the problem by starting with the stream of photons and air vibrations that Augie, and all of us, receives—and that reaches the computer as pixels of a digital image and sound samples of an audio recording. It then tries to extract a series of patterns in the digital data that can detect and identify whole objects in the surrounding world. This so-called bottom-up approach has roots in the ideas of philosophers such as David Hume and John Stuart Mill and psychologists such as Ivan Pavlov and B. F. Skinner, among others.

In the 1980s scientists figured out a compelling and inge-

IN BRIEF

How do young children know what they know? That question has long preoccupied philosophers and psychologists—and now computer scientists.

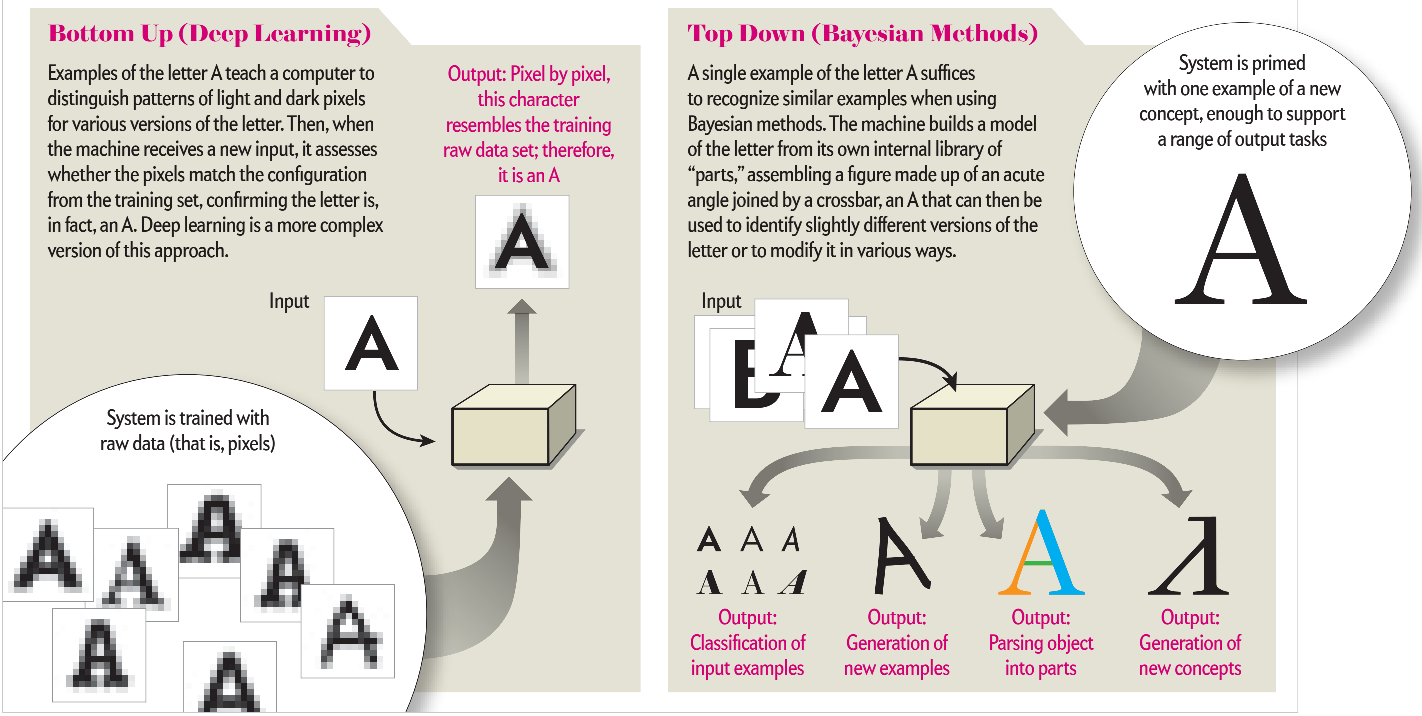
Specialists in artificial intelligence are studying the mental reasoning powers of preschoolers to develop ways to teach machines about the world.

Two rival machine-learning strategies—both halting attempts to mimic what children do naturally—have begun to transform AI as a discipline.

OPPOSING STRATEGIES

Two Paths to AI’s Resurgence

Problems the average five-year-old solves readily can stump even the most powerful computers. AI has made a spirited comeback in recent years by teaching computers to learn about the world somewhat like a child does. The machine recognizes the letter “A” either from raw sensory information—a bottom-up approach—or by making a guess from preexisting knowledge—a top-down approach.



SOURCE: “HUMAN-LEVEL CONCEPT LEARNING THROUGH PROBABILISTIC PROGRAM INDUCTION,” BY BRENDEN M. LAKE, RUSLAN SALAKHUTDINOV AND JOSHUA B. TENENBAUM, IN *SCIENCE*, VOL. 350; DECEMBER 11, 2015 (*Bayesian example*)

nious way to apply bottom-up methods to let computers hunt for meaningful patterns in data. “Connectionist,” or “neural network,” systems take inspiration from the way that neurons convert light patterns at your retina into representations of the world around you. A neural network does something similar. It uses interconnected processing elements, akin to biological cells, to transform pixels at one layer of the network into increasingly abstract representations—a nose or an entire face—as data are crunched at progressively higher layers.

Neural-network ideas have gone through a recent revival because of new techniques called deep learning—technology now being commercialized by Google, Facebook and other tech giants. The ever increasing power of computers—the exponential increase in computing capability that is captured by what is known as Moore’s law—also has a part in the new success of these systems. So does the development of enormously large data sets. With better processing capabilities and more data to crunch, connectionist systems can learn far more effectively than we might have once thought.

Over the years the AI community has seesawed between favoring these kinds of bottom-up solutions to machine learning and alternative top-down approaches. Top-down approaches leverage what a system already knows to help it learn something new. Plato, as well as so-called rationalist philosophers such as René Descartes, believed in a top-down approach to learning—and it played a big role in early AI. In the 2000s such methods also experienced their own rebirth in the form of probabilistic, or Bayesian, modeling.

Like scientists, top-down systems start out by formulating abstract and wide-ranging hypotheses about the world. The systems then make predictions about what the data should look like if those hypotheses are correct. Also like scientists, the systems then revise their hypotheses, depending on the outcome of those predictions.

NIGERIA, VIAGRA AND SPAM

BOTTOM-UP METHODS are perhaps the most readily understood, so let’s consider them first. Imagine that you are trying to get your computer to separate important messages from the spam that arrives in your in-box. You might notice that spam tends to have certain distinguishing characteristics: a long list of recipient addressees, an originating address in Nigeria or Bulgaria, references to $1-million prizes or perhaps mention of Viagra. But perfectly useful messages might look the same. You don’t want to miss the announcement that you have earned a promotion or an academic award.

If you compare enough examples of spam against other types of e-mails, you might notice that only the spam tends to have qualities that combine in certain telltale ways—Nigeria, for instance, plus a promise of a $1-million prize together spell

Illustration by Jen Christiansen

trouble. In fact, there might be some quite subtle higher-level patterns that discriminate between the spam messages and the useful ones—misspellings and IP addresses that are not at all obvious, for example. If you could detect them, you could accurately filter out the spam—without fear of missing a notice that your Viagra has shipped.

Bottom-up machine learning can ferret out the relevant clues to solve this kind of task. To do this, a neural network must go through its own learning process. It evaluates millions of examples from huge databases, each labeled as spam or as an authentic e-mail. The computer then extracts a set of identifying features that separate spam from everything else.

In a similar way, the network might inspect Internet images labeled "cat," house," "stegosaurus," and so on. By extracting the common features in each set of images—the pattern that distinguishes all the cats from all the dogs—it can identify new images of a cat, even if it has never seen those particular images before.

One bottom-up method, called unsupervised learning, is still in its relative infancy, but it can detect patterns in data that have no labels at all. It simply looks for clusters of features that identify an object—noses and eyes, for example, always go together to form a face and differ from the trees and mountains in the background. Identifying an object in these advanced deep-learning networks takes place through a division of labor in which recognition tasks are apportioned among different layers of the network.

An article in *Nature* in 2015 demonstrated just how far bottom-up methods have come. Researchers at DeepMind, a company owned by Google, used a combination of two different bottom-up techniques—deep learning and reinforcement learning—in a way that enabled a computer to master Atari 2600 video games. The computer began knowing nothing about how the games worked. At first, it made random guesses about the best moves while receiving constant feedback about its performance. Deep learning helped the system identify the features on the screen, and reinforcement learning rewarded it for a high score. The computer achieved a high proficiency level with several games; in some cases, it performed better than expert human players. That said, it also completely bombed on other games that are just as easy for humans to master.

The ability to apply AI to learn from large data sets—millions of Instagram images, e-mail messages or voice recordings—allows solutions to problems that once seemed daunting, such as image and speech recognition. Even so, it is worth remembering that my grandson has no trouble at all recognizing an animal or responding to a spoken query even with much more limited data and training. Problems that are easy for a human five-year-old are still extremely perplexing to computers and much harder than learning to play chess.

Computers that learn to recognize a whiskered, furry face often need millions of examples to categorize objects that we can classify with just a few. After extensive training, the computer might be able to identify an image of a cat that it has never seen before. But it does so in ways that are quite different from human generalizations. Because the computer software reasons differently, slipups occur. Some cat images will not be labeled as cats. And the computer may incorrectly say an image is a cat, although it is actually just a random blur, one that would never fool a human observer.

ALL THE WAY DOWN

THE OTHER APPROACH to machine learning that has transformed AI in recent years works in the opposite direction, from the top down. It assumes that we can get abstract knowledge from concrete data because we already know a lot and especially because the brain is already capable of understanding basic abstract concepts. Like scientists, we can use those concepts to formulate hypotheses about the world and make predictions about what data (events) should look like if those hypotheses are right—the reverse of trying to extract patterns from the raw data themselves, as in bottom-up AI.

APPLYING AI TO LEARN FROM LARGE DATA SETS—MILLIONS OF INSTAGRAM IMAGES OR E-MAIL MESSAGES—ALLOWS SOLUTIONS TO PROBLEMS THAT ONCE SEEMED DAUNTING.

This idea can best be illustrated by revisiting the spam plague through considering a real case in which I was involved. I received an e-mail from the editor of a journal with a strange name, referring specifically to one of my papers and proposing that I write an article for the publication. No Nigeria, no Viagra, no million dollars—the e-mail had none of the common indications of a spam message. But by using what I already knew and thinking in an abstract way about the process that produces spam, I could figure out that this e-mail was suspicious.

To start, I knew that spammers try to extract money from people by appealing to human greed—and academics can be as greedy to publish as ordinary folks are for $1-million prizes or better sexual performance. I also knew that legitimate "open access" journals have started covering their costs by charging authors instead of subscribers. Also, my work has nothing to do with the journal title. Putting all that together, I produced a plausible hypothesis that the e-mail was trying to sucker academics into paying to "publish" an article in a fake journal. I could draw this conclusion from just one example, and I could go on to test my hypothesis further by checking the editor's bona fides through a search-engine query.

A computer scientist would call my reasoning process a "generative model," one that is able to represent abstract concepts, such as greed and deception. This same model can also describe the process that is used to come up with a hypothesis—the reasoning that led to the conclusion that the message might be an e-mail scam. The model lets me explain how this form of spam works, but it also lets me imagine other kinds of spam or even a type that differs from any I have seen or heard about before. When I receive the e-mail from the journal, the model lets me work backward—tracing step by step why it must be spam.

SCIENTIFIC AMERICAN ONLINE Read more about how researchers use Bayesian methods at ScientificAmerican.com/jun2017/gopnik

Generative models were essential in the first wave of AI and cognitive science in the 1950s and 1960s. But they also had limitations. First, most patterns of evidence might, in principle, be explained by many different hypotheses. In my case, it could be that the e-mail really was legitimate, even though it seemed unlikely. Thus, generative models have to incorporate ideas about probability, one of the most important recent developments for these methods. Second, it is often unclear where the basic concepts that make up generative models come from. Thinkers such as Descartes and Noam Chomsky suggested that you are born with them firmly in place, but do you really come into this world knowing how greed and deception lead to cons?

Bayesian models—a prime example of a recent top-down method—attempt to deal with both issues. Named after 18th-century statistician and philosopher Thomas Bayes, they combine generative models with probability theory using a technique called Bayesian inference. A probabilistic generative model can tell you how likely it is that you will see a specific pattern of data if a particular hypothesis is true. If the e-mail is a scam, it probably appeals to the greed of the reader. But of course, a message could appeal to greed without being spam. A Bayesian model combines the knowledge you already have about potential hypotheses with the data you see to let you calculate, quite precisely, just how likely it is that an e-mail is legitimate or spam.

This top-down method fits better than its bottom-up counterpart with what we know about how children learn. That is why, for the past 15 years, my colleagues and I have used Bayesian models in our work on child development. Our lab and others have used these techniques to understand how children learn about cause-and-effect relationships, predicting how and when youngsters will develop new beliefs about the world and when they will change the beliefs they already have.

Bayesian methods are also an excellent way to teach machines to learn like people. In 2015 Joshua B. Tenenbaum of the Massachusetts Institute of Technology, with whom I sometimes collaborate, Brenden M. Lake of New York University and their colleagues published a study in *Science*. They designed an AI system that could recognize unfamiliar handwritten characters, a job that is simple for people but extremely taxing for computers.

Think of your own recognition skills. Even if you have never seen a character in a Japanese scroll, you can probably tell if it is the same or different from one on another scroll. You can probably draw it and even design a fake Japanese character—and understand as well that it looks quite different from a Korean or Russian character. That is just what Tenenbaum's team members got their software to do.

With a bottom-up method, the computer would be presented with thousands of examples and would use the patterns found in those examples to identify new characters. Instead the Bayesian program gave the machine a general model of how to draw a character: for example, a stroke can go right or left. And after the software finishes one character, it goes on to the next.

When the program saw a given character, it could infer the sequence of strokes that were needed to draw it, and it went on to produce a similar set of strokes on its own. It did so the same way that I inferred the series of steps that led to my dubious spam e-mail from the journal. Instead of weighing whether a marketing scam was likely to lead to that e-mail, Tenenbaum's model guessed whether a particular stroke sequence was likely to produce the desired character. This top-down program worked much better than deep learning applied to exactly the same data, and it closely mirrored the performance of human beings.

A PERFECT MARRIAGE

THESE TWO LEADING APPROACHES to machine learning—bottom up and top down—have complementary strengths and weaknesses. With a bottom-up method, the computer does not need to understand anything about cats to begin with, but it does need a great deal of data.

The Bayesian system can learn from just a few examples, and it can generalize more widely. This top-down approach, though, requires a lot of work up front to articulate the right set of hypotheses. And designers of both types of systems can run into similar hurdles. The two approaches work only on relatively narrow and well-defined problems, such as recognizing written characters or cats or playing Atari games.

Children do not labor under the same constraints. Developmental psychologists have found that young children somehow combine the best qualities of each approach—and then take them much further. Augie can learn from just one or two examples, the way a top-down system does. But he also somehow extracts new concepts from the data themselves, like a bottom-up system. These concepts were not there to begin with.

Augie can actually do much more. He immediately recognizes cats and tells letters apart, but he can also make creative and surprising new inferences that go far beyond his experience or background knowledge. He recently explained that if an adult wants to become a child again he or she should try not eating any healthy vegetables, because they make a child grow into an adult. We have almost no idea how this kind of creative reasoning emerges.

We should recall the still mysterious powers of the human mind when we hear claims that AI is an existential threat. Artificial intelligence and machine learning sound scary. And in some ways, they are. The military is researching ways to use these systems to control weapons. Natural stupidity can wreak far more havoc than artificial intelligence, and we humans will need to be much smarter than we have been in the past to properly regulate the new technologies. Moore's law is an influential force: even if advances in computing result from quantitative increases in data and computer power, rather than conceptual revolutions in our understanding of the mind, they can still have momentous, practical consequences. That said, we shouldn't think that a new technological golem is about to be unleashed on the world. SA

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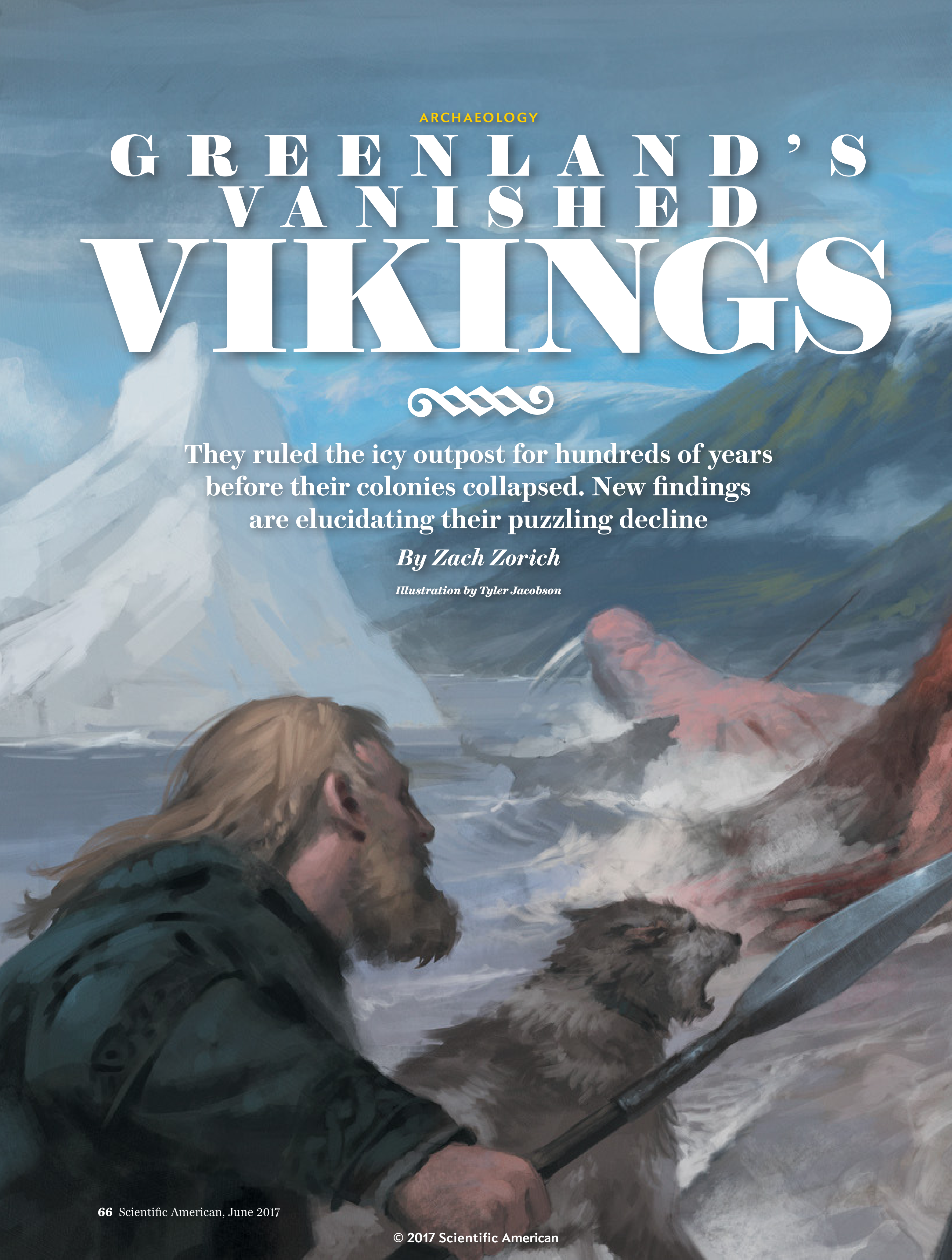
ARCHAEOLOGY

GREENLAND'S VANISHED VIKINGS

They ruled the icy outpost for hundreds of years before their colonies collapsed. New findings are elucidating their puzzling decline

By Zach Zorich

Illustration by Tyler Jacobson



Zach Zorich is a Colorado-based freelance writer. His last feature article for *Scientific American* described how the construction of the Giza pyramids revolutionized Egyptian social organization.

THE YEAR WAS A.D. 1000. A CREW OF VIKINGS TRAVELED NORTH ALONG Greenland's western coast in an open, six-oared boat, headed to the edge of the world as they knew it. With little protection from wind and rain and the frigid saltwater spray, it must have been a miserable trip. Drowning and hypothermia would have been constant threats. Yet at the end of their 15-day voyage, described in a historical text, the Vikings would arrive at the beaches of what is now called Disko Bay, where the walruses haul themselves out of the water to mate and rest. The animals were easy targets, and their ivory tusks fetched a fortune in Europe. The grueling journey paid off handsomely.

For hundreds of years the Vikings, also known as the Norse, ruled this Arctic outpost. They established two thriving colonies that, at their height, included thousands of members. But then in the early to mid-1400s the colonies disappeared.

The classic explanation for their decline holds that settlers stubbornly clung to the European way of life, farming pasturelands for cows and sheep, even though it was not well suited to Greenland's cold climate and rocky terrain. Mounting archaeological evidence indicates that the reasons for the collapse of the Greenland Viking colonies were far more complex than that, however. For one thing, the Vikings there did in fact depart from European tradition to adapt to the unique challenges of Greenland, taking up walrus hunting, for example. These adaptations allowed the settlements to persevere through climate change that made their already hostile environment even harder to inhabit. Ultimately, though, even these new practices could not protect the Greenland Vikings from large-scale political and cultural shifts that marginalized them and may have posed a greater threat than climate change did.

The Vikings might never have settled Greenland had it not been for a series of murders committed by the famously fearsome Erik the Red, whose exploits were chronicled in the Icelandic Sagas. Erik and his father had been small landowners in Norway before they were exiled to Iceland for their involvement in some slayings, according to the sagas. Not one to learn a lesson the first time, Erik was exiled again a number of years later, when he killed several people during disputes with two different neighbors. But this time there was no other known land he could move to. And so Erik sailed west with little knowledge of what lay beyond the sea in front of him and found the landmass that came to be known as Greenland. After his exile ended, in 985, he returned to Iceland, where he and a group of settlers packed their belongings into 25 longships and set out for the new land. Only 14 of the ships survived the trip.

Exactly why other Vikings came to Greenland to settle is unclear. Historians and social scientists long thought it was a last resort: all of the good farmland in Iceland and the Faroe Islands was spoken for, they surmised, and the Vikings were desperate to find open space in which to raise livestock. Alternatively, the settlers may have fallen for a marketing ruse. Erik the Red is said to have called the rocky, ice-covered place Greenland to attract more settlers.

Whether it was sheer desperation that motivated them or visions of paradise, the Vikings began to flock to Greenland from Iceland and Europe in an initial wave of migration that took place by about the year 1000. They settled most of the best farmland and harbors. Those who arrived later had to build their farms in more marginal areas. A society started to take

IN BRIEF

After prospering for hundreds of years, the Viking colonies in Greenland were mysteriously abandoned.

Scholars have long viewed their decline as the result of a stubborn refusal to adapt their European customs to the conditions of this Arctic land.

Yet recent findings show that the Greenland Vikings did change their ways. The latest evidence suggests that a complex interplay of cultural and political forces abroad brought about their demise.

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ARTIFACTS reveal facets of Viking life in Greenland. A ring and staff from a bishop's grave (*1*) attest to the influence of the Catholic Church on the colonies. The Greenland Vikings maintained cultural ties to Europe, sharing their fashions (*2*) and customs. But they also carved out an economic niche for themselves by taking up new practices, such as walrus hunting, exporting the ivory tusks to Europe, where they were used for ornaments, including, perhaps, the famed Lewis Chessmen (*3*). The Vikings also met resident Inuit groups, who appear to have carved likenesses of the newcomers in wood (*4*).

shape as these free farmers brought their families to claim any empty land where they could grow grass to feed their sheep and cows. The farms were concentrated in two areas on the island's western coast: the so-called Western Settlement, which was some 800 kilometers south of the walrus hunting grounds at Disko Bay, and the Eastern Settlement, which was another 500 kilometers south of the Western Settlement.

Ruins discovered at Vatnahverfi, located near the southernmost point of Greenland, have helped archaeologists piece together a picture of what these settlements were like. Vatnahverfi appears to have been one of the richer farming areas in the Eastern Settlement. The land there extends like fingers into the ocean. Beyond those narrow, stony beaches, grass carpets the earth, providing good pasture for the sheep today, as it did during Viking times. Piles of moss-covered stones are all that remains of the ancient buildings. Their arrangement shows that the farms were set up like others across Scandinavia and Iceland, with the main farm building at the center of the best pasture surrounded by less desirable grazing land and smaller buildings where people could live when they moved the herds to graze in different places around the farmland. An excavation team led by Konrad Smiarowski, a Ph.D. candidate at Hunter College, identified 47 farmsteads organized around eight farms in Vatnahverfi.

The Viking farms at the site spanned such large areas that they necessitated the construction of smaller structures known as shielings that served as temporary shelters for the herds and as work spaces where farmers could milk the cows, shear the sheep, and process dairy and meat products. Smiarowski's team has found 86 shielings in this region during the past 12 years. Together his findings and those of other teams suggest that the farming community at Vatnahverfi housed between 255 and 533 people.

The farms established the hierarchy that gave Greenland society its foundation, explains Thomas McGovern, an archaeologist who is also at Hunter and has been working at sites in Greenland and elsewhere in the North Atlantic since the 1970s. The elite Vikings who owned the land depended on keeping people there, adds Jette Arneborg of the National Museum of Denmark in Copenhagen. The landowners thus housed the farming families and granted access to the pastures in exchange for a cut of the profits from the livestock products. The colonies thrived under this system, growing to around 3,000 residents at their peak in around 1200 to 1250, Arneborg says.

When climate conditions took a turn for the worse, as they did soon after the settlers arrived, the Greenland Vikings met the challenges head on. Supplying pigs and cattle with enough hay to get through the winter was proving difficult in Greenland, so the farmers switched to raising mostly sheep. In places where the grazing was especially bad, they kept goats—animals that can eat nearly anything. Milk from the sheep and goats replaced cow milk as a staple of their diet. They raised only a few pigs and cattle, mostly for feasting and consumption by the wealthy.

Because the farms were not productive enough to sustain all the settlers, people had to find entirely new sources of food. The garbage deposits left by the Greenlanders showed that they began hunting seals on a large scale soon after they arrived. The Vikings probably hunted seals in the open water of the fjords, using boats and nets to gather the animals into tight groups where they could be speared. They also started hunting caribou and walrus. Exploiting these animals would have required communal hunting by a substantial labor force, with tight coordination between a headman and the rest of the hunting party. The Vikings were in a good position to adopt this new practice, having worked in a similar arrangement on the farms. The organization of the farms provided a framework for managing hunting labor and food resources effectively. The communal hunts, as well as the shift in farming practices, became a unique adaptation to the environment of Greenland.

The Vikings did not create these strategies out of whole cloth. Their innovations seem to have arisen from the know-how that they brought with them from Iceland and Scandinavia. Ecologists call this body of expertise "traditional ecological knowledge," the set of behaviors and technologies that people have honed for generations through contact with the environment. Seal hunting was practiced in the Baltic Sea and Iceland, but those seals belonged to a different species than the ones that were primarily hunted in Greenland. The Vikings may have also gained experience hunting walrus in Iceland. In both cases, the settlers had to adapt their previously known techniques to the unique circumstances they encountered in Greenland.

As the workers were trying to figure out how to fill their bellies, elite landowners were looking for ways to amplify their influence. One way to do this was by building churches and consecrating ground for cemeteries. Farms were spread across the landscape, so central meeting places were crucial for the social life of the settlements. "They had to be a community somehow," Smiarowski says. The churches became a way to bring people together for weddings, funerals and regular services.

The churches also served another function. In 1123 the Catholic Church appointed a priest named Arnald to be the Bishop of Greenland. It was starting to look to Greenland as an economic resource.

As trade between Europe and Greenland increased, the independent settlers began to search for ways to leverage the relationship. They petitioned Haakon IV, the king of Norway, to make Greenland part of his realm. The Greenlanders would pay taxes to Norway, and the king would guarantee that a ship called the *Greenland Carrier* would travel to Greenland every year to buy and sell trade goods. These trade missions kept Greenland part of the European economy and culture. As a result, the Vikings "had the same dresses and the same kind of double-sided [hair] combs" that Europeans wore, Arneborg says.

Trading ships such as the *Greenland Carrier* may have also been transporting goods and people for the Catholic Church. In 1341 the Bishop of Bergen, Norway, sent a priest to Greenland to make a list of the churches there and the property they owned. The Vatican was fond of ivory ornaments, and the bishop may have been in charge of keeping supply lines open between Greenland and the Vatican, explains Mikkel Sørensen, an expert in the history and archaeology of the Greenland Inuit at the University of Copenhagen. Arneborg, for her part, believes that the church was more interested in the money from the ivory trade than the ivory itself. Either way the Norwegian kings controlled what was practically the only supply of ivory in Europe at the time. The relationship seems to have been very

Ties That Bind

Vikings started to flock to Greenland from Iceland and other parts of Europe around A.D. 1000, establishing two colonies, the Eastern Settlement and the Western Settlement. Yet they maintained political and cultural links to Europe. They set up their farms at sites such as Vatnahverfi in the style of Viking farms found across Scandinavia and Iceland, growing grass for their cows and sheep. Still, they had to find new sources of food and income. They began to hunt seals and caribou. And they took small boats up the western coast to Disko Bay to hunt walruses for their ivory tusks. The Vikings exported ivory and furs to Europe via a boat sent from Bergen, Norway. The arrangement worked well until such luxury goods fell out of favor in the European markets.

profitable for everybody for more than a century. Walrus ivory debris has been found at medieval workshop sites from Scandinavia to Ireland and Germany, showing that demand for it extended across Europe.

Dramatic changes were coming, however. Analyses of sediment cores from the seafloor northwest of Iceland show that around 1250 the climate began to enter a phase called the Little Ice Age. During this time temperatures dropped and weather systems became erratic. Storms grew more frequent and severe. The long ocean voyage between Iceland and Greenland would have become more treacherous and might have discouraged fortune seekers who did not want to risk losing their ships, McGovern surmises.

Although the Vikings' Greenland settlements lasted for about another 200 years, many scholars have viewed the onset of the Little Ice Age as the beginning of their end. Unwilling or unable to change with the times, these experts supposed, the colonies started to crumble.

But McGovern is not convinced that the bad weather was enough to do the settlements in. "By the time the 1250s roll around, the Greenlanders had been there for many years, and it hasn't all been warm and cozy," he says, "so they've been through some bad times, and they know the storms come, and sometimes people drown."

Contrary to assumptions that they were stuck in their ways, the Vikings seem to have dealt with these challenges pretty effectively. Bones found in garbage middens at medieval farms across Greenland indicate that they moved to focus even more strictly on raising sheep and goats, which are hardy enough to survive on smaller amounts of grass. Even so, small landowners struggled to feed their herds. They either had to become tenants of the big landowners or sell their land and find a new way to make a living. So they became tenants. And it worked, for a while anyway.

But the world was also changing in ways that did not involve the climate. It may have been the complex interplay of these shifts that doomed the Greenland Viking colonies.

Perhaps most important, world events began to erode their trade in walrus ivory. Ongoing wars between Christians and Muslims in the Middle East had helped make Greenland a major player in the ivory trade. The wars led to rampant piracy on the Mediterranean Sea, which stymied the transport of elephant ivory from Africa and Asia to Europe. As elephant ivory became rarer and more valuable in Europe, the 2,800-kilometer voyage to Greenland for walrus ivory became a more profitable option than the shorter but more dangerous routes to Africa and Asia. Yet when the wars in the Middle East subsided and trade with Africa and Asia reopened, Europe may have

SOURCES: ROWAN JACKSON AND ANDREW DUGMORE *University of Edinburgh (trade routes)*

Map by Michael Newhouse

STONE RUINS of Hvalsey Church, built on a farmstead in the Vikings' Eastern Settlement, are thought to date to the 14th century.

turned its attention away from Greenland, explains Søren Sindbæk, a professor of medieval archaeology at Aarhus University in Denmark.

At the same time, shifting fashions may have lowered demand for ivory and other luxury goods. Ivory went from being a rare and sought-after material for jewelry and other decorations to falling out of favor with the elites starting around 1200. This trend seems to have coincided with a change in the type of trade the European markets were interested in, McGovern notes. Trade shifted from high-prestige goods such as gold, furs and ivory to high-bulk, low-value goods such as the bales of dried fish and rolls of woolen cloth that Iceland produced. "The walrus ivory is only valuable if people say it is," he says. In contrast, fish and wool are food and clothing that can provision armies.

This transition marked a fundamental change in the way the European economy worked. "Greenlanders were stuck in the old economy," McGovern observes. "Icelanders are much more positioned to take advantage of the expanding trade in bulk goods, and that's what they do."

The onslaught of the Black Death in Europe further challenged Greenland's economy. Between 1346 and 1353, roughly a third of Europe's population died of the plague. Norway was particularly hard hit, losing some 60 percent of its people. It sent no ships after 1369, preventing the Vikings from selling their furs and walrus ivory, demand for which was already declining.

New threats also met the Greenland Vikings on their home turf: invaders from the north. When Erik the Red settled his farm, it seemed that no other people lived in Greenland. It is possible that a group known as the Paleoeskimos, or the Dorset people, did dwell there, but they would have resided far to the north of Disko Bay, out of sight in uncharted territory, as far as the Vikings were concerned. Later, in the 1300s, an Inuit group known to scholars as the Thule began making its way down the coast in skin-covered boats called *umiaks* toward the Vikings' walrus hunting grounds.

The Thule specialized in whaling, and their *umiaks* organized Thule society in the same way that farms organized the Vikings. Each *umiak* could seat about 15 people, with the owner of the boat taking the role of leader, Sørensen explains. They were probably on whaling voyages when they first met the Vikings at the Disko Bay hunting grounds. A 14th-century document called *Description of Greenland* indicates that the encounter was not a peaceful one: the Vikings met the Thule with their typical diplomacy, meaning that they fought them.

Yet for all their fierceness, the Vikings may have found themselves on the losing end of that battle. By roughly 1350 they left

CINDY HOPKINS *Alamy*

the Western Settlement, which was closer than the Eastern Settlement to the hunting grounds at Disko Bay. Why they abandoned the 80 farms there, and the easier access to walrus, is open for debate. But according to McGovern, all the references the sagas make to the Inuit in Greenland involve combat. One likely reason the Vikings vacated that area, then, is that they could not defend themselves against the invading Thule.

THE WORSENING CLIMATE, THE CHANGING POLITICS AND fashion, the spread of plague and the arrival of invaders together formed a set of problems that the Vikings had not seen before. They found themselves in a situation that went beyond their traditional ecological knowledge. As a result, the Greenlanders faced difficult decisions about what to do to keep their society going. Would they double down on the tried-and-true strategies, such as communal hunting, that allowed their ancestors to survive the Arctic climate? Or would they develop novel adaptations to the new challenges they encountered? According to Arneborg and McGovern, the archaeological evidence suggests that the Greenlanders refocused their efforts on keeping the hunts going and doing what had worked so well when the colonies were first settled, and they kept doing so right up to the end.

Wealthy landowners even continued upgrading their churches almost until the colonies were abandoned, which might have been part of the problem. "If you invest in buildings, in a church, it fixes you to a location," says Marten Scheffer, an applied mathematician at Wageningen University in the Netherlands. Scheffer has devoted a large part of his career to mathematical models of the causes of societal collapse. When a society gets close to a tipping point, he says, it becomes slower to recover from adversities, even small ones. Whatever gives that society resilience—food, wealth, technology—becomes scarce, hampering adaptation. But another thing that slows down recovery is what Scheffer calls "sunk-cost effects"—buildings and equipment that allow the society to get what it needs from the environment. In the case of the Vikings, this not only would have meant the boats and equipment for hunting seals and walrus but also would have included the parts of their culture that linked them to Europe, such as new churches. The effort that has gone into making buildings and equipment factors into how likely people are to leave them behind even when it would make economic sense to do so. "They tend to stay too long in the same place," Scheffer says, and "in the end, they leave. It takes quite a long time, and then they leave massively." He thinks this may have been what happened to the Vikings.

Could the colonies have made different choices that might have allowed them to hang on? Some experts have suggested that the Vikings should have adopted a more Inuit-like way of life. After all, the Inuit peoples managed just fine and live in Greenland to this day. Yet that argument overlooks the reason that the Vikings came there in the first place. If they had wanted to make their fortunes selling walrus tusks to the European market, the Inuit vision of becoming captain of one's own *umiak* may not have held the same appeal for them. "They were on the fringe of the whole European system, so it was very important to be connected back by trading," Sørensen says. "They wanted to be real Europeans up there. It's very much the question of identity."

By the mid-1400s the choices may have been stark. Even the landowners with the largest farms and the best churches would have had to ask themselves, if they were faced with death by starvation or combat, why not pack up the farm, get on a ship and sail back to Europe? The answer may be that their prospects there might have been even worse: they would have been returning to a Europe that was part of a new economic system with no place for seal and walrus hunters. The Vikings may have conquered Greenland, but in the end, forces in the world beyond its icy shores conquered them. SA

MORE TO EXPLORE

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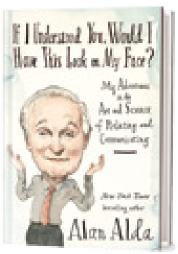
scientificamerican.com/magazine/sa

By Andrea Gawrylewski

If I Understood You, Would I Have This Look on My Face?
My Adventures in the Art and Science of Relating and Communicating

by Alan Alda.
Random House, 2017 ($28)

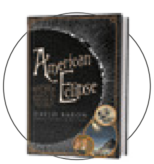


ALAN ALDA (*left*) visits CERN near Geneva in 2012 and talks to physicist Steven Goldfarb (*right*).

Alda is practiced at getting scientists to explain their research to a broad audience. The longtime *M*A*S*H* actor hosted *Scientific American Frontiers* (produced in association with this magazine) on PBS for more than 11 years. The program took viewers to research sites and inside laboratories, with Alda as their inquisitive guide. In this book, he proposes improv classes for scientists in which they participate in games that require close observation, active listening and mirroring emotions. Afterward, the scientists become more at ease and in touch when addressing a group. Alda also discusses the science behind what makes a good communicator and offers advice from experts on effective storytelling, all in hopes of better conveying research to the public. —*Andrea Marks*

American Eclipse: A Nation's Epic Race to Catch the Shadow of the Moon and Win the Glory of the World

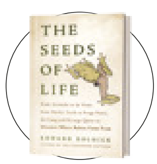
by David Baron. Liveright, 2017 ($27.95)



Total eclipses in which the moon completely obscures the sun are rare, only gracing any given part of the planet once every 360 years on average (at least 12 states in the U.S. will be able to witness one in August). In antiquity, they were often interpreted as omens of doom, but the eclipse that occurred over the American West in 1878 signified the young nation's arrival as a global scientific power. Baron, an award-winning journalist, uses exhaustive research to reconstruct a remarkable chapter of U.S. history. He tells the surprising story of how the eclipse spurred three icons of the 19th century—inventor Thomas Edison, planet hunter James Craig Watson, and astronomer and women's-rights crusader Maria Mitchell—to trek into the wild Western frontier to observe it. —*Lee Billings*

The Seeds of Life: From Aristotle to da Vinci, from Sharks' Teeth to Frogs' Pants, the Long and Strange Quest to Discover Where Babies Come From

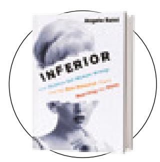
by Edward Dolnick. Basic Books, 2017 ($28)



Where do babies come from? People pondered this question for millennia, yet it was not until 1875 that an answer finally materialized. Science journalist Dolnick documents the centuries-long hunt for answers by intrepid scientists who charged forward, only to be drawn, time and again, into misguided hypotheses and off-base conclusions. Some spent decades convinced, for example, that tiny, fully formed humans are tucked inside eggs and sperm like an infinite set of Russian nesting dolls. Fights broke out, and sides were chosen, as these scientists circled a truth that was simply too far-fetched for them to grasp. Dolnick weaves a suspenseful tale of discovery, failure and often just plain weirdness while never losing sight of the mystery at hand. —*Catherine Caruso*

Inferior: How Science Got Women Wrong—And the New Research That's Rewriting the Story

by Angela Saini. Beacon Press, 2017 ($25.95)



The Enlightenment brought revolutions in science, philosophy and art while ushering in respect for human reason over religious faith. But the era also created a narrative about women—that they are intellectually inferior to men. Indeed, science itself is an establishment rooted in exclusion, writes science journalist Saini, citing a long history of unrecognized achievement by women scientists: Lise Meitner, Rosalind Franklin and Emmy Noether, to name a few. The process of science is also riddled with inherent biases that have done nothing to improve society's views of women. Neurosexism, for example, is a term that describes scientific studies that fall back on gender stereotypes. New science and awareness are overturning a great deal of flawed thinking, as Saini shows, but there is still a long way to go.

SALVATORE DI NOLFI *Getty Images*

Michael Shermer is publisher of *Skeptic* magazine (www.skeptic.com) and a Presidential Fellow at Chapman University. His next book is *Heavens on Earth.* Follow him on Twitter @michaelshermer

Romance of the Vanished Past

Did an advanced civilization disappear more than 12,000 years ago?

By Michael Shermer

Graham Hancock is an audacious autodidact who believes that long before ancient Mesopotamia, Babylonia and Egypt there existed an even more glorious civilization. One so thoroughly wiped out by a comet strike around 12,000 years ago that nearly all evidence of its existence vanished, leaving only the faintest of traces, including, Hancock thinks, a cryptic warning that such a celestial catastrophe could happen to us. All this is woven into a narrative entitled *Magicians of the Gods* (Thomas Dunne Books, 2015). I listened to the audio edition read by the author, whose British accent and breathless, revelatory storytelling style are confessedly compelling. But is it true? I'm skeptical.

First, no matter how devastating an extraterrestrial impact might be, are we to believe that after centuries of flourishing every last tool, potsherd, article of clothing, and, presumably from an advanced civilization, writing, metallurgy and other technologies—not to mention trash—was erased? Inconceivable.

Second, Hancock's impact hypothesis comes from scientists who first proposed it in 2007 as an explanation for the North American megafaunal extinction around that time and has been the subject of vigorous scientific debate. It has not fared well. In addition to the lack of any impact craters determined to have occurred around that time anywhere in the world, the radiocarbon dates of the layer of carbon, soot, charcoal, nanodiamonds, microspherules and iridium, asserted to have been the result of this catastrophic event, vary widely before and after the megafaunal extinction, anywhere from 14,000 to 10,000 years ago. Further, although 37 mammal genera went extinct in North America (while most other species survived and flourished), at the same time 52 mammal genera went extinct in South America, presumably not caused by the impact. These extinctions, in fact, were timed with human arrival, thereby supporting the more widely accepted overhunting hypothesis.

Third, Hancock grounds his case primarily in the argument from ignorance (because scientists cannot explain X, then Y is a legitimate theory) or the argument from personal incredulity (because *I* cannot explain X, then my Y theory is valid). This is the type of "God of the gaps" reasoning that creationists employ, only in Hancock's case the gods are the "magicians" who brought us civilization. The problem here is twofold: (1) scientists do have good explanations for Hancock's X's (for example, the pyramids, the Great Sphinx), even if they are not in total agreement, and (2) ultimately one's theory must rest on positive evidence in favor of it, not just negative evidence against accepted theories.

Hancock's biggest X is Göbekli Tepe in Turkey, with its megalithic, T-shaped seven- to 10-ton stone pillars cut and hauled from limestone quarries and dated to around 11,000 years ago, when humans lived as hunter-gatherers without, presumably, the know-how, skills and labor to produce them. Ergo, Hancock concludes, "at the very least it would mean that some as yet unknown and unidentified people somewhere in the world, had already mastered all the arts and attributes of a high civilization more than twelve thousand years ago in the depths of the last Ice Age and had sent out emissaries around the world to spread the benefits of their knowledge." This sounds romantic, but it is the bigotry of low expectations. Who is to say what hunter-gatherers are or are not capable of doing? Plus, Göbekli Tepe was a ceremonial religious site, not a city—there is no evidence that anyone lived there. Moreover, there are no domesticated animal bones, no metal tools, no inscriptions or writing, and not even pottery—all products that much later "high civilizations" produced.

Fourth, Hancock has spent decades in his vision quest to find the sages who brought us civilization. Yet decades of searching have failed to produce enough evidence to convince archaeologists that the standard timeline of human history needs major revision. Hancock's plaint is that mainstream science is stuck in a uniformitarian model of slow, gradual change and so cannot accept a catastrophic explanation.

Not true. From the origin of the universe (big bang), to the origin of the moon (big collision), to the origin of lunar craters (meteor strikes), to the demise of the dinosaurs (asteroid impact), to the numerous sudden downfalls of civilizations documented by Jared Diamond in his 2005 book *Collapse,* catastrophism is alive and well in mainstream science. The real magicians are the scientists who have worked this all out. SA

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Illustration by Izhar Cohen

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.

Food Fright!

Spiders eat a ridiculous amount of stuff (mostly insects, thankfully)

By Steve Mirsky

The United Nations puts the current population of planet Earth at around 7.5 billion people. Seems like a large number. But there are way more spiders. By the way, now would be a good time to stop reading if you suffer from arachnophobia.

The April issue of the journal *The Science of Nature* featured a study that tried to determine how much prey the world's spider population puts away annually. The work was done by Martin Nyffeler of the University of Basel in Switzerland and Klaus Birkhofer of Sweden's Lund University and Germany's Brandenburg University of Technology Cottbus-Senftenberg.

Switzerland and Germany are places that have a lot of spiders. So is any given forest. And the Arctic tundra. And your house. Because almost every place is a place that has a lot of spiders. American Museum of Natural History arachnologist Norman Platnick once wrote, "Wherever you sit as you read these lines, a spider is probably no more than a few yards away." As most spiders have eight eyes, it's probably looking at you, too.

Back to Nyffeler and Birkhofer. Just as you need to know how many people are coming to dinner before you know how much food to prepare, the spider speculators needed to come up with an estimate for the planet's spider population before they could try to determine how much all those spiders ate. They perused the known literature and found 65 previous publications tallying the biomass of spiders in seven particular habitats, ranging from grasslands to farms to deserts to the aforementioned forests and tundra. They pooled the data (if you have a pool, it's got spiders) and came up with 25 million metric tons of spiders worldwide.

The researchers did not report numbers of individuals represented by their gross (and I mean that) tonnage. So I did a rough calculation: 25 million metric tons (total spider weight) divided by an itsy-bitsy bit (the weight of the average spider) comes out to eleventy bazillion spiders. More or less.

The spider-men then used two techniques to count up what spiders collectively eat. The first method had them simply compute how much prey all the world's spiders would need to perform their necessary life tasks, such as climbing up waterspouts, trying to get flies to check out their parlors, and sitting down beside hungry young women parked on tuffets. That approach led them to a figure of about 700 million metric tons annually. Which they downgraded to only 460 million metric tons, assuming that spiders would avoid hunting on the estimated one third of days that included precipitation—said spiders instead preferring to wait until out came the sun and dried up all the rain.

Method two had the arachnophiliacs round up "published studies of the annual prey kill of spider communities in various biome types." Eighteen previous assessments in various biomes offered enough raw data to place the annual prey amount in a range of 400 million to 800 million metric tons. Which means the two estimation procedures arrive in the same ballpark. (Not League Park, home to Major League Baseball's 1899 Cleveland Spiders, who crawled to a wretched record of 20–134.)

Much of the press coverage of this study noted that the world's spiders could consume every person on Earth (less than 300 million metric tons total) and still be hungry. But spiders do not show any predilection for human flesh, preferring the taste of insects and another small beastie called collembola, or springtail. So counting on spiders for population reduction is a bad plan.

In fact, Nyffeler and Birkhofer avoided talk of humans as food, although they did cite a 1958 paper that claimed that British spiders ate more weight in insects than the combined weight of all Britons. Keep calm and nom, nom, nom.

The researchers actually hoped "that these estimates and their significant magnitude [would] raise public awareness and increase the level of appreciation for the important global role of spiders in terrestrial food webs." And that their work would "emphasize the important role that spider predation plays" in controlling "many economically important pests and disease vectors."

So when you see a spider in your home, you could stomp it. Or put it outside. Or you could thank it and wish it bon appétit! 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

JUNE

1967 Cosmic Radiation and TV "Snow"

"It now appears that radio astronomers have discovered another basic cosmological phenomenon that, like the recession of the galaxies, provides a view of the universe on a truly universal scale. It is low-energy cosmic radio radiation that apparently fills the universe and bathes the earth from all directions. Intense enough to be received by conventional radio telescopes, it has undoubtedly been detected, but not recognized, for years; indeed, it accounts for some of the 'snow' seen on a television screen. When it was discovered by Arno A. Penzias and Robert W. Wilson of the Bell Telephone Laboratories about two years ago, they realized that it could not have originated in the earth's atmosphere or in our galaxy. It did fit in well, however, with an earlier suggestion by Robert H. Dicke of Princeton University that one ought to be able to detect a new kind of cosmic radio radiation: a 'primeval fireball' of radiation surviving from the earliest days of the universe, when the universe was enormously hot and contracted. The theory and observation of this primeval fireball has been the subject of considerable work and excitement for us.—P.J.E. Peebles and David T. Wilkinson"

1917 Invasive Species

"American Gray Squirrels, introduced into Richmond Park, near London, have spread into the adjacent country and proved such a pest that the authorities are taking measures to exterminate them. They not only drive away the native red squirrel, but work great damage in gardens and orchards."

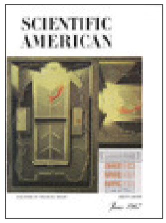
The gray squirrel had been introduced to England more than 40 years earlier.

Underground Warfare

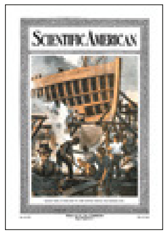
"In this war, mining operations have at times developed into commendable engineering undertakings on the Western front. After the explosion of the mine charges, craters have been formed which could readily accommodate a six-story building. While a tunnel is being driven under 'No Man's Land' toward the enemy lines, the enemy is usually driving a tunnel toward one's own lines. Various devices have been drafted into the service of the sappers for the purpose of detecting and locating enemy mining operations, among them a modified form of stethoscope of the type depicted in our illustration, and super-sensitive electric microphones. The service is as hazardous as any to be found on land or water or in the air, for at any moment the sapper is apt to be blown to pieces or buried alive by enemy counter-measures."

1917: War underground was a grim contest, where silence equaled life.

SCIENTIFIC AMERICAN, VOL. CXVI, NO. 23; JUNE 9, 1917



1967



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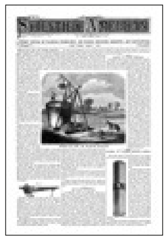


1867

The Modern Cow

"An electrically charged rod for driving rebellious cattle is being introduced upon some of the ranches in western Texas, according to recent reports. It is understood that the rod or prod consists of four small dry cells, a step-up induction coil, a push button and suitable electrodes for applying the high-tension current to the animal. For driving cattle into dipping vats, branding pens and other enclosures, the electric prod is said to be especially suited."

1867 Suez Canal Doubts

"The prospects for a speedy completion of the Suez Canal are not very flattering. From recent and trustworthy reports, it appears that the maritime canal has been partially excavated as far as Ismaileh [in Egypt], a distance of 48 miles, or just half the total length. Great engineering difficulties must be overcome before the task will be successfully completed. The proposed route passes through high drift sands which when once excavated, it would seem, must continue to be an endless source of trouble and expense. At the present rate of progress fully five years must pass before it, as a commercial highway, begins to repay the funds which its protracted construction has absorbed."

Put the Milk in the Fridge

"It is stated that dairywomen have discovered, but philosophers have not explained the reason, that milk suddenly cooled after being drawn from the cow will keep much longer than otherwise. The cheap, artificial methods of reducing temperature in three or four minutes to any desired point, may yet find a general and very useful application in milk dairies, although its effect upon the production of butter is questionable."

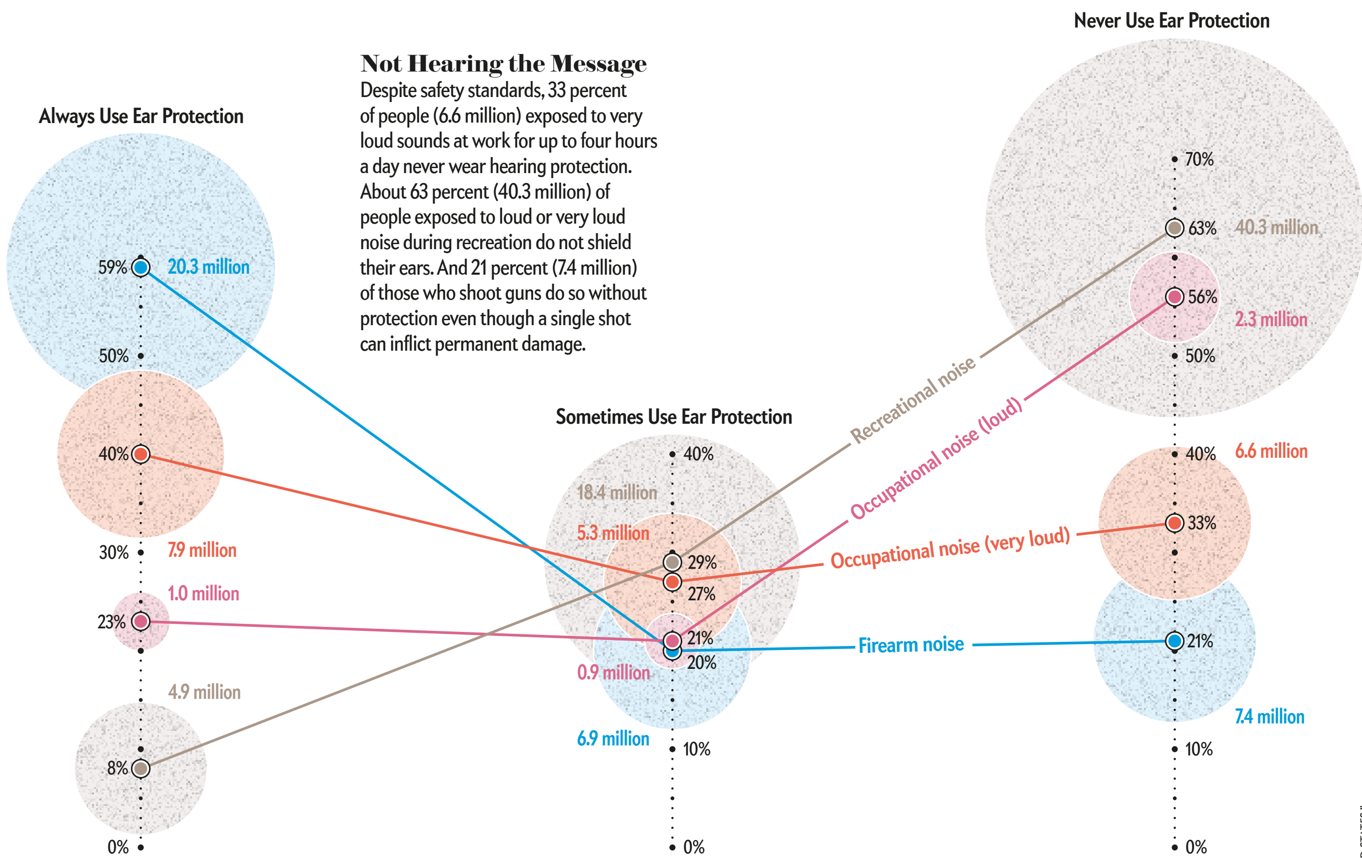
Sounds Like Trouble

Millions of people do not protect themselves against dangerously loud noise

Modern life can be deafening. Yet even though many people know that they should use earplugs or earmuffs when mowing the lawn or partying at the club, they do not do so, according to a sweeping analysis by Harrison Lin, an ear surgeon at the University of California, Irvine, Medical Center and his colleagues. They also found that a large percentage of Americans who work at very loud jobs do not protect their ears. Given safety guidelines, that is concerning. Perhaps the biggest surprise is that one in five people in their 20s now has some hearing loss, probably because he or she is cranking up the volume while wearing earbuds for music or video games. "Our ears have not evolved to handle such trauma," Lin says. *—Mark Fischetti*

Not Hearing the Message

Despite safety standards, 33 percent of people (6.6 million) exposed to very loud sounds at work for up to four hours a day never wear hearing protection. About 63 percent (40.3 million) of people exposed to loud or very loud noise during recreation do not shield their ears. And 21 percent (7.4 million) of those who shoot guns do so without protection even though a single shot can inflict permanent damage.

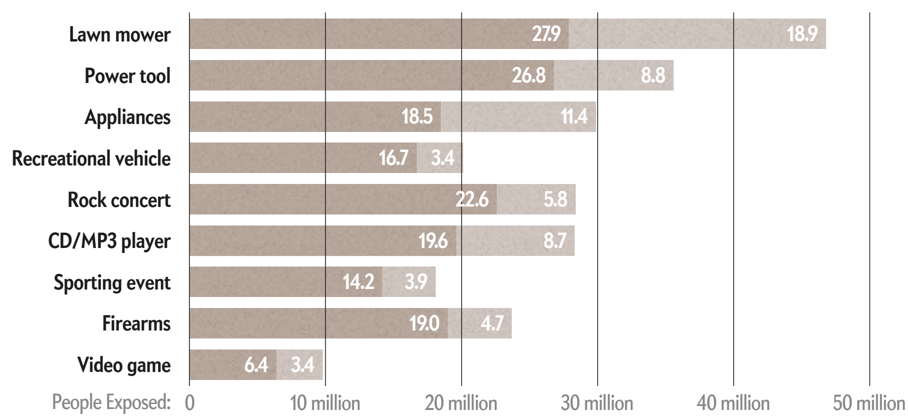


Home and Play

Mow the lawn. Turn on the food processor. Crank up the TV. People may not realize that many everyday occurrences can threaten their hearing. Here are the noisiest activities we engage in.

Very loud (must shout to be heard 3 feet away)

Loud (must raise voice to be heard)



SOURCE: "EPIDEMIOLOGY OF FIREARM AND OTHER NOISE EXPOSURES IN THE UNITED STATES," BY JAY M. BHATT ET AL., IN LARYNGOSCOPE. PUBLISHED ONLINE MARCH 16, 2017

Graphic by Pitch Interactive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