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SCIENTIFIC AMERICAN

THE FUTURE OF MONEY

Cryptocurrencies cut banks and governments out of financial networks

Will they fix a flawed system—or could they make it worse?

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THE RACE TO SAVE THE CORALS

Helping them adapt to warmer oceans

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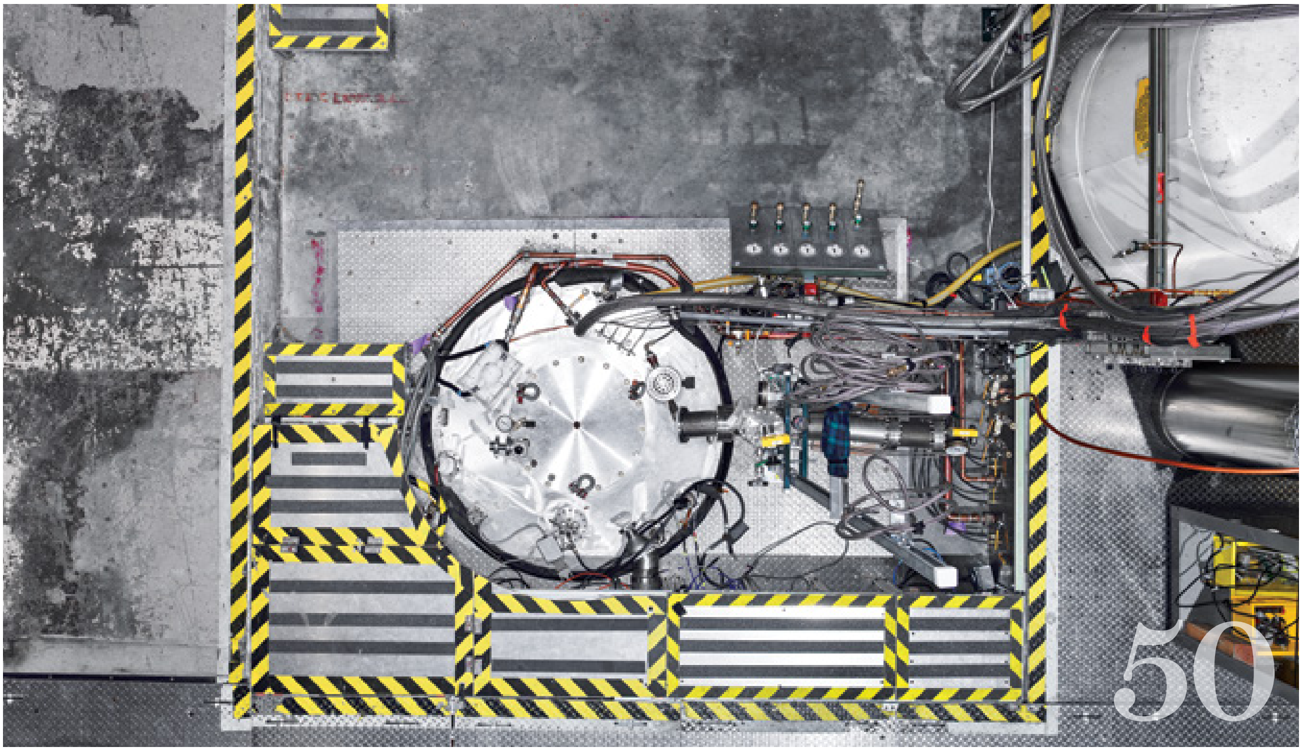
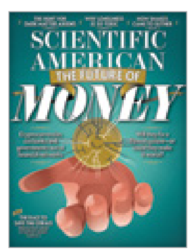


ON THE COVER

Cryptocurrencies such as Bitcoin and Ether have attracted major investment and massive hype, yet much of the public—and many business leaders—find them bewildering. Advocates say digital currencies will change the world for the better. Skeptics say we should tread carefully on this rapidly shifting terrain. **Illustration by Borja Bonaque.**



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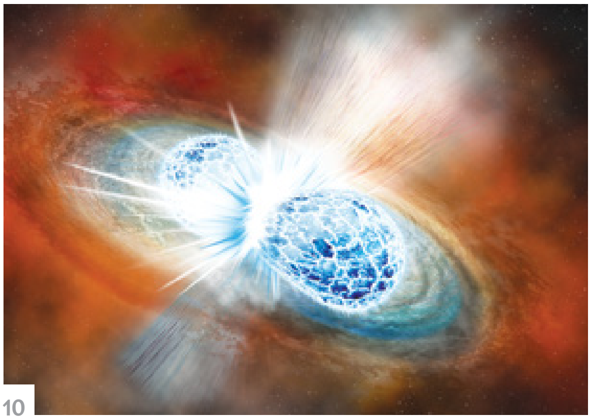

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ON THE WEB

Power in Puerto Rico
Scientific American explores the U.S. territory's severe blackout after Hurricanes Irma and Maria and options to make the island's power grid more resilient.
Go to www.ScientificAmerican.com/jan2018/pr-grid

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FROM THE EDITOR

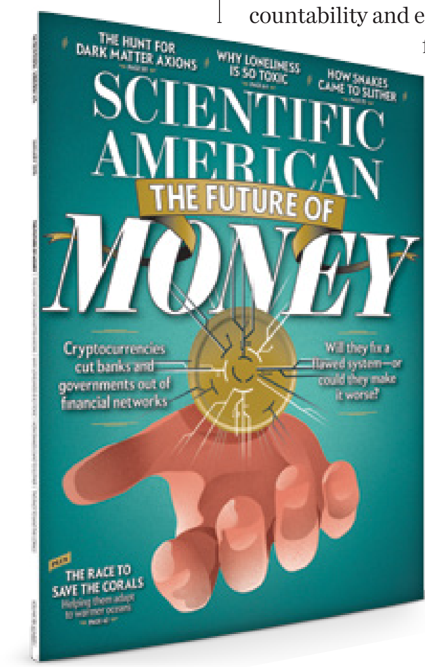
Mariette DiChristina is editor in chief of *Scientific American.* Follow her on Twitter @mdichristina

Science Is …

As a member of an editorial team covering the international endeavor known as science, I often find myself on airplanes. Recently my seatmate was a bright young woman. She spoke passionately about her specialty areas of design and marketing and was also eager to hear about my career.

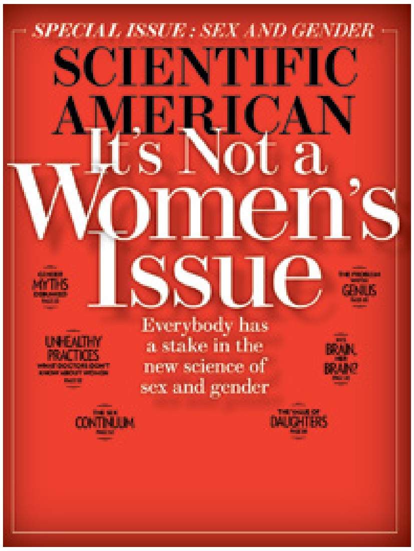
"Science?" she asked. "Why would you write about that instead of, say, culture or design?" I was surprised by the question but quickly realized she was genuinely curious. I told her I couldn't think of anything more exciting than covering science. I tried to explain: science isn't something apart, a bunch of people in lab coats in the ivory towers of academia—it's part of everything, the way we advance discoveries about the workings of our world and create innovations to solve problems and address human needs.

Take money. Today's monetary system has become too complex to regulate and manage. Now big data and the emergence of digital currencies and digital contracts are making it possible to simulate every trade and transaction, the better to understand all potential outcomes. In our special report "The Future of Money," Alexander Lipton and Alex "Sandy" Pentland, both at the Massachusetts Institute of Technology, discuss these phenomena and the rise of digital currencies. Distributed monetary systems, with large alliances of diverse players, could eventually bring transparency, accountability and equity to global finance. Turn to page 26. If you finally want to grasp what people are talking about with Bitcoin and blockchain, page 32 takes you to a wonderfully designed explainer by journalist John Pavlus. On page 38, cultural anthropologist Natalie Smolenski argues that digital currencies are about more than money—they represent the evolution of trust itself.



Elsewhere in the issue, you can see how science is working on new breeding and distribution techniques to save the coral reefs (*page 42*); a way to gain a better understanding of dark matter through the search for whether axion particles exist (*page 50*); a probe into the cause and solutions for the toxic condition of social disconnection, also known as loneliness (*page 64*); and even how to elucidate the long-sought origins of how snakes got their slither (*page 70*). We invite you to dive in. Science awaits.

Illustration by Nick Higgins



September 2017

BALANCE BOARD

In "Welcome to Everybody's Issue" [From the Editor], editor in chief Mariette DiChristina invites ideas to increase gender equality at *Scientific American*. Below her editorial is a list of the 42 members of the magazine's board of advisers, of which six are women. Adding more women scientific leaders to the board seems advisable if the aim is gender parity.

Shana Aelony *via e-mail*

THE EDITORS REPLY: We agree, and we promise to do better.

CHILDREN AND GENDER

"When Sex and Gender Collide," by Kristina R. Olson, discusses children who choose to change gender. From age six until about 16, I wanted to be a boy. I played almost exclusively with boys, was a "tomboy," hated anything "girly" and found girls rather silly. My thinking, to this day, is much closer aligned with the masculine world, but I am definitely a woman, happily married to a man. There is no way a child has the maturity to make the drastic decision to start taking medication to change sex.

Elsa Huntley *Vancouver, B.C.*

OLSON REPLIES: Huntley makes a useful point that, like Charlie in my story, many children who defy sex-based stereotypes are not transgender. She also raises concerns about children "taking medication." The

"Adding more women scientific leaders to *Scientific American*'s advisory board seems advisable if the aim is gender parity."

SHANA AELONY *VIA E-MAIL*

article and my research are focused on early social transitions, which do not involve medical intervention. Instead they include changing one's pronoun and first name. As a researcher who is not a clinician, I do not advocate for or against any intervention. Rather, given that some children undergo social transitions, I study them to learn about gender and well-being. My hope is that one day we will use such research to determine which children are likely to grow up to identify as cisgender or transgender adults—and to then clarify which interventions maximize their well-being.

BUG-EYED REFRACTION

"A Moth's Eye," by Morgen Peck [Advances], reports on research by Shin-Tson Wu of the University of Central Florida and his colleagues on replicating the surface properties of the titular organ to reduce glare on cell-phone screens. Think of the benefit if this technology were used to increase the practical efficiency of solar panels.

Also, the moth's eye uses raised bumps to achieve the desired effect, whereas the researchers produced it using dimples. Have they looked into cleanability with this approach? Such pits may trap dirt.

Alex Smith *Littleton, Mass.*

WU REPLIES: The antireflective coatings have actually already been used in solar cells, and they do indeed help improve energy-harvesting efficiency.

One reason we chose dimples is that they are simpler for mass production. The bump geometry is easier to clean, but because of a special coating, our film exhibits a self-cleaning effect, similar to a lotus leaf.

KNOWLEDGE DENIAL

In "Postmodernism vs. Science" [Skeptic], Michael Shermer associates recent strife on campuses with so-called "postmodern professors," falsely claiming they teach "that there is no truth, that science and empirical facts are tools of oppression by the white patriarchy." It is ironic that a top science magazine would publish an article about an area of scholarship in which the author holds no expertise and that decries scientific knowledge denial while denying knowledge produced in other fields.

Scholars in many fields, including natural scientists, have shown that science has sometimes been used to justify oppression and inequality and that the institution is still struggling with sexism, racism and classism. But they have also explored how it has been central to destigmatization, liberation, progress and survival.

Countering knowledge denial, whether about climate or inequality, is an urgent, shared project. Perhaps *Scientific American* can join us in this endeavor?

Charis Thompson *University of California, Berkeley*

SEX DEVELOPMENT

"Beyond XX and XY," by Amanda Montañez, contributes to intersex visibility by showing that variations from what we typically think of as male or female are natural and numerous. There is just one thing we wish it had shown intersex is *not:* in need of "fixing." The flowchart indicates where surgeries can "modify" the genitals and remove the gonads of children with certain diagnoses but does not point out the serious consequences. A "feminizing" genitoplasty can cause scarring, chronic pain and permanent loss of sexual sensation, and gonadectomy results in sterilization.

Montañez also neglects to note that raising a child as a boy or girl does not require surgery. Children's gender identity may not match the one they were raised with, and it should not be irreversibly enforced.

Kimberly Zieselman *Executive director, interACT: Advocates for Intersex Youth*

MONTAÑEZ REPLIES: The graphic presents only the science of sex and gender as a spectrum, and its scope did not allow for addressing potential health impacts. I included surgery as an optional way a person might shift along that spectrum because many do undergo such procedures. The ways intersex and transgender or non-

binary identities might overlap is another area in which the graphic represents an incomplete picture of a very complex topic.

DISCERNING CURVE

The graph "A Labor U-Turn" in "Women's Work," by Ana L. Revenga and Ana Maria Munoz Boudet, claims to show a link between female labor force participation and countries' per capita GDP with a parabola. I believe it is mathematically unsound. If instead of highlighting a few data points very close to the fitted curve, we colored all of them the same shade, what remained would look like a dart board. I'm also surprised no countries are given with lower than 46 percent female participation.

Thomas A. Conner *Mountain View, Calif.*

THE AUTHORS REPLY: The U curve shows a nonparametric regression of labor force participation. It represents predicted values and is based on publicly available data from the International Labor Organization and the World Bank. Details on the methodology and similar results have been documented in a vast array of papers, including those by economists Claudia Goldin in 1995 and Kristin Mammen and Christina Paxson in 2000. The highlighted dots are only included as an example of different countries along the U curve. And the Y axis is truncated for presentation purposes. There are indeed countries with female participation below the 50 percent line. The countries included or left out of the figure do not change the results.

ERRATA

Clara Moskowitz's review of *Significant Figures,* by Ian Stewart [Recommended], incorrectly referred to Chinese mathematician Liu Hui's third-century A.D. proof of the Pythagorean theorem occurring hundreds of years before Pythagoras' birth. Liu Hui proved the theory independently of Pythagoras but did not predate him.

In "Postmodernism vs. Science" [Skeptic], Michael Shermer wrote that students at Middlebury College "physically attacked" Charles Murray and Allison Stanger. A police investigation determined that several demonstrators against Murray came from outside the campus community. Although the attackers were not identified, Middlebury maintains they were not students.

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A School Is Not a Military Post

Educational facilities are used in armed conflicts—with children inside. We need to stop this

By the Editors

In October 2017 Joy Bishara recounted to United Nations Security Council members her experience of being one of nearly 300 girls abducted in 2014 from a boarding school in Nigeria by the Islamist group Boko Haram. She described to a hushed audience how, after her capture, she jumped from a moving truck and ran through the bush for hours to escape. More than 100 of her classmates remain in captivity.

Before the kidnapping, the girls—and their families—thought that they were in a place dedicated to learning and fun. And with good reason. Schools are meant to be safe zones, not war zones.

All too often, however, that is not the case. Around the world, troops use schools and universities as barracks, observation posts, weapons depots or centers for interrogation. The Global Coalition to Protect Education from Attack, made up of major U.N. agencies and nongovernmental organizations (NGOs), such as Human Rights Watch, has recorded a range of incidents since 2013, including killings, torture, abductions and forced occupations involving students, teachers, and schools and universities in 32 countries. In 2016 alone, the U.N. documented assaults on nearly 500 schools in 18 of the 20 nations designated as conflict countries.

Keeping schools safe is a critical public health issue in strife-torn regions. Educational sites are more than just places for learning to read and count; they can also serve as refuges from the psychological impact of living in a war zone and as centers to furnish health information and instruction in protective measures, such as ways to avoid land mines.

A document known as the Safe Schools Declaration was put forward in 2015 at an international conference in Oslo. Developed in consultation with foreign ministries, defense and education officials, and the International Committee of the Red Cross, among other groups, it stipulates that countries agree to assist victims of attacks on schools; help to keep classes running; investigate violent incidents; promote "conflict-sensitive" education policies to lessen tension among diverse social or ethnic groups; and implement various other measures.

Dozens of countries have signed on, but notably absent on the list are 10 of the 15 members of the U.N. Security Council, including the U.S., China, Russia and the U.K. Officials from these countries have argued that an endorsement increases their commitments beyond what is specified by the Geneva Conventions and other international law.

Signatories are not legally bound by the agreement, but that does not make it by any means an empty statement. A number of signing nations have already taken concrete steps to defend schools. Somalia's defense ministry, for example, has expanded its child protection unit. The education ministry in Afghanistan has cited the declaration in attempting to remove military checkpoints and barracks from school facilities. Nigeria has bolstered school security. Efforts go beyond enlisting government help. NGOs have sought to steer armed opposition groups in Africa, Asia and the Middle East away from occupying schools.

Bringing the issue of keeping schools safe to the international stage has begun to yield real payoffs. Still, the sanctity of a school yard or university campus should be a lesson learned long ago. Protecting schools and teachers is an idea that goes back to the Romans. In A.D. 333 Roman emperor Constantine I told his subjects that professors of literature were relieved of the duty of quartering soldiers in their homes so that "they may more easily train many persons in the liberal arts." Constantine I was not the only Roman ruler to make such proclamations.

The same month that Bishara spoke to the U.N., war-ravaged Yemen, where students have been killed by Saudi air strikes, became the 70th country to sign the Safe Schools Declaration. Every other nation that has yet to do so should follow suit. SA

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Illustration by Gloria Pizzilli

Andrew A. Rosenberg is director of the Center for Science and Democracy at the Union of Concerned Scientists.
Kathleen Rest is executive director of the Union of Concerned Scientists.

War on Science Agencies

Budget cuts and layoffs threaten the nation's health and safety

By Andrew A. Rosenberg and Kathleen Rest

As scientists, we have watched with dismay as senior positions in our federal science agencies remain unfilled, science advisory panels get disbanded and science-based policies are undermined.

But amid this governmental turmoil, another, longer-term development is under way that will affect the lives of everyone in the U.S. and take its toll on others around the world—the loss of critical expertise and capacity in the science agencies of the federal government, including the Environmental Protection Agency, the Centers for Disease Control and Prevention, the Occupational Safety and Health Administration, the National Oceanic and Atmospheric Administration, and the National Aeronautics and Space Administration, among many others.

The science-related cuts proposed by the Trump administration come in programs that deal with issues it opposes ideologically, such as climate change and the use of regulation to reduce pollution. These changes are only part of a larger effort to "deconstruct the administrative state," as former White House Chief Strategist Steve Bannon has put it, and they reflect this administration's uniquely antiscience attitude.

Thousands of highly trained scientists across a huge range of disciplines have worked diligently at the federal level for decades. These government scientists—and we were once among them at different stages in our careers—are critical to the missions of these agencies. These departments are essential to the health and safety of all Americans: protecting public health; ensuring clean air, water, and the safety of our food and consumer goods; protecting our natural resources; and responding to national emergencies of all kinds, from terror attacks to natural disasters.

Budget cuts are only one highly visible strategy. Other executive actions are eroding the capacity of our nation's science agencies. For one thing, Trump officials are taking advantage of additional methods to reduce agency staffing. In the fine print of the president's budget proposal are reductions in staffing by 20 percent or more in some bureaus (the EPA, for example), often with science programs faring the worst. There are buyout offers for eligible employees and staff transfers to shut down specific areas of work. Virtual hiring freezes have been put in place for most civilian agencies. And there are ongoing consultations on how to conduct "reductions in force," otherwise known as layoffs.

We are seeing three troublesome developments unfold: the loss of senior scientists in public service, the dwindling of new scientific and technical talent coming into public service, and the chilling effect on the work of scientists who decide to stay. These issues have come up over and over again in many conversations with our colleagues who have experience as scientists and managers in the federal agencies.

A loss of senior scientists means a downgrading of expertise, institutional knowledge, and perhaps even entire programs and areas of work led by those scientists. This is the science that helps us identify, understand and deal with existing risks, as we anticipate future, unknown risks. Science that spurs innovation and incubates solutions. This loss of decades' worth of experience will take even more time to rebuild, precisely as the complexity and pace of the world's science-based challenges increase.

Then there's the pipeline issue—even more concerning from a public service perspective. All the signals seem to be telling scientists (and nonscientists as well) not to go into federal public service. Talented, highly trained scientists early in their careers are turning away from the idea of joining federal laboratories or divisions. Many of these younger scientists tell us they just assume there are no opportunities with federal agencies, historically one of the major employers of scientists in many fields. Or that they worry about working in the current political climate.

Our agencies need that new talent to draw on in years to come to protect our nation's public health, safety and environment. Government organizations, as with most large groups in any sector, depend on people. Without the influx of new talent, the Trump administration, whether by strategy or ineptitude, or some combination thereof, is threatening to hollow out these vital government bodies to the point at which they will cease to function as we need them to. We can't let this happen. SA

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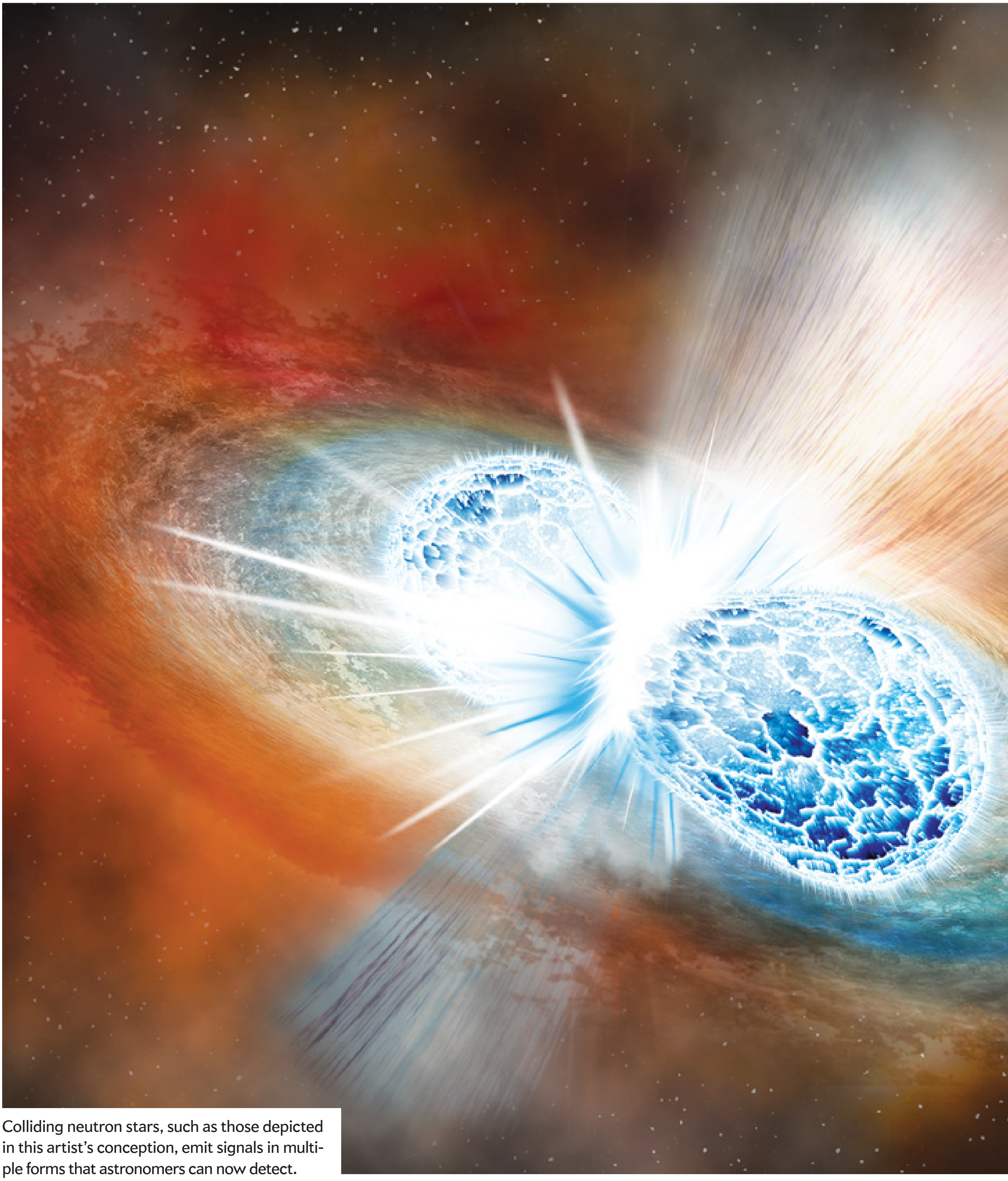
Illustration by Matt Harrison Clough

ADVANCES



Colliding neutron stars, such as those depicted in this artist's conception, emit signals in multiple forms that astronomers can now detect.

INSIDE

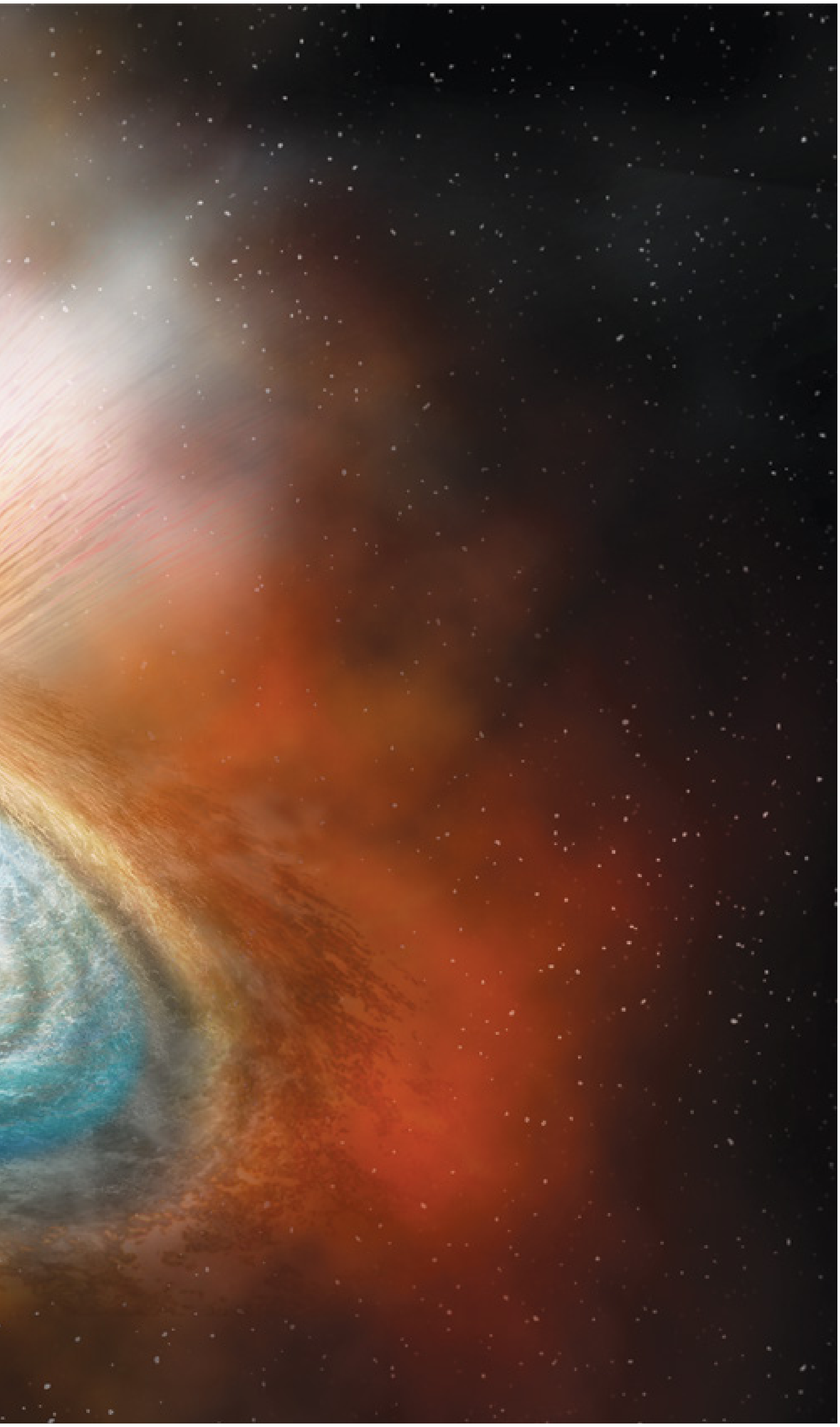


ILLUSTRATION BY ROBIN DIENEL; COURTESY OF CARNEGIE INSTITUTION FOR SCIENCE

ASTRONOMY

Cosmic Messengers

The ability to see, hear and even "taste" extreme astrophysical events is poised to be the next big thing in astronomy

On the morning of August 17 last year, a new era of astronomy dawned with a flash in the sky. The burst of gamma rays, glimpsed by the Fermi Gamma-ray Space Telescope, came from the merger of two neutron stars (extremely dense objects formed when massive stars collapse and die) somewhere in the universe. But gamma rays weren't the only thing the merger produced. Within seconds of Fermi's detection, ripples in spacetime from the merger had echoed through two facilities—the U.S.-based LIGO and the Italy-based Virgo observatories—like rolling thunder after a lightning strike.

These ripples are known as gravitational waves, and detecting them is more like "hearing" than "seeing." Based on the waves' arrival times and strength, astronomers pinpointed their source to a galaxy 130 million light-years from Earth. Next, thousands of scientists around the world mobilized to conduct a coordinated study of the merger's afterglow across the entire electromagnetic spectrum, the range of frequencies from gamma rays to visible light to radio waves.

The payoff was worth it. The observations revealed that the merger had produced vast quantities of elements heavier than iron, confirming a theory that colliding neutron stars are a primary cosmic source of gold and other precious metals. As more such mergers are detected and studied, the collective census could reveal much about the inner workings of neutron stars—city-sized stellar corpses so dense they are on the cusp of collapsing into black holes. Furthermore, by comparing a merger's brightness with the strength of its gravitational waves, astronomers can gauge its exact distance. This knowledge could allow them to probe the nature of dark energy, the mysterious force thought to be accelerating the universe's expansion.

The scientific haul from the first observed neutron star merger, though impressive, could have been even greater. The IceCube observatory in Antarctica looked for ghostly particles called neutrinos from the collision but found none—most likely because these particles were emitted as a beam that missed Earth, according to IceCube's top scientist, Francis Halzen. If detecting light and gravitational waves from the merger was akin to seeing and hearing it, finding neutrinos would have been like tasting it, too.

Researchers call this coordinated approach "multimessenger" astronomy, in which the messengers can be electromagnetic radiation, gravitational waves or subatomic particles. Astronomers pioneered the method in 1987, when they saw light and tasted neutrinos from a supernova detonating in one of the Milky Way's small satellite galaxies. Yet only now can scientists turn an ear to gravitational waves as well, thanks to LIGO and Virgo. The multimessenger approach is in many respects the fulfillment of one of astronomers' wildest dreams—still, it will require wrangling a nightmarish deluge of data from disparate observatories.

"We need to rethink how we do this because we may soon see an event like this merger once per month or even per week," says Vicky Kalogera, an astronomer at Northwestern University and a prominent member of the LIGO team. "This one took [over] people's lives. We all dropped everything, told our families and kids we wouldn't see them until the results were announced." Mergers may begin to pop up so frequently, Kalogera says, that most will simply not be studied in such great detail.

Already IceCube has sparked another global multimessenger follow-up campaign—this time studying the origins of a high-energy neutrino detected on September 22, 2017. That effort tentatively traced the neutrino to a flaring debris disk orbiting a supermassive black hole in the center of a galaxy more than a billion light-years away. This discovery suggests, Halzen says, that such "active galactic nuclei" are the probable sources of most of the high-energy neutrinos and cosmic rays streaming through the universe. "We may be in the home stretch for revealing the origins of cosmic rays, which have been a mystery in astronomy for more than a century," he says.

Astronomers using the Swope telescope at Las Campanas Observatory in Chile pinpointed the source of the neutron star merger on August 17, 2017.

COURTESY OF YURI BELETSKY

There are already several small telescopes dedicated to investigating alerts from LIGO, Virgo and IceCube. But their capabilities pale in comparison to the eagerly awaited Large Synoptic Survey Telescope (LSST), an observatory with an 8.4-meter-wide mirror set to begin a 10-year survey in 2022. Imaging the entire visible sky every few nights from its perch on a Chilean mountaintop, LSST's all-seeing eye could become crucial for probing the optical counterparts of future events heard by LIGO and Virgo—or tasted by IceCube. But "not if there are 10 of them every night—that would destroy our survey!" says LSST chief scientist Tony Tyson. Pinning down the electromagnetic source of any given gravitational wave or neutrino signal would require hours of telescope time and sifting through terabytes of raw data, Tyson explains.

Most astronomers agree that the promise of this field outweighs the challenges, however. "Very rarely do you establish this kind of new frontier in astronomy," says Avi Loeb, an astrophysicist at Harvard University, who has worked extensively on multimessenger approaches. "It seems nature has been almost too kind to us."

—Lee Billings

BIOLOGY

Gluten-Free Wheat?

Genetically engineered grain may be safer for celiacs

A freshly baked roll is as delightful as a soft, fluffy cloud on a summer's day. What gives bread much of its appealing texture is gluten, a group of proteins found in wheat, rye and barley. But in people with a serious autoimmune disorder called celiac disease, gluten damages the small intestine. Many others may have milder gluten intolerance and avoid foods that contain it.

Most gluten-free bread is made from alternative flours such as rice or potato, so it tastes and feels different from wheat bread. Now, however, researchers say that they have found a way to genetically engineer wheat that contains far less of the most troublesome type of gluten—but still has other proteins that give bread its characteristic taste and springiness.

Genetically modified crops are the subject of fierce debate around the world; some countries, including France and Germany, outlaw their cultivation. The biggest concern involves the practice of inserting DNA from one species into another, says Francisco Barro, a plant biotechnologist at the Institute for Sustainable Agriculture in Spain. To avoid this genetic crossover, Barro and his colleagues used the gene-editing technique CRISPR/Cas9

PUBLIC HEALTH

The Deadliest Weapon

Gun terrorism kills more people per attack in high-income countries than any other method

Terrorist bombings garner a lot of news coverage—but gun assaults are often more coldly efficient. Although firearms are used in only a small fraction of terror strikes, a recent study found that on a per-attack basis, guns are four times deadlier than other methods in high-income countries.

"What was surprising was the lethality of firearm attacks compared with other things like explosions and vehicles," says lead author Robert Tessler, a senior fellow at the Harborview Injury Prevention and Research Center in Washington State. Tessler and his colleagues also found that guns are involved in a higher proportion of terror attacks in the U.S. than in other high-income countries. The findings add to an existing body of research that points toward the unique nature of gun violence in the U.S., where overall firearm deaths reached 36,000 in 2015.

After the recent terrorism incidents in San Bernardino, Orlando and London, Tessler wondered whether attackers' methods differed by region. He and his colleagues turned to the University of Maryland's Global Terrorism Database to analyze weapons used and fatalities in each of the 2,817 attacks carried out between 2002 and 2016 in the U.S., Canada, western Europe, Australia and New Zealand.

Firearms were used in fewer than 10 percent of the attacks but accounted for 55 percent of fatalities, the researchers reported online in October in *JAMA Internal Medicine.* They found guns to be significantly deadlier than vehicular, explosive, biological, chemical or incendiary methods. The U.S. accounted for the greatest proportion of firearm attacks—20 percent—followed by the Netherlands, with 14 percent.

The authors did not factor gun ownership laws into their analysis, but other studies have indicated that tougher regulations are associated with fewer deaths. A 2017 review of nearly 50 years of scientific literature found that firearm homicide rates are lower in U.S. states with stricter gun control, and a 2014 study of a nationwide sample of all inpatient minors sent to hospitals for trauma revealed that children are safer in states with tighter firearm restrictions.

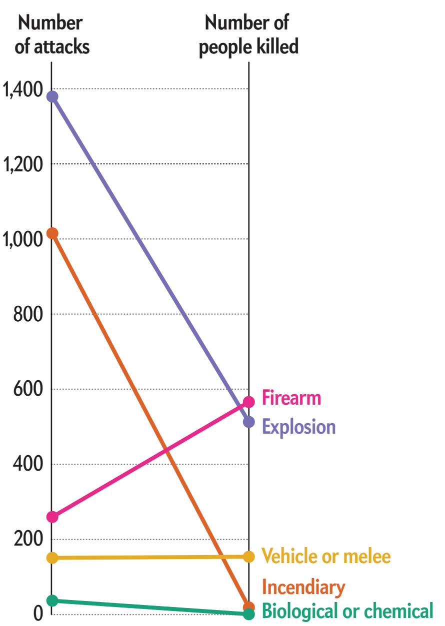
Illustration by Thomas Fuchs

to cut selected genes from a wheat genome.

Their study zeroed in on alpha-gliadins, gluten proteins believed to be wheat's major troublemakers in the immune system. The researchers designed bits of genetic material that directed the scissorlike Cas9 protein to cut out 35 of the 45 alpha-gliadin genes. When the modified wheat was tested in a petri dish, it produced an 85 percent weaker immune response, the team reported online last September in *Plant Biotechnology Journal.*

Wendy Harwood, a crop geneticist at the John Innes Center in England, who was not part of the study, notes that the engineered wheat has a ways to go before it can be turned into anything marketable. "I don't think it's the end of the story," she says. "This is just a really important step in maybe producing something that is going to be incredibly useful." To develop a completely safe strain of wheat for celiac patients, the researchers may need to target more of the gluten genes. Barro says his team is working on that. —*Yasemin Saplakoglu*

Terror Attacks in High-Income Countries, 2002–2016



SOURCES: "USE OF FIREARMS IN TERRORIST ATTACKS: DIFFERENCES BETWEEN THE UNITED STATES, CANADA, EUROPE, AUSTRALIA, AND NEW ZEALAND," BY ROBERT A. TESSLER ET AL., IN *JAMA INTERNAL MEDICINE.* PUBLISHED ONLINE OCTOBER 6, 2017; GLOBAL TERRORISM DATABASE *www.start.umd.edu/gtd*

"I would encourage policy makers to consider this relationship between terrorism and firearms," Tessler says, "not only as part of the national security policy agenda but also as part of the public health policy agenda." —*Rachel Nuwer*

Graphic by Amanda Montañez

EVOLUTION

Sea Smarts

The complex social behaviors of whales and dolphins correspond to bigger brains

Killer whales have group-specific dialects, sperm whales babysit one another's young and bottlenose dolphins cooperate with other species. These social skills are all closely linked with the aquatic mammals' brain sizes, according to a recent study in *Nature Ecology & Evolution.*

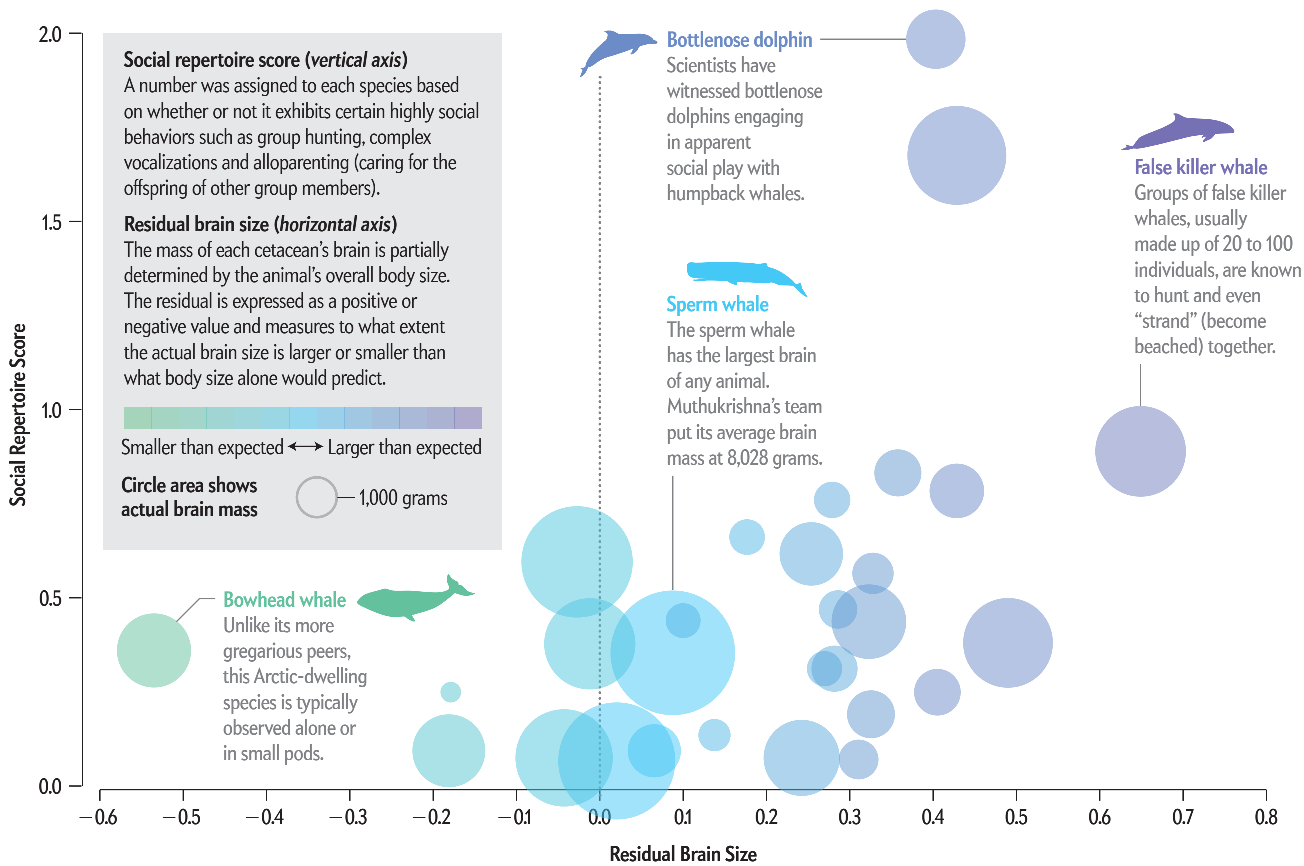
Scientists first proposed a relation between social living and brain expansion, or encephalization, nearly three decades ago, when they observed that primate species with larger brains typically lived in bigger groups. This theory was later broadened to associate brain size with other social characteristics, such as resolving conflicts and allocating food.

Michael Muthukrishna, an economic psychologist at the London School of Economics, and his colleagues went searching for a similar link between big brains and sociality in cetaceans—the mammalian order that includes whales, dolphins and porpoises. They compiled a comprehensive data set of cetacean brain and body mass, group size and social characteristics. The team's analyses, which covered 90 species, revealed that brain size was best predicted by a score based on various social behaviors such as cooperation with other species, group hunting and complex vocalizations. Bigger brains were also linked to other factors, including dietary richness and geographical range.

The authors say these results are consistent with theories that cetaceans developed large brains to deal with the challenges of living in information-rich social environments. Yet Robert Barton, an evolutionary biologist at Durham University in England, who did not take part in the work, cautions against drawing conclusions about causation from correlation. He also asserts that it is important to examine specific regions of the brain because they might evolve differently. For example, his own research team has found that nocturnal primates' brains develop larger olfactory structures—regions associated with smell—than those found in species active during the day.

Muthukrishna notes that his study's main limitation is the lack of available research on many cetacean species. Discovering more about whales and dolphins could reveal that other factors—such as life span and the duration of the juvenile phase—might also be involved in brain size, he adds.

Understanding how cetaceans developed such big brains could ultimately help us piece together humanity's own evolutionary history. Because these animals occupy a completely different environment than people do, Muthukrishna says, "they provide us with a useful control group for testing hypotheses about human evolution." *—Diana Kwon*



SOURCE: "THE SOCIAL AND CULTURAL ROOTS OF WHALE AND DOLPHIN BRAINS," BY KIERAN C. R. FOX ET AL., IN *NATURE ECOLOGY & EVOLUTION*, VOL. 1, NO. 11; NOVEMBER 2017

Graphic by Amanda Montañez

SUSTAINABILITY

The Price of Gold

Illegal mining in Peru's rain forest has increased at a staggering rate

In July 2015 Peru eliminated dozens of illegal gold mining camps within the Madre de Dios region, where hundreds of thousands of acres of rain forest have been destroyed.

SEBASTIAN CASTANEDA *Getty Images*

For decades gold miners have pillaged the lush Peruvian Amazon forest of Madre de Dios in search of the precious metal. Now a study reports that illicit mining is sharply on the rise despite local government efforts to curb it—and this is taking a heavy toll on the ecosystem.

In 2012 the Peruvian government announced a slew of legal decrees to defend Madre de Dios—considered the country's biodiversity capital—against miners. Authorities conducted raids, dismantled clandestine camps, and regulated fuel and supply traffic. Despite the crackdown, the total mining area had increased by about 40 percent (to around 170,000 acres) just four years later. According to the most comprehensive analysis to date, the practice—possibly enabled by poor control of the region and greater highway access—extended into at least one of the forest's two national reserves, protected areas where mining is prohibited.

Extracting gold from rock can contaminate the environment. Illegal mining activities often use liquid mercury, a toxic chemical that can drip into the soil or be burned off and released as toxic fumes. And the consequences of illicit mining go well beyond those of the extraction process. Miners often chop down thousands of acres of forest with heavy machinery that scars the landscape.

"You can see those dredging machines sucking silt from the river, hear their engines," says Raul Tupayachi, a Peruvian biologist at the Carnegie Institution for Science and a co-author of the study. "We hoped our data would show a drop in deforestation rates after the government actions tried to [curb mining] activities," he says. "But we saw that, in the long run, they haven't really made much of an impact."

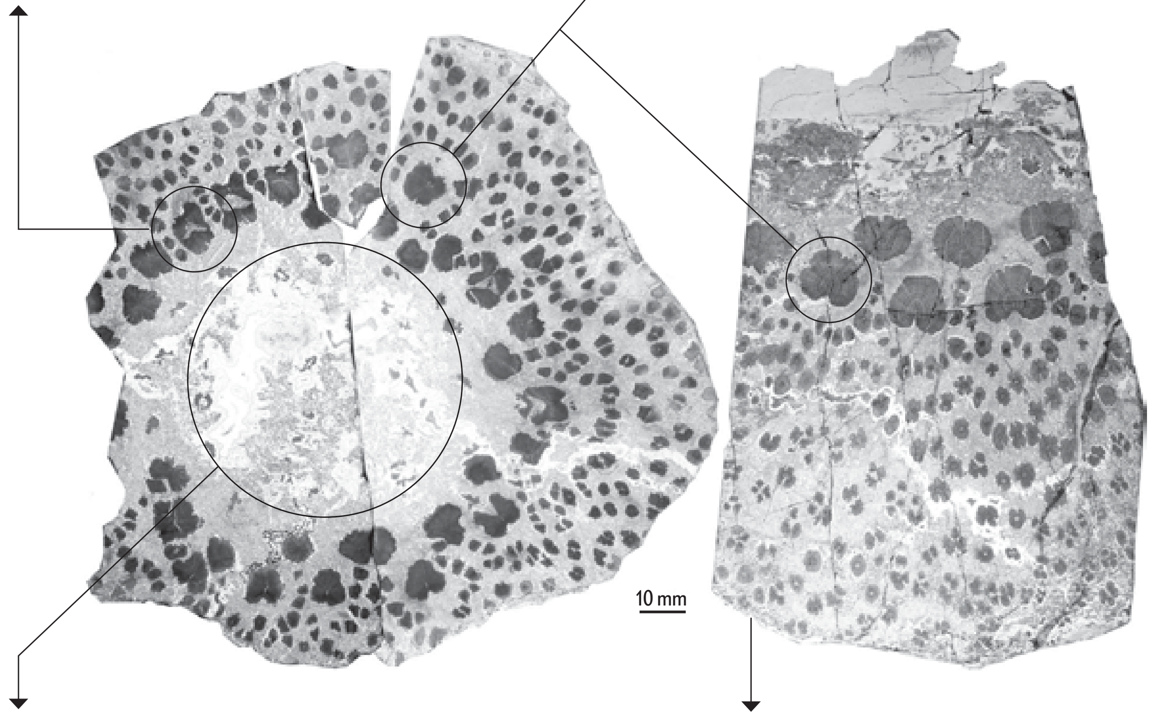
The study, which analyzed satellite images taken between 1999 and 2016 and was published last August in *Environmental Research Letters,* found an initial decline in deforestation after the government's actions in 2012. By 2013, however, forest loss rates had ballooned. New mines started to appear in the following years. They invaded protected areas such as the Tambopata National Reserve—home to the indigenous Ese Ejja, Quechua and Aymara peoples, as well as brightly colored macaws, giant river otters and jaguars. By 2016 mining operations had felled at least 1,287 acres of forest within the reserve.

William Llactayo, a geographical engineer at Peru's Ministry of Environment, who did not take part in the work, says the study comes at a critical time. If the mining trend continues, Llactayo says, "a lot of these areas will be [irreversibly] degraded in the years to come."

—Emiliano Rodríguez Mega

As the tree grew, a single xylem strand would split itself into two parts; tissue would grow between these strands, and wood rings would wrap around them, healing the divide.

These dark shapes are strands of xylem cells surrounded by rings of wood, like miniature pine or oak trees—although researchers have not yet determined whether they can age the cladoxylopsid tree by its rings.



Small tree fossil: The trunk's center is made up of soft tissues, which, as the tree grew, would have hollowed out.

Large tree fossil: This fossil is one of several—the wedge shape is like a slice from a larger pie. Such specimens revealed that, in broad-trunked trees, the trunk's core was empty.

FROM "UNIQUE GROWTH STRATEGY IN THE EARTH'S FIRST TREES REVEALED IN SILICIFIED FOSSIL TRUNKS FROM CHINA," BY HONG-HE XU, CHRISTOPHER M. BERRY, WILLIAM E. STEIN, YI WANG, PENG TANG AND QIANG FU, IN *PROCEEDINGS OF THE NATIONAL ACADEMY OF SCIENCES USA*, VOL. 114, NO. 45; NOVEMBER 7, 2017

PALEOBOTANY

Ring Cycle

Ancient trees had a complex, unique growth strategy

Cut into the trunk of a pine tree, and you will see a familiar series of concentric rings, each corresponding to a season of growth. But not all stumps tell the same story. A study published in November in the *Proceedings of the National Academy of Sciences USA* reveals that the world's oldest trees had a very different structure.

Some 370 million years ago cladoxylopsid trees stood at least eight meters tall, capped by branches with twiggy appendages instead of leaves. They looked a bit like spindly palm trees. Today their scant remains reveal little about their insides; in most cases their innards had rotted before the trees fossilized, and storms had filled them with sand. But the recent find of two well-preserved fossils in China has exposed the trees' inner workings—which are like no other species studied before.

At its heart, the mature cladoxylopsid tree was hollow. Around the edges ran thick, vertical strands containing xylem, the tubelike structures that carry water through many plants. Modern trees add new layers of multiple xylem as they grow, creating a woody trunk with a single set of concentric rings. But in cladoxylopsids, "each strand of xylem had its own growth rings," says paleobotanist Christopher M. Berry of Cardiff University in Wales, who coauthored the study with colleagues at the Chinese Academy of Sciences in Nanjing and Binghamton University, S.U.N.Y.

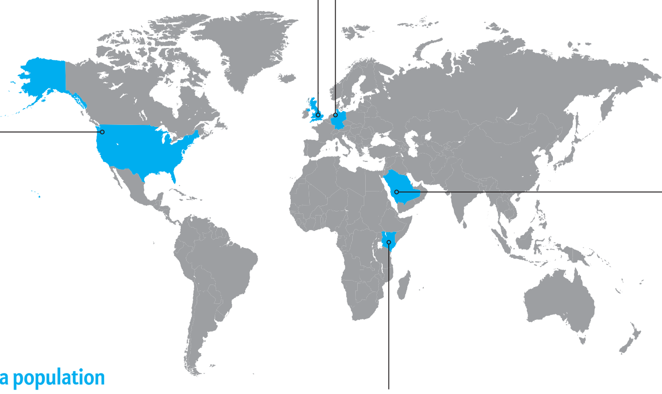
Peering into a single cladoxylopsid tree stump would be like looking at dozens of smaller "trees," the woody strands held together by the plant's soft tissue. As the cladoxylopsids grew, these columns of xylem split themselves apart—most likely to supply water to the expanding plant. Rings of wood then formed around the newly created strands.

Over a tree's lifetime these strands would weave and cross, forming an intricate latticework around a hollow core. "It's just incredibly complex," Berry says. He likens these networks of flexible tissues and structures to the Eiffel Tower—if said tower could grow, stretch and rip itself apart over time.

Although the cladoxylopsid tree has no living descendants today, it does have an important legacy. Brigitte Meyer-Berthaud, a paleobotanist at the French National Center for Scientific Research, who did not participate in this work, explains that these trees were among "the major carbon reservoirs of the Paleozoic," a time period from 542 million to 251 million years ago. Cladoxylopsids made up our planet's first forests, capturing carbon from the atmosphere and playing a part in modulating Earth's climate. Given this fact, maybe we should study these trees for the forests. —*Daisy Yuhas*

IN THE NEWS

Quick Hits



U.K.

Engineers have debuted a car-plane hybrid powered by a jet engine, dubbed the "Bloodhound SSC," in southwestern England. They now plan to add rockets to the vehicle in hopes of breaking the world land-speed record.

GERMANY

The total mass of flying insects in German nature reserves has decreased by more than 75 percent since 1989. The cause is unclear, but researchers caution that if this trend continues, it could disrupt the entire food chain.

U.S.

Scientists tracked the ice loss in around 1,200 mountain glaciers across the U.S. They estimate that Washington State's Mount Rainier has lost roughly 0.7 cubic kilometer of ice since 1970.

SAUDI ARABIA

Archaeologists using Google Earth discovered 400 rectangular stone "gates" strewn across the Arabian Desert. They think these structures, whose purpose remains unclear, may be the work of ancient nomadic tribes.

ANTARCTICA

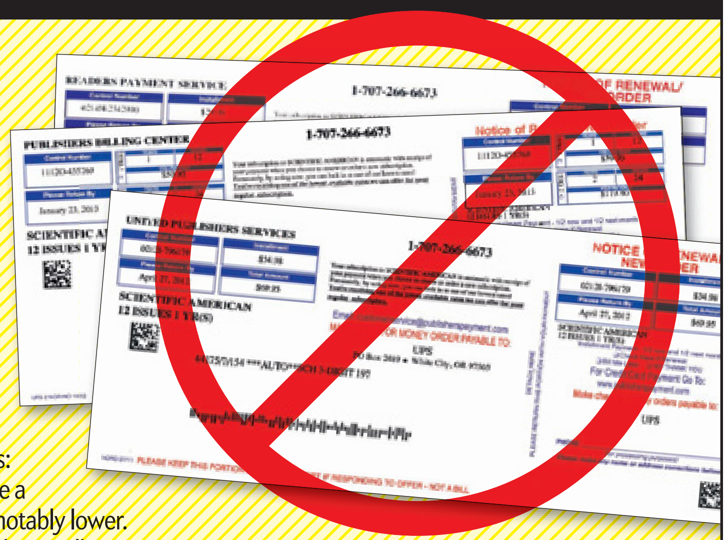
Only two Adélie penguin chicks out of a population of thousands survived last summer's breeding season. Researchers blame abnormally large expanses of ice that forced adults to travel farther to find food, while their young starved.

KENYA

A perfume made from an antelope's scent protected cattle from tsetse flies, a study of around 1,100 cows found. The flies can transfer the parasite that causes "sleeping sickness" (African trypanosomiasis) in humans to cows as well, causing losses in milk and meat.

—Yasemin Saplakoglu

For more details, visit www.ScientificAmerican.com/jan2018/advances



MATERIALS SCIENCE

Cobalt Blues

A shortage of the metal could create a bottleneck for electric vehicles

Cobalt is a critical component in batteries for electric cars and portable electronics.

COLE BURSTON *Getty Images*

An electric car future is speeding closer; economic analysts project that a third of all automobiles could be battery-powered by 2040. Most of these vehicles rely on large lithium-ion batteries, prompting worries about whether the world's lithium supply can keep up. But another element—cobalt—is a bigger concern, scientists reported in October in the journal *Joule.*

"The best lithium battery cathodes [negative electrodes] all contain cobalt, and its production is limited," says study lead Elsa Olivetti, a materials scientist and engineer at the Massachusetts Institute of Technology. Olivetti and her colleagues calculated just how short cobalt supplies could fall if electric vehicles (EVs) take off as expected—and the findings are sobering.

Lithium battery cathodes are made of layers of lithium metal oxides that contain some combination of cobalt and other metals. Cobalt's unique atomic properties let cathodes pack a lot of energy into a small space and help to maintain the cathodes' layered structure.

Olivetti and her colleagues extrapolated trends in lithium and cobalt supply through 2024. To calculate demand, they created two scenarios based on estimates of slow or speedy growth in battery use for EVs and portable electronics.

Lithium is unlikely to be a limiting factor in the long run, they found. But even with a very conservative estimate of 10 million EV sales in 2025, the demand for cobalt that year could reach 330,000 metric tons, whereas the available supply at that time would be at most 290,000 metric tons.

Cobalt is a by-product of copper and nickel mining, so its production depends on the demand for those metals. Furthermore, more than half of the world's cobalt stores are found in the politically unstable Democratic Republic of the Congo.

Recycling lithium batteries is complicated and rarely done. Even with higher rates and cheaper processes, "recycling won't make a dent until 10 or more years after mass-market penetration of EVs," says Linda Gaines, a transportation systems analyst at Argonne National Laboratory, who was not involved in the work.

Newer cathode chemistries offer hope, however. Recently developed nickel-rich formulations will reduce cobalt demand, Gaines says. Cobalt-free cathodes are also under development, and researchers hope to make them practical. —*Prachi Patel*

Claudia Wallis is an award-winning science writer and former managing editor of *Scientific American Mind.*

The Messy Facts about Diet and Inflammation

Can certain foods really help you fight heart disease, arthritis and dementia?

By Claudia Wallis

In health, as with so many things, our greatest strength can be our greatest weakness. Take our astonishingly sophisticated response to injury and infection. Our bodies unleash armies of cellular troops to slaughter invaders and clear out traitors. Their movements are marshaled by signaling chemicals, such as the interleukins, which tell cells where and when to fight and when to stand down. We experience this as the swelling, redness and soreness of inflammation—an essential part of healing.

But when the wars fail to wind down, when inflammation becomes chronic or systemic, there's hell to pay. I'm looking at you, arthritis, colitis and bursitis, and at you, diabetes, colon cancer, Alzheimer's and cardiovascular disease.

Cardiovascular disease is the world's biggest killer, and we've known for 20 years that inflammation (along with too much cholesterol) ignites the buildup of plaque in our arteries. Still, no one knew if runaway inflammation could actually pull the trigger on heart attacks and strokes—until this summer. Results from a large, well-designed trial showed that certain high-risk patients suffered fewer of these "events" (as doctors so mildly call them) when given a drug that precisely targets inflammation (aiming at interleukin 1). It was sweet vindication for cardiologist and principal investigator Paul Ridker of Harvard University, who had long contended that inflammation was as vital a target as cholesterol.

The patients in Ridker's study had already suffered a heart attack and had persistent inflammation (as measured by blood levels of C-reactive protein). But it is tempting to extrapolate lessons for all of us. Given that chronic inflammation plays a nefarious role in heart disease and many other disorders, shouldn't we all do what we can to keep it in check? And I'm not talking about taking drugs like ibuprofen, which ease short-term inflammation. I mean something we can do every day of our lives: eat right.

Hop on the Internet or visit a bookstore, and you will see "anti-inflammatory" diets galore, dishing out recipes and hope. Many aim at specific ailments—arthritis, breast cancer, heart disease, various autoimmune disorders. Health guru Andrew Weil goes so far as to offer an "Anti-Inflammatory Food Pyramid."

The underlying science, however, is somewhat shaky. Sure, plenty of foods have been found to reduce inflammation—many of them in laboratory experiments as opposed to in people: turmeric, blueberries, ginger, tea, various vegetables, dark chocolate, fish. University of South Carolina epidemiologists James Hébert and Nitin Shivappa valiantly surveyed 1,943 such studies and published in 2014 a Dietary Inflammatory Index, with 45 food elements. They created it as a research tool for evaluating diets but concede it's built from studies that varied widely in methodology.

When I asked Ridker his views on anti-inflammatory diets, he grew uneasy. "This has caught on like wildfire," he says, "but I have seen extremely little data that say this piece of food is 'anti-inflammatory' and this piece is 'pro-inflammatory.'" He advises his own patients to eat a Mediterranean-type diet, heavy on vegetables, whole grains and fish and light on red meat and processed foods.

That diet, long endorsed by cardiologists, has been shown in well-designed studies to reduce key markers of inflammation and the risk of heart disease. Would it be even more effective if it incorporated more blueberries and turmeric? No one knows for sure.

Diet research is tricky. Turmeric may work anti-inflammatory wonders for mice, but "that's in the context of rodent chow with a whole different set of macro and micro nutrients," explains Martha Clare Morris, a nutritional epidemiologist at Chicago's Rush University. And context matters. The typical Mediterranean diet calls for loads of seafood a week, and yet studies of people taking fish oils as a supplement have not found much benefit. The virtues of fish may lie elsewhere or have more to do with displacing meat.

That's why researchers such as Morris prefer to study overall dietary patterns rather than particular ingredients. Her current project examines whether cognitive decline can be slowed with a regimen called the MIND diet, which combines elements of the Mediterranean diet with another well-studied diet called DASH. It will look at inflammation, but results won't be out before 2021.

Until then, there is no harm in adding more so-called anti-inflammatory ingredients to your diet. Hébert suggests a spicy chai (loaded with ginger, turmeric and pepper). But remember, context! So don't drink it with cookies and chips. SA

Illustration by Celia Krampien

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

How Well Do Films Predict Our Tech Future?

They get lots wrong but a surprising amount right

By David Pogue

Everyone judges the plausibility of a movie through a different lens. If you're a doctor, you may think: "That character would not have survived that fall." If you're an astrophysicist: "That's not how black holes work." And if you're me, it's more like: "What a dumb concept of future personal technology!"

It makes me crazy when sci-fi moviemakers dream up stuff with no basis in science. Human teleporters? Sorry, *Star Trek.* A bed that detects and cures cancer in seconds? No, *Elysium.*

On the other hand, some movies depict futuristic technologies that are so plausible and practical, people invent them in the real world. *Star Trek*'s self-opening doors are now a standard feature of grocery store entrances, and the driverless cars from *Total Recall* (and many other movies) are already on American roads.

Lately it's clear that Hollywood's production designers have been putting serious thought into the tech we'll someday carry. *Her,* for example, is about a man who falls in love with his Siri-like voice assistant. He talks to her through a single earbud, through which he gets a surprising amount done: processing e-mail, flipping through news stories, sending messages. When an image is essential to the communication, he flips open his phone, where the picture appears.

This solution makes a lot of sense—more than, for example, Google Glass, a now discontinued headband that placed a miniature screen above your eyebrow. Social missteps, not technical ones, hastened its demise: Glass's camera intimidated others and made you look like an obnoxious cyborg. The *Her* earpiece delivers many of the same benefits, albeit discreetly and comfortably.

My only beef with *Her* is that nobody ever precedes a command with, say, "Alexa" or "Hey, Siri." How do the movie's computers know when you're speaking to *them?* Otherwise, *Her* nails it in the plausibility department. Already Apple's AirPods and Google's Pixel Buds let you converse with your voice assistant in much the same way, although at this point, you're more likely to receive news and weather than love and fulfillment.

In a recent Netflix movie called *What Happened to Monday,* humans live in a dystopian future where, to control overpopulation, it's illegal to have more than one child. The characters wear wristbands containing tiny projectors. They shine perfectly crisp, color images onto their palms, which the characters tap as though they are touch screens. I'll bet the screenwriters were inspired by a viral 2014 video about a slim wristband called the Cicret. (It raised more than $500,000 from individual backers before being debunked as wishful thinking.)

You can see why people went nuts over the concept: imagine having all the power of a smartphone without actually needing a smartphone. We won't see this in the real world, though. Even if a pico projector, battery and processor could be shrunk and squeezed into a thin band, insurmountable challenges remain. How would the projector attain sharp focus on an irregular, moving palm? How would it project enough light on sunny days? How would it work on very light or very dark skin? Above all, how would multitouch gestures work, when any finger in the projector's beam would cast a black shadow over the rest of the "screen"?

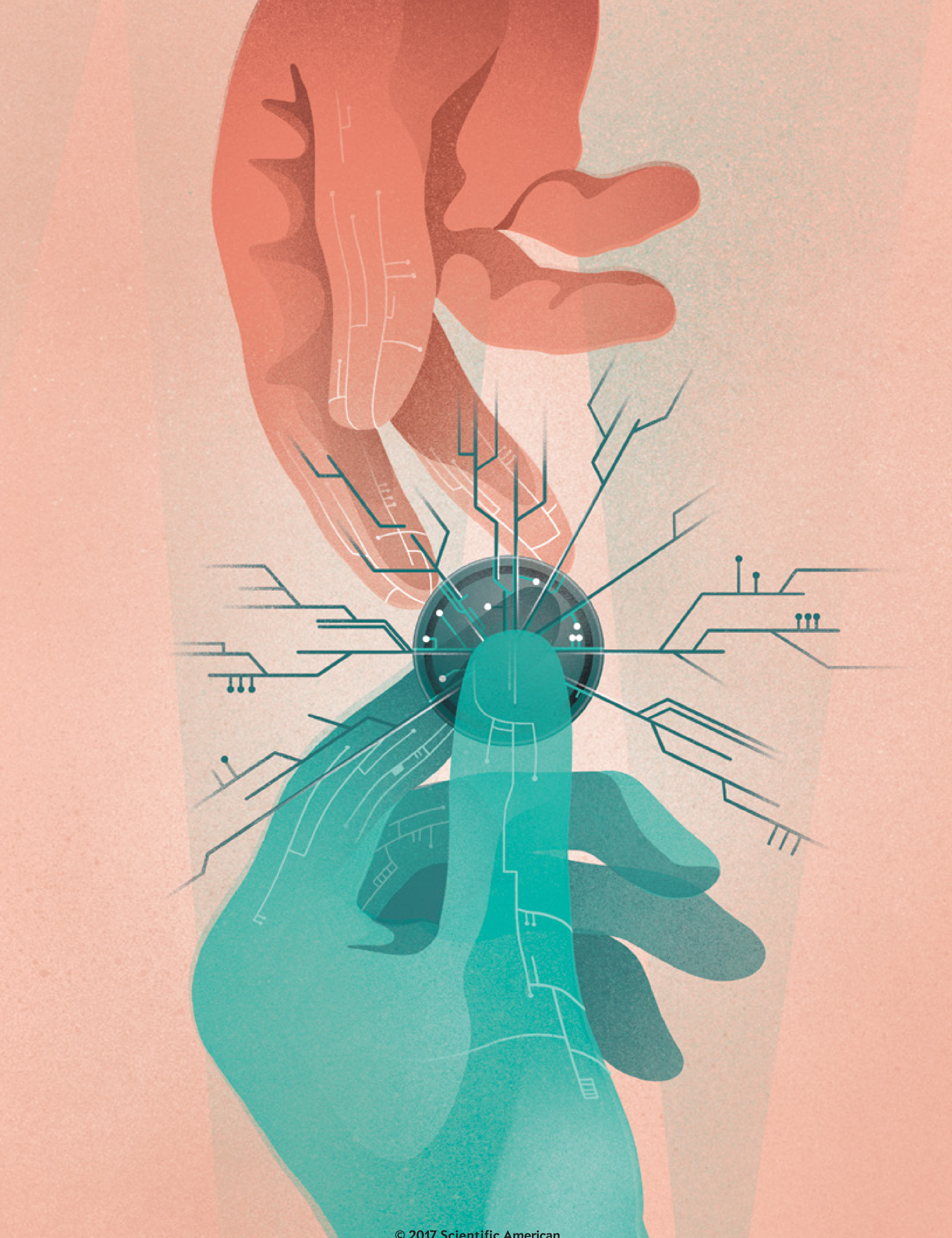
The robots in HBO's *Westworld*—so sophisticated that they are indistinguishable from humans—might be a bit of a stretch. Yet the personal tech in that series makes a lot of sense: the characters carry cardboard-thin, trifold phones. When you need a quick check, you glance at its "cover"; when you need the bigger picture, you unfold it into a tablet.

Most of these shows, however, continue to get one thing absurdly wrong: apparently, in the future, our computers make little chirps and beeps as their text and images appear. Why do moviemakers think that adding silly sound effects make their futuristic machines more rather than less plausible? In the real world, a room full of burbling screens makes us crazy.

Well, I suppose I should let that part go. They're just movies, right? They're not a depiction of the future—at least not yet.

SCIENTIFIC AMERICAN ONLINE
READ ABOUT *STAR TREK*'S TECH PREDICTIONS:
scientificamerican.com/jan2018/pogue

Illustration by Jay Bendt



THE FUTURE OF MONEY

SPECIAL REPORT

BITCOIN WAS ONLY THE BEGINNING. MACHINES THAT BROKER trust without human intermediaries could fix the financial system's biggest flaws, but they also raise unnerving questions. Are we ready for a world in which any asset—from currency to personal identity—can be traded and tracked in an indelible ledger? What if a technology designed to strip banks and governments of power ends up giving them unprecedented control? *—The Editors*

Illustrations by Borja Bonaque

THE FUTURE OF MONEY

BREAKING THE BANK

NEW FINANCIAL NETWORKS COULD STOP THE CONCENTRATION OF WEALTH AND INCREASE PARTICIPATION IN THE ECONOMY—BUT ONLY IF USED WITH CARE

BY ALEXANDER LIPTON AND ALEX "SANDY" PENTLAND

IN BRIEF

The modern financial system has become dangerously complex. Increasing transparency would reduce risk, but that requires modeling the monetary circuit at a level of detail beyond the capacity of current technology.

New technologies such as digital currencies are now making it possible to simulate every trade and transaction. These tools could build more efficient financial networks and decentralize the control of money. People could exchange directly with one another instead of relying on banks.

The potential for sweeping change is real, but there are many uncertainties. These digital networks will only promote equity and accountability if they are properly built and responsibly used. They could just as easily lead to extreme levels of centralized control.

ON A SPRING DAY MORE THAN 5,000 YEARS AGO IN THE MESOPOTAMIAN CITY OF UR, A FOREIGN merchant sold his wares in exchange for a large bundle of silver. He didn't want to carry the bundle home because he knew he'd be back in Ur again to buy grain at the end of harvest season. Instead the merchant walked to the local temple, where valuables were often stored, and asked the priest to hold onto the silver for him.

Shortly after, the priest's nephew showed up to ask for a loan. The young man wanted to buy seed to grow his own crops, a wish that tugged at his uncle's heartstrings. So the priest loaned him some of the silver, reasoning that if his nephew failed to repay him by the time the merchant needed the silver back, he could fill in the missing amount with his personal funds or borrow it from friends. By using a long-term contract with the foreign merchant to support a short-term loan to his nephew, the priest doubled the number of commercial transactions by using the same money twice. In other words, he invented fractional banking.

Based on archaeological evidence, we know that some scenario like this one occurred in Mesopotamia, and it profoundly changed the financial environment in two ways. First, it increased the overall productivity of the economy, because the nephew could now afford seed. Second, it introduced risk: the nephew might not be able to pay the money back in time.

A few millennia later the emergence of government-backed central banks in 17th-century Europe connected this "double spending" with taxation. The king would borrow money from merchants to fight wars or build roads, and he would use it to pay arms manufacturers, purveyors and troops. That money began circulating, generating economic activity and profits, and at each step the amount of money was doubled—or more. The king typically repaid the loans with taxes imposed on profits, launching a prototype monetary circuit that marks the beginning of the banking system we use today.

Distilled to its simplest form, the modern circuit works along these lines: First, firms borrow money from private banks like JPMorgan Chase or HSBC to pay workers' salaries and other expenses. This is the step where money is created. Second, consumers purchase goods produced by firms or deposit the money as savings in banks. Finally, those firms use the money they receive to repay banks, and the cycle is complete. At this stage, the originally lent money is destroyed, but the interest stays in the system forever. That's how private banks can jump-start economies by creating money "out of thin air." Their power to do so is regulated in part by central banks, which impose limits on the amount of capital and liquidity private banks must always have to back lending activities.

If only it were so simple. Unfortunately, the monetary circuit introduces some fundamental problems into society. For one thing, it inevitably creates a handful of billionaires who control a high concentration of total wealth. It is also distressingly common to see leveraged money creation without sufficient understanding of (or care for) the risks. Which is how we get financial crashes, such as the one in 2008: when bankers and politicians spurred an insatiable demand for mortgages, it was met by a significant increase in the amount of money created—along with an even more significant increase in risk.

It may seem obvious to blame the monetary circuit itself for these problems. But it's not the root of the issue. Leveraged money creation works well as long as we can understand and control its inherent risks while suppressing undesirable wealth concentration. Today, however, a tangled web of factors, such as a booming population, global trade and powerful computers, makes the system far too complicated to manage and regulate, let alone understand.

What's more troubling is that the prevailing framework we use to guide macroeconomic activity is based on outdated paradigms. Models that are typically used to govern money creation and interest rates, for example, still treat private banks as simple intermediaries, ignoring the fact that they are big, active, money-creating elements unto themselves. That banks have their own motivations and profit-making strategies injects major opacity into the system. It's no wonder that the 2008 mortgage crisis was difficult to see coming.

Today's supercomplex monetary circuit needs to be modeled in unprecedented detail for us to actually understand it. Technological limitations have long prevented such a gargantuan task. But big data and the emergence of digital currencies and digital contracts are finally changing that. Rather than using historical averages to estimate what might happen in any economic system, it is finally becoming possible to completely simulate every individual trade and transaction and analyze all potential outcomes. The prospect of this feat is shaking up the functionality and ideology of global finance, and its implications could make economic security much better—or much worse.

THE RISE OF DIGITAL CURRENCIES

NEW TECHNOLOGIES that make it feasible to reinvent our financial system have exploded on the scene in only the past decade. Most everyone has heard of Bitcoin, but that's only one piece of an up-and-com-

Alexander Lipton is founder and CEO of StrongHold Labs and Connection Science Fellow at the Massachusetts Institute of Technology. Previously he served at Bank of America in senior managerial roles, while holding visiting professorships at the University of Oxford and Imperial College London. In 2000 he received the first Quant of the Year award.

Alex "Sandy" Pentland is a professor at M.I.T., one of the most cited authors in computer science and a member of the U.S. National Academies. In 2011 *Forbes* named him one of the world's seven most powerful data scientists. His most recent book is *Social Physics* (Penguin Books, 2015).

ing financial-technology industry characterized by buzz and speculation. What is important to know is that the core invention is a "distributed ledger," a database shared and managed by multiple participants. Think of it as a communal, digital bookkeeping system. It represents the foundational technology that has made cryptocurrencies—simply, digitally encrypted currencies—such as Bitcoin possible. Its underlying data structure, called a blockchain, is held in a series of sequentially encrypted blocks. To make those blocks reliable and secure, they are consensually updated by a variety of "proving" mechanisms that involve both humans and computers.

Conceptually speaking, blockchains and distributed ledgers are not new—blockchains, for instance, naturally occur whenever power, land or property changes hands. What *is* new is the marriage of the two concepts in a tamper-resistant computer system that can be applied to a wide range of practical problems. New technologies for blockchain-based distributed ledgers are making it possible to create digital currencies that are far more efficient than the U.S. dollar and more efficient than even Bitcoin.

These tools could enable us to monitor and analyze transactions at such a granular level that we can finally understand the monetary circuit. With a whole new level of clarity, we could learn to recognize and act on early-warning signals that arise from within the trillions of transactions recorded in the ledger, thus increasing system stability and safety. This kind of open-book, real-time monitoring is also safer for the community as a whole. In the 2008 crash, for example, there was not enough bureaucratic capacity to deal with the individual losses of tens of millions of citizens. As a consequence, regulators focused mostly on triaging the much smaller number of big banks, leaving ordinary people to suffer the most.

As this rapidly evolving technology gets tapped for an expanding range of applications, confusion abounds. Because Bitcoin is currently the most well-known (some might say notorious) form of digital currency, it is worth backing up to explore its origins and its weaknesses and how it is different from more promising forms that are now being pursued. Bitcoin was designed as a peer-to-peer digital payment system that operates without central authority. Anyone can join, which is both a strength and a weakness. Users make financial transactions with one another directly, without the help of intermediaries. These transactions are recorded in a publicly distributed blockchain ledger, for all participants to (theoretically) see. Since Bitcoin's inception in 2009, its price has gone up several orders of magnitude, making it the darling of speculators.

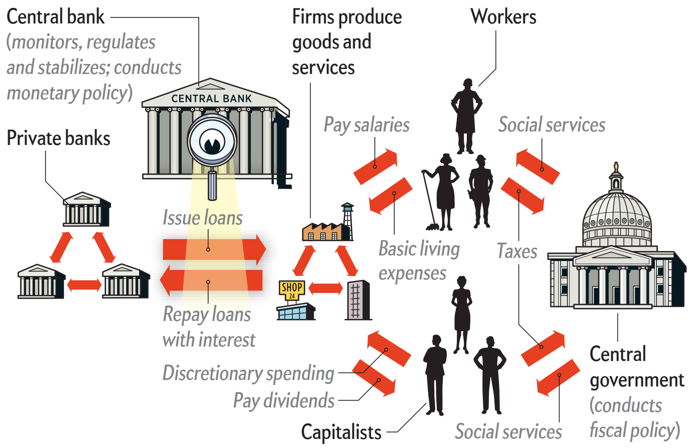
Bitcoin's promises are grand. Its proponents—mostly techno-savvy idealists and libertarians but also some criminal types—expect it to become a global currency that eventually supplants national cur-

Three Types of Financial Systems, Visualized

The current monetary circuit has become too complicated to understand. Emerging "blockchain technologies," such as the one driving Bitcoin, decentralize (and defog) the system. New networks are in development.

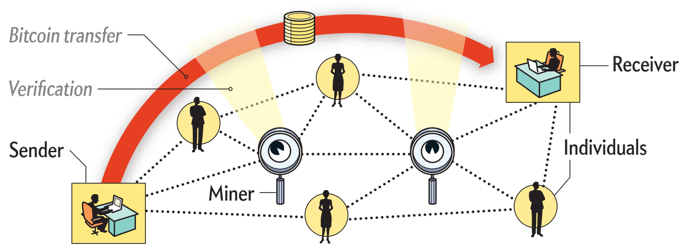
Fractional Banking (current monetary circuit)

Banks create money "out of thin air" when they issue loans to firms. Firms pay salaries and dividends to households. Households buy goods and services from firms. When loans are repaid, the "created" money is destroyed, but interest stays in the system for good.



Peer-to-Peer Bitcoin Network

Transactions are made directly between users, without the help of designated intermediaries. They are publicly broadcast and recorded in a blockchain. Consensus is maintained by random validators. Bitcoin has no value, so its price is inherently unstable.



Peer-to-Peer Tradecoin Network

As with Bitcoin, transactions would be made directly between users and are publicly recorded in a blockchain. But consensus is maintained by designated validators. Tradecoin's value is backed by real assets supplied by sponsors, so its price is relatively stable.

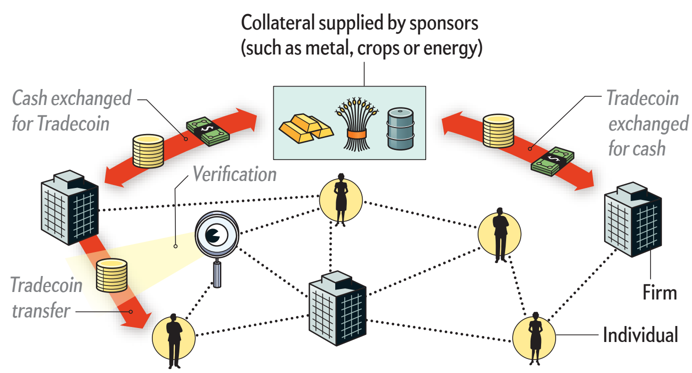


Illustration by Peter and Maria Hoey

rencies, which, in their minds, can be easily manipulated. Some enthusiasts even believe that Bitcoin is the digital version of gold, perhaps forgetting that gold gains stability both from its physical attributes and from billions of stakeholders and that in the digital world, good technologies are routinely overtaken by better ones.

Bitcoin is actually not the first digital currency, and it's very likely not the last major one either. It also has serious logistical constraints. For example, the number of transactions that can be handled per second is approximately seven, compared with the 2,000 on average handled by Visa. It's an energy suck, too: mining—the process by which nodes of the cryptocurrency network compete to securely add new transactions to the blockchain—depends on a huge amount of electricity. In high energy-cost countries, miners go bust if they cannot afford the utility bills for the computing power. While exact numbers are not known, it is believed that Bitcoin consumes as much electricity as eBay, Facebook and Google combined. The system was also set up to distribute authority among many miners, but by banding together into gigantic pools, a small number of groups have become powerful enough to control the Bitcoin system. So much for peer-to-peer!

Bitcoin's use is limited, too. The term "money" can be defined by its three types of use: for transactions, for store of value, and as a unit of account. Because Bitcoin's price versus the U.S. dollar (and other government-designated legal tender) is extremely unstable, it is difficult to use on a day-to-day basis. Bitcoin and Ether, another major digital currency, are not backed by real-world assets or even by government promises; consequently, they are purely speculative. In colloquial terms, that means they are not "real" money: what has no value can have any price. Some Bitcoin enthusiasts frame its valueless nature as a virtue and claim that in the future all money is going to be Bitcoin-like. This is highly unlikely for both technical and political reasons.

As the first successful decentralized digital currency, though, Bitcoin is an impressive breakthrough. The underlying technology and the philosophy of an unregulated, peer-to-peer financial system are innovative, and Bitcoin poses practical solutions to big problems. Of course, it's only one application of blockchain-based distributed ledgers. Blockchain, after all, is a technology, not a singular ideology: it should not be conflated with the driving philosophy behind Bitcoin or with the motivations of any of its current and future applications. Just as it has the potential to solve some of the existing problems of our financial system, it can be used to entrench them instead. And when you consider that a key element of power is the control of money—both existing money and future money creation—we can already peek into the Pandora's Box of moral hazards that this technology has opened.

A Brief History of Money

7th century B.C.: Lydians and Greeks create standard coinage.

14th century: Merchant banks such as the Medicis expand involvement in multistate finance, trade and manufacturing.

17th century: By loaning out the value of deposited money, bankers increase economic productivity while creating new sources of risk that regularly result in local crashes and even widespread depressions. Central banks emerge, linking banking with taxation.

18th century: The gold standard evolves from previous tactics in which circulating money was loosely controlled by a reserve of precious metals. This lowers risk.

20th century: The gold standard is replaced by the Basel Accords, which say that holding easily sold assets is just as good as holding gold.

Take the central banks of the major reserve currencies such as the U.S. Federal Reserve and the Bank of England. Trust is often associated with size—the bigger, the more trustworthy—but these players have proved such thinking to be a grave mistake. They have repeatedly chosen to make the "little guys" poorer by diluting their financial obligations through inflation, suppressing interest rates and other policies. Recently they have been testing negative interest rates and contemplating ways to get rid of cash.

What is more alarming is that some central banks are discussing the possibility of making *all* of their currency digital and recording purchases directly on a ledger. This could bypass input from private banks and give the government absolute control over the economy. It would also mean that the government has a record of everything you buy—including the stuff you currently purchase with cash to intentionally avoid a paper trail. This is increasingly looking like a possible scheme, and countries such as China, the U.K., Singapore and Sweden have announced plans for studying and potentially implementing such a strategy. The critical takeaway here is that although the technology itself is decentralized by design, it can be used to create centrally controlled systems.

TOWARD A MORE STABLE FINANCIAL SYSTEM

IT IS CLEAR that the invention of blockchain and distributed ledgers won't eradicate problems like financial crashes and unhealthy inflation—at least not in the short term. But it does enable the creation of legitimate alternatives to the big, powerful players. Technology now makes it possible to form specialized global currency systems that previously would not have had sufficient scale, trust or political stability to compete. That is why a natural next step is for the little guys—such as emerging economies or large numbers of individual citizens—to band together to form alternatives to central banks.

With that possibility in mind, our lab at the Massachusetts Institute of Technology is working on creating a digital currency suitable for large-scale transactional purposes. Called Tradecoin, it will be indelibly logged on a blockchain and anchored at all times to a basket of real-world assets such as crops, energy or minerals. Doing so will help stabilize its value and make it easier for the public to trust it. The core idea is that a broadly useful currency needs both human trust and efficient trade systems.

A digital Tradecoin built on a distributed ledger can allow alliances of small nations, businesses, commercial traders, credit unions or even farmers to put together enough assets to back a large, liquid currency that would potentially be as trustworthy and at least as efficient as the national currencies used by the World Bank and the International Monetary Fund. This would give the Tradecoin alliance members some protection from the selfish policies of the big players. The cryptographic structure makes it much easier, safer and cheaper for them to engage in international trade. If the alliance members are geographically and politically diverse, they could have greater immunity from the risk of default than if they were backed by a single large entity. Indeed, this is exactly how the Bank of England got started in 1694: as an alliance of merchants.

By design, the principles behind currencies such as Tradecoin are fundamentally different from cryptocurrencies like Bitcoin, which are not backed by real-world assets and do not involve alliances. Tradecoin can also avoid the energy-intensive process of mining by using a preapproved network of diverse and trusted "validators." Participants can choose a set of validator nodes who are sufficiently diverse so that no one can bribe 51 percent of the validators all at once. The result is a fast, fully scalable, reliable and environmentally friendly financial instrument. It combines the most recent technologies with the very old idea of a gold coin having intrinsic value, giving it the necessary trust to be used far away from its place of origin.

Currencies such as Tradecoin can be even safer than today's currencies because they can be designed to make the details of the monetary circuit visible for supervision. Oversight by human stakeholders is still necessary, much as ICANN oversees the Internet system or regulators such as the Federal Reserve Board oversee the banking system in the U.S. They allow for easy distributed accounting, which means we can more reliably model and predict risks. Right now this kind of transparency is impossible because the details of financial transactions and contracts are tightly restricted. But if such a system had been in place in 2008, it could have monitored the extreme concentration of some traders in mortgage-backed credit-default obligations and "simulated" in detail the consequences of changes in home values. Instead of hidden packages of bad mortgage deals, there could have been bright red flags.

We are taking on these transparency challenges. For instance, we are building "trust network" software systems for European Union nations and major U.S. financial companies to use as pilot programs. They will allow recording and "playback" of transactions and contracts among different parties without exposing proprietary data or violating privacy. This software is also the core system for Tradecoin. We are exploring how to pilot two Tradecoin currencies: one that is intended for international commerce and backed by an alliance of small nations and another that is backed by farmers for use in commodity markets. We are now recruiting alliance members to test the idea.

It is exciting that for the first time ever, there is the possibility of worldwide digital currencies that are largely immune to selfish policies of the rich central banks that control much of the money. Indeed, a flurry of new alternatives is likely to emerge, and a few might ultimately rise to compete with the biggest reserve currencies. That we can now create monetary systems that are truly understandable means we can potentially build the tools for minimizing risk, avoiding crashes, and maintaining individual freedom from intrusive governments and overly powerful corporations. And because they will be backed by (and convertible into) traditional assets, they have a real baseline value. That means they are less likely to be targeted for speculative attacks and will be strongly resistant to both political manipulation and inflation caused by the problems of single nations.

Taken together, next-generation cryptocurrencies such as Tradecoin could dramatically reduce frictions in global trade, even amid the chaos of the current political and economic climate. As a result, major currencies such as the dollar might become less dominant, or else the U.S. financial system might become better behaved. The hope is that these distributed systems, backed by broad alliances of diverse players, can bring more transparency, accountability and equity to the world.

MORE TO EXPLORE

The Macroeconomics of Central Bank Issued Digital Currencies. John Barrdear and Michael Kumhof. Staff Working Paper No. 605. Bank of England, July 2016.

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scientificamerican.com/magazine/sa

THE FUTURE OF MONEY

THE WORLD BITCOIN CREATED

THE FIRST BIG DIGITAL CURRENCY GAVE US A GLIMPSE OF A NEW ECONOMIC ORDER—ONE THAT RAISES MORE QUESTIONS THAN ANSWERS

BY JOHN PAVLUS

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BITCOIN. CRYPTOCURRENCIES. SMART CONTRACTS. MANY PEOPLE HAVE NOW heard of the rapidly changing ecosystem of financial technology, but few have wrapped their heads around it. Hundreds of central banks and corporations are incubating a game-changing technology called blockchain—and investors are betting billions on it. Yet only 24 percent of global financial services professionals surveyed in 2017 by PricewaterhouseCoopers (PwC) described themselves as "extremely" or "very" familiar with it. Much of the public is unsure if any of this is legal, if they understand it at all. Evangelists say it has the power to upend entire economic systems; others, such as Emin Gün Sirer, a blockchain researcher at Cornell University, warn that while the technical core is "fascinating and disruptive, there's also a lot of hokum out there." How to parse the nuance—or get a handle on what a blockchain is?

It all starts with Satoshi Nakamoto, the world's most reclusive pseudonymous billionaire. In October 2008 Nakamoto published a paper via an obscure Internet mailing list detailing a design for the world's first blockchain: a public database distributed and synchronized every 10 minutes across thousands of computers, accessible to anyone and yet hackable by no one. Its purpose? To provide a decentralized, bulletproof record of exchange for a new digital currency Nakamoto called Bitcoin.

Until that point, the trouble with "peer-to-peer electronic cash" was that nobody could reliably prevent you from spending it twice. Blockchain technology changed all that by inscribing every transfer of Bitcoin into a "distributed ledger"—a kind of digital spreadsheet that, thanks to the laws of mathematics and cryptography, was more inviolable than carving it in stone. The *Economist* dubbed it "the trust machine."

The technology that underpins Bitcoin quickly outgrew it, driving a frenetic period of innovation. Think of blockchain as a scaffolding that can hold any data that need secure provenance: financial histories, ownership documents, proofs of identity. This "worldwide ledger"—as Don Tapscott, co-author of *Blockchain Revolution,* calls it—is a blank slate. But the technology, imperfect as it is, can be tapped for evil, too, and some are pumping the brakes on the frenzy. Here's a guide to the digital landscape that Satoshi Nakamoto—whoever he is—has thrust before us.

CORE CONCEPTS

CRYPTOCURRENCY A form of digital currency that relies on the mathematics of cryptography to control how and when units of the currency are created and to ensure secure transfer of funds.

PEER-TO-PEER (P2P) NETWORK A web of computers linked in a decentralized way, such that any computer can communicate directly with any other without going through a central server or other administrator. Napster, the network for sharing music files that launched in the late 1990s, popularized the concept.

NODE A computer connected to a P2P network. The Bitcoin network currently has thousands of nodes spread across the globe.

DISTRIBUTED LEDGER A list of recorded, time-stamped transactions that is simultaneously broadcast, copied and verified via consensus across many different computers in a P2P network. If every node in the network has an identical copy of the ledger, falsified entries or corrupted versions can be easily detected.

BLOCK A grouping of individual transaction records on a blockchain. On the Bitcoin network, new blocks are added to the chain every 10 minutes.

HASHING A cryptographic method that uses a mathematical function to condense any amount of data into a unique string of alphanumeric characters of a certain fixed length—called a hash value. This creates an easily verifiable digital fingerprint for the hashed data. If even a single bit of the original data is changed or corrupted, the fingerprint that emerges from the hash function will be drastically different, making it easy to detect errors or tampering. Hashes are also "one-way"—the data cannot be reassembled or extracted from the fingerprint.

MINING The process by which nodes of a cryptocurrency network compete to securely add new blocks of transactions to a blockchain. Units of the currency are the reward—and hence, a financial incentive to ensure security. Mining involves downloading the latest version of the blockchain's transactions for verification, then using brute-force computation to randomly search for the solution to a difficult mathematical puzzle created via hashing. The first node to discover the correct solution "mines" that block, adding it to the blockchain and claiming the reward associated with it. Humans control nodes, but the competition has nothing to do with skill: simply, the more raw computing power a miner applies toward the solution, the more likely he or she is to find it—a process called proof of work.

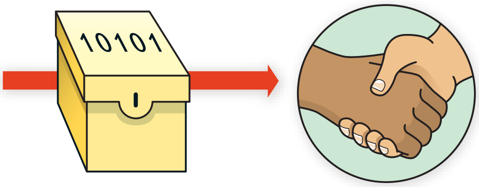
Illustrations by Peter and Maria Hoey

HOW BLOCKCHAIN WORKS

How does digital currency—or any data—reliably pass back and forth on a decentralized network full of strangers that don't have a reason to trust one another at all? By generating a permanent ledger of transactions that can't be changed by any single network member.

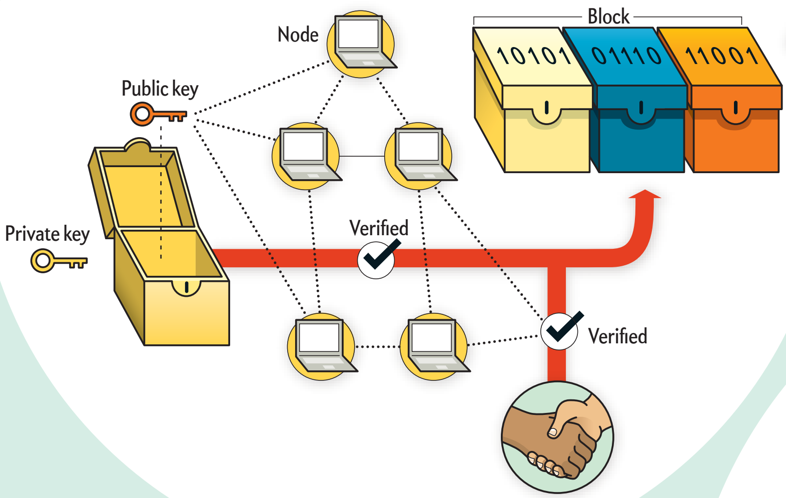
1

A blockchain transaction begins with one party agreeing to send data to another. These data could be anything. But because the point of a blockchain is to create a permanent, verifiable record of exchange, the data usually represent some valuable asset. Common examples: units of a cryptocurrency or other financial instrument; contracts, deeds or records of ownership; medical information or other identity data.



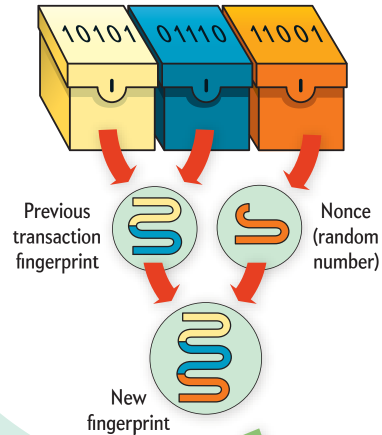
2

The transaction is broadcast for verification to a peer-to-peer network of computers operating the blockchain. Every node on the network is equipped with a procedure for verifying whether the transaction is valid or not. (In a Bitcoin transaction, for example, the network would verify whether those paying actually have the amount of Bitcoins they say they do.) Once the network has reached a consensus, algorithms package up the validated transaction with other recent transactions into a block.



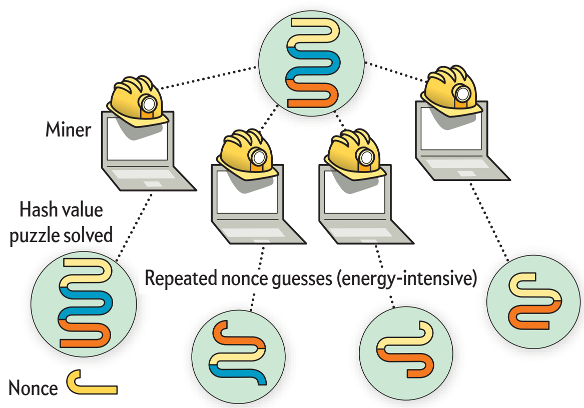
3

Software creates a "fingerprint" for the new block by hashing the data inside it, together with two other pieces of information: the fingerprint of the preceding block and a random number called a nonce.



4

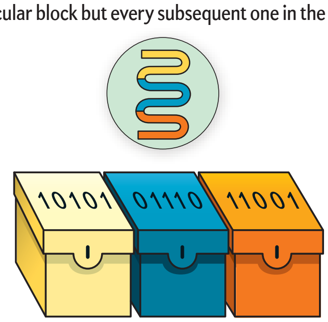
Special nodes called miners begin competing with one another for the right to add the new block to the blockchain. Their computers perform a tedious set of hash-based calculations over and over again by trial and error, hoping to generate a solution that satisfies an arbitrary rule defined by the network. (On the Bitcoin blockchain, the miners are searching for solutions—or "hash values"—that have a particular number of zeros at the beginning.) Whoever is first to complete this proof-of-work process and find the matching solution successfully "mines" that block, earning a financial reward.



AS AN ALTERNATIVE: Proof-of-work mining is energy-intensive, so some new blockchains are doing away with it, instead using a preapproved network of "validator" nodes who can notarize transactions via an alternative process called proof of stake. Because this process doesn't rely on difficult hashing calculations, it uses much less computing power (and much less electricity).

5

The validated block is added to the blockchain with a digital fingerprint that also mathematically encodes the validated fingerprints of every block preceding it. These nested fingerprints make the blockchain increasingly secure with every new block that gets added because altering a single bit of information anywhere in the blockchain would drastically change not only the fingerprint of that particular block but every subsequent one in the chain as well.



BLOCKCHAIN DEMYSTIFIED: FREQUENTLY ASKED QUESTIONS ABOUT A RAPIDLY EXPANDING TOPIC

1. ARE BITCOIN AND BLOCKCHAIN THE SAME?

No, but it's easy to get them confused because they both came into public awareness in 2008, when Satoshi Nakamoto published his paper describing how to implement them simultaneously. Bitcoin is one type of cryptocurrency. What people call "blockchain" is a technology that makes Bitcoin possible—an infrastructure that can be used for tracking many types of transactions. Blockchain technology exists without Bitcoin—but not the reverse. Think of Bitcoin as a kind of application that runs "on" the blockchain, much like Web sites run on the Internet.

2. WHERE DOES THE VALUE OF A CRYPTOCURRENCY COME FROM?

Some experts say that a cryptocurrency like Bitcoin has value because of its security (the Bitcoin blockchain has never been hacked—yet) or its mathematically imposed "scarcity" (a fixed supply of 21 million Bitcoins means they can never be devalued by "printing more money"). Others say that they have intrinsic value because mining them is tedious work that makes the network stronger—in other words, there's value in effort. But what about cryptocurrencies that aren't mined? According to Christian Catalini of the Massachusetts Institute of Technology, "value comes from consensus. We all *agree* it has value." In this sense, cryptocurrencies may have more in common with social networks than with central banks. "Money is a way for society to keep track of checks and balances," Catalini says. "If cryptocurrencies end up being a better way to track information," their value is secured—whether they represent a physical asset or just a number.

3. IS THE BLOCKCHAIN A NEW KIND OF INTERNET?

Not quite, because the blockchain itself requires the Internet to support and maintain its peer-to-peer network. It's also important to note that when people talk informally about "the" blockchain, they're almost always referring to the specific system that Nakamoto implemented to support Bitcoin. The Bitcoin blockchain was the first distributed ledger system that didn't require a centralized server or organization to support it. It's still one of the biggest: as of November 2017 it contains more than 130 gigabytes (140 billion bytes) of information, and every new transaction increases its size. But that's still many orders of magnitude smaller than the amount of data on the Internet, which is estimated to be on the yottabyte scale (10^{24}, or septillions of bytes).

4. ARE BLOCKCHAINS EVEN LEGAL?

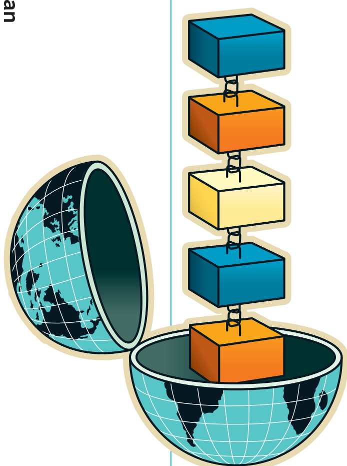
Yes. But their decentralized nature and association with Bitcoin—which has been used in illegal transactions such as drug and arms sales—can give blockchains an "outlaw" reputation it doesn't necessarily deserve. Blockchains can be used for many different purposes, good or ill, just like Facebook, e-mail or any other Internet technology.

5. HOW ARE CRYPTOCURRENCIES SECURE AND TRUSTWORTHY?

Because they're ultimately nothing but software, the trustworthiness of a cryptocurrency "comes from the code base," says M.I.T. researcher Catalini. Anyone can gin up a cryptocoin and raise funds by selling it through an initial coin offering—even Paris Hilton did it, lending her name to promote an obscure token. But it's no coincidence that the two most popular cryptocurrencies, Bitcoin and Ether, were engineered by computer-programming savants. That said, even coins with impressive technical bona fides can be risky. The DAO—a "decentralized autonomous organization" running on Ethereum that raised over $100 million in 2016—"had a bug" (in Catalini's understated terms) that allowed hackers to make off with $50 million worth of Ether.

10%

Predicted amount of the world's gross domestic product that will be stored in blockchain-based technology by 2025, according to a 2015 survey report from the World Economic Forum.



WHO IS USING BLOCKCHAIN TECHNOLOGY?

It's not just for cyberlibertarians, and it goes way beyond finance. Here's an incomplete lineup:

- **FINANCIAL INSTITUTIONS:** Global banks and investment institutions are researching and pursuing blockchain projects, sometimes joining forces in consortiums. Since 2012 Ripple has been a thriving, blockchain-based system for settling international transactions among banks. Start-ups such as Bloom intend to deploy blockchains to credit reporting, hoping to end data breaches like the Equifax hack.
- **GOVERNMENTS:** Delaware and Illinois use distributed ledgers for birth certificates. A Vermont law allows blockchain technology to verify the authenticity of legal documents. Dubai integrated blockchains into many of its administrative services, such as obtaining licenses. In 2016 Tunisia began issuing a blockchain-backed version of its digital national currency called the eDinar.
- **TECH ENTREPRENEURS:** The Ethereum network—which was designed to support new applications, rather than just a digital cash ecosystem like Bitcoin—is like an App Store for blockchain start-ups. Hundreds of projects and businesses are running on it. One notable: WePower wants to let households buy and sell renewable energy (from, say, roof-mounted solar panels) directly to one another.
- **COPYRIGHT AND IP HOLDERS:** U.K. musician Imogen Heap started Mycelia, a tech incubator that tracks metadata associated with creative works, cutting out intermediaries like iTunes.
- **NONPROFITS AND AID GROUPS:** The BitGive Foundation is boosting the accountability of philanthropic giving. And the United Nations World Food Program is streamlining how it tracks and delivers assistance to Syrian refugees in Jordan.
- **ACADEMIC INSTITUTIONS:** Forget sheepskins. The Blockcerts project wants to make all manner of academic and professional credentials more trustworthy and shareable.
- **ASSET MANAGERS:** London-based Everledger is targeting the diamond industry by recording the attributes and provenance of each precious stone. Fine wine and art are tracked, too.
- **JOURNALISTS:** To push back against fake news, Civil gives news makers a platform to create ad-free, inalterable journalism that's immune to outside interests (Russia; Facebook) and supported by readers.
- **REGULAR PEOPLE:** For migrant workers who send money to their families back home, using Bitcoin costs less than using Western Union, which is why an estimated 20 percent of international remittances between South Korea and the Philippines now rely on it.

77%

of the global financial services industry is expected to adopt blockchain as part of a production system or process by 2020, according to PwC.

SO, BITCOIN: THE FUTURE OR A FLASH IN THE PAN?

Bitcoin is the world's most popular digital currency. But it's also wildly speculative, and many financial experts point to its legendary volatility: the currency's value has risen more than 10-fold since 2016, but it lost 40 percent of its value in a span of two weeks in September 2017—only to regain (and surpass) it just as quickly. (Who knows what it will be by the time you read this.) To others, the network's technical limitations—it is sluggish at handling transactions—combined with its unsustainable mining costs make it the equivalent of a financial time bomb. "We don't bet on Bitcoin," says Charlie Morris, chief investment officer of NextBlock Global, a firm that invests in blockchain technology.

Bitcoin legitimized the basic economics of a global cryptocurrency. But the next-largest "altcoin" may have more staying power: Ether is less a cashlike currency than a "blockchain asset," as Morris calls it, used to power and secure the Ethereum network. Much like renting virtual servers in Google's "cloud," developers who want to create applications using Ethereum's blockchain must pay for access in tokens of Ether. The more useful Ethereum becomes as a mainstream platform, the more stable and valuable Ether becomes, too. New currencies and platforms are very likely to emerge—the race for prominence has only just begun.

WHY WOULD YOU USE A CRYPTOCURRENCY INSTEAD OF A NATIONAL CURRENCY?

Imagine holding a $100 bill that buys only $50 worth of goods. In Venezuela, where the official currency is crashing in value, that scenario is a reality. "You're losing something like half of the value of your net income every year to hyperinflation," says venture capitalist Morris. "People are thinking: 'How can I stop that?' And they're buying Bitcoin."

Why would a hard-to-understand cryptocurrency with no government guaranteeing its value as "legal tender" seem like a better bet than a more traditional value-holding commodity such as gold? For one thing, converting Venezuelan bolivars into Bitcoin is simply a lot easier for ordinary folks—anyone with access to the Internet can do it. Because Bitcoin has no physical form, you don't have to stash it somewhere unsafe—like a mattress or, in Venezuela's case, a bank. Of course, Bitcoin doesn't have a stable value, either. But while the bolivar has nose-dived, the value of a Bitcoin is at least trending ever upward. In a country where inflation is expected to exceed 2,300 percent in 2018 (according to the International Monetary Fund), it seems like a reasonable risk to take.

Zimbabweans have the opposite problem. After ditching its own currency for the U.S. dollar, the country now relies on currency imports to run its economy—and it's facing a shortage. Bitcoin is now common enough that it's even accepted by car dealers.

ARE WE FACING THE END OF CASH?

It may seem that printed money is headed for the same fate as newspapers. But experts say that cash is far from dead. "We're still using great piles of paper to pay for things like international shipping of sea containers," says Vinay Gupta, CEO of Mattereum, a legal services firm for smart contracts. "The system is not so broken that people are willing to tear it up." The trouble with Bitcoin and Ether is that while they can function as a store of value or unit of exchange, they're not accepted as legal tender in enough places to compete with cash.

In places such as Kenya, where few people have traditional bank accounts and "mobile money" services such as M-Pesa have made saving and sending money by phone much easier than exchanging physical cash, cryptocurrencies might seem like a natural fit. But mining still requires a lot of processing power—not a common resource in Africa, where inexpensive feature phones outsell smartphones and not many own PCs. The computations required to secure blockchain transactions could, in theory, happen on "your old Nokia SIM card," Gupta says. Still, cold, hard paper won't soon disappear.

3 4 5

3

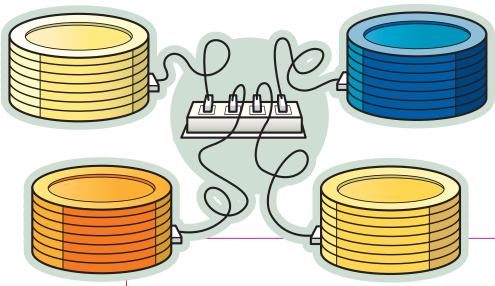
IS THE BLOCKCHAIN A NEW KIND OF INTERNET?

4

ARE BLOCKCHAINS EVEN LEGAL?

5

HOW ARE CRYPTOCURRENCIES SECURE AND TRUSTWORTHY?

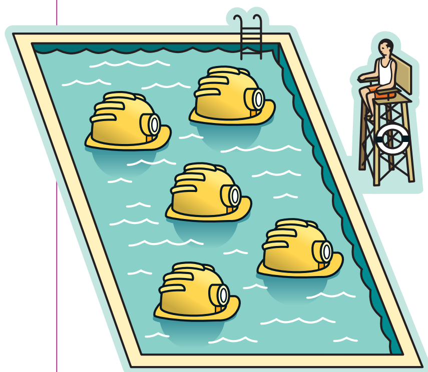


IF CRYPTOCURRENCIES ARE DIGITAL, WHAT POWERS THEM?

Just because cryptocurrencies have no physical attributes doesn't mean that there's no cost to using them. The intentionally effortful process by which new Bitcoins are "mined"—how new transactions are added to the ledger—requires that the entire P2P network cycle through a mind-boggling number of random computations to validate blockchain transactions. All of that processing requires energy.

How much energy? Start with the amount of computation. In late 2017 the Bitcoin network's "hash rate" was around 10 exahashes—that's 10 million trillion calculations—per second. Deriving a precise energy estimate from that figure is impossible because the network, being decentralized, can't account for individual nodes. But credible estimates peg the Bitcoin network's annual electricity consumption at around 27 terawatt-hours—roughly equivalent to that of Ireland. To put that in perspective, producing a year's worth of Bitcoin alone requires the equivalent of burning about 11 million tons of coal, which pours nearly 29 million tons of carbon dioxide into the atmosphere. Fueling Bitcoin by solar power would require harnessing more than half of the entire U.S.'s annual utility-scale solar capacity.

Ethereum's creator, Vitalik Buterin, is currently transitioning the network's blockchain to a different validation mechanism called proof of stake, which doesn't rely on mining at all. Bitcoin's larger, more decentralized network is unlikely to make a similar move anytime soon. But Vinay Gupta, who designed Dubai's blockchain strategy, believes that the same greed that motivates miners to turn kilowatts into cryptocurrency will ultimately spur them to innovate their way out of this scalability problem. Venture capitalist Charlie Morris thinks that as proof-of-stake cryptocurrencies prove their mettle in the market, "mining will become like a little blip in history," he says. "People will say, 'Remember when we all did that—wasn't that ridiculous?'"



WHERE DOES MINING ACTUALLY OCCUR?

71%

of Bitcoin is mined in China; the next most active country is India, at 4 percent. Tip: Don't try mining at home—alone. The task is now dominated by giant mining pools akin to the ones in China, so the chances of a solo node mining a block today is about one in eight million. Lone operators would spend far more on energy bills than they'd get in profits. Want to become a mining hobbyist? Join a public mining pool.

WHAT DOES THE PUBLIC THINK ABOUT BLOCKCHAIN?

62% of Americans believe cryptocurrencies are used for illegal purchases or don't know what they're used for at all, according to a 2017 YouGov survey.

59% of global consumers polled in a 2017 HSBC survey said they had never heard of blockchain technology; 80 percent of those who had heard of the technology still don't understand what it is.

39% of senior executives at large U.S. companies indicated they had little or no knowledge about blockchain technology, according to a 2017 Deloitte survey.

HOW WILL THIS TECHNOLOGY BE USED IN THE FUTURE?

Anyone building on blockchain technology is, by definition, a futurist. Once distributed ledger technology gets out of its training-wheels phase, what might we create with it?

- **SELF-DRIVING, SELF-OWNING CARS:** Instead of driving for Uber, your car would drive itself while you work or sleep. Blockchain-backed smart contracts could remove middlemen like Uber and Lyft from the car-sharing equation by automating their two basic functions—matching cars with riders and facilitating payments. You could also own "shares" of a car represented by cryptocurrency tokens.
- **PORTABLE MEDICAL DATA:** The same technology that allows two people to exchange units of Bitcoin without necessarily trusting each other could also vouchsafe medical information, putting control firmly in the hands of patients, says Brian Behlendorf, executive director of the Linux Foundation's Hyperledger project, a tool kit for building blockchain applications. Patients would receive a "'health wallet" with their data and histories. A doctor could go to a ledger and request your blood type, generating an access request on the user's phone. "You get an audit trail of who you shared that data with and the option to delete it when the treatment is over," Behlendorf says.
- **A GLOBAL SUPERCOMPUTER:** Linking your devices to thousands of others in a P2P network—and using a blockchain to pay you for their use—would create a financial incentive to support a worldwide, decentralized supercomputer. While you sleep, your laptop and phone could be rented by scientists who want to run models, for example. A project called Golem is already working on it. "The number of idle laptops is so much larger than the computing power of the data centers," Gupta says. "Artificial intelligence, climate modeling—all of that stuff could be accelerated 1,000-fold."

4

WHAT ARE THE LIMITATIONS AND DANGERS OF BLOCKCHAIN?

"Blockchains provide a substrate that, if certain assumptions are held to, is very difficult to modify ex post facto," says Cornell blockchain researcher Emin Gün Sirer. "But that doesn't mean that everything recorded to a blockchain is true or desirable. If I get hacked and someone steals my cryptocoins and tries to use them, I would very much like to undo that transaction. That's where immutability becomes a liability." It's also easy to confuse a blockchain's theoretical immutability with actual data security: public blockchains like Ethereum and Bitcoin don't actually encrypt any information. The Linux Foundation's Brian Behlendorf goes one step further: "The ledger should never be used to store personal data or anything sensitive, not even in encrypted form," he says, "because we know that no matter what we encrypt today, probably in 40 or 50 years we'll be able to decrypt it" with more advanced technology. Some advocates speak of blockchain as a panacea for any social problem involving trust, but that's blindly optimistic. For more on the limitations of blockchain as a societal savior, see page 38.

HOW DO YOU REGULATE A DECENTRALIZED SYSTEM?

Given the Wild West reputations of decentralized digital currencies, it's easy to assume that they were created to dismantle or avoid financial regulation. But that's not quite accurate. Bitcoin is full of regulations, after all—they're just defined and enforced by source code (and the collective activity of its P2P network) rather than by governments or financial institutions. "The whole innovation about Bitcoin is in eschewing social governance of record keeping," says Patrick Murck, a lawyer who researches blockchain policy and regulation at Harvard University's Berkman Klein Center for Internet and Society. Ethereum's stated purpose—to support the deployment of autonomous smart contracts—is essentially regulatory. A blockchain is arguably nothing *but* regulation: a mathematically enforced system of rules about what can and cannot be done with records in a database.

What always matters about financial regulation, decentralized or not, is who gets to do the regulating and how. "If you have a system that's decentralized, there's nowhere to attach regulation—but wherever that system gets reintermediated [by third parties], regulation will follow," Murck says. In 2013 China banned cryptocurrencies from its banking system, and last September it ordered all domestic Bitcoin exchanges to shut down. The U.S. and Japan are moving to regulate cryptocurrency exchanges and "initial coin offerings" with the same vigilance they apply to stock trading and investment banking.

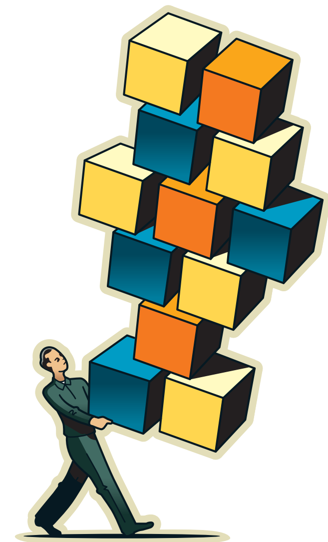
One future application of blockchain technology is in securing digital identity records, and according to venture capitalist Charlie Morris, new cryptocurrencies may emerge that marry identity data with financial information. They wouldn't have the anonymity of Bitcoin (Morris estimates the number of Bitcoin holders who pay honest taxes on them to be mere hundreds). But as digital money goes mainstream, the trade-off in perceived security and stability may make oversight tolerable—or even desirable. Says Murck: "If I'm trusting you with some property to hold on my behalf and transact with it—whether it's Bitcoin or Beanie Babies—then you're either regulated or about to be regulated."

5

CAN BLOCKCHAINS FAIL?

To date, the Bitcoin blockchain—the world's first and at present its largest and most widely used—has never been compromised or hacked. But that doesn't mean that every blockchain is invulnerable by definition. "There's no such thing as a perfect technology," says Cornell's Gün Sirer, co-director of the Initiative for Cryptocurrencies and Contracts. Here are three gaps in a blockchain's armor:

51% ATTACK: Blockchain-backed cryptocurrency networks rely on two bottomless resources for security: the speed and greed of their miners. But it's theoretically possible to overpower both. To subvert the blockchain's consensus mechanism, hackers would need to gain control over a majority of nodes in the network. This would give them the power to control how and which blocks get mined. They could reverse new transactions, allowing them to double spend digital currency. Or they could prevent other people's transactions from being validated. Bitcoin's P2P network, with thousands of nodes worldwide, seems unlikely to fall prey to such an attack. But smaller "altcoins" are at risk: one called Krypton was hit in 2016 by a group called the 51 crew. Even blockchains that don't use mining are vulnerable because they still rely on an "assumption that a majority of nodes in their network are benign," Gün Sirer warns.



GOOD OLD-FASHIONED HUMAN ERROR: It may take the computing equivalent of moving mountains to compromise the blockchain itself. But anything built on it or attached to it is just as vulnerable as it is now. Mt. Gox, a Bitcoin currency exchange (that is, an intermediary that lets people convert traditional currencies—like dollars—into Bitcoin) plagued by mismanagement and faulty code, lost 850,000 Bitcoins (worth $620 million at the time) in 2014. Ultimately blockchains are just distributed ledgers with no help desk—so if you have a digital wallet full of cryptocurrency and you lose the password, that money is almost certainly gone. There is rich irony in the fact that some cryptocurrency users keep a hard copy of their pass codes (or even the currency itself, stored on a USB drive) in a safety deposit box at the bank—a practice known as cold storage.

"BLOCKCHAIN BLOAT": This is less of a vulnerability than a natural consequence of blockchains working too well. Because every new block essentially revalidates every block before it, that means every node performing the validation needs a copy of the latest version of the entire chain to deal with every new transaction. At more than 130 gigabytes and growing, the Bitcoin blockchain is already getting unwieldy. Ethereum's ledger, designed to be more flexible (so that it can act as a platform for more sophisticated transactions such as smart contracts), is already bigger than Bitcoin's—if everyone were to start using it, would only high-performance supercomputers be able to handle the load? That could effectively decentralize the network, defeating the purpose of the distributed ledger in the first place.

THE FUTURE OF MONEY

THE EVOLUTION OF TRUST

THE ULTIMATE SOCIAL IMPACT OF BLOCKCHAIN TECHNOLOGY DEPENDS ON WHO CONTROLS OUR DIGITAL IDENTITIES

BY NATALIE SMOLENSKI

IN BRIEF

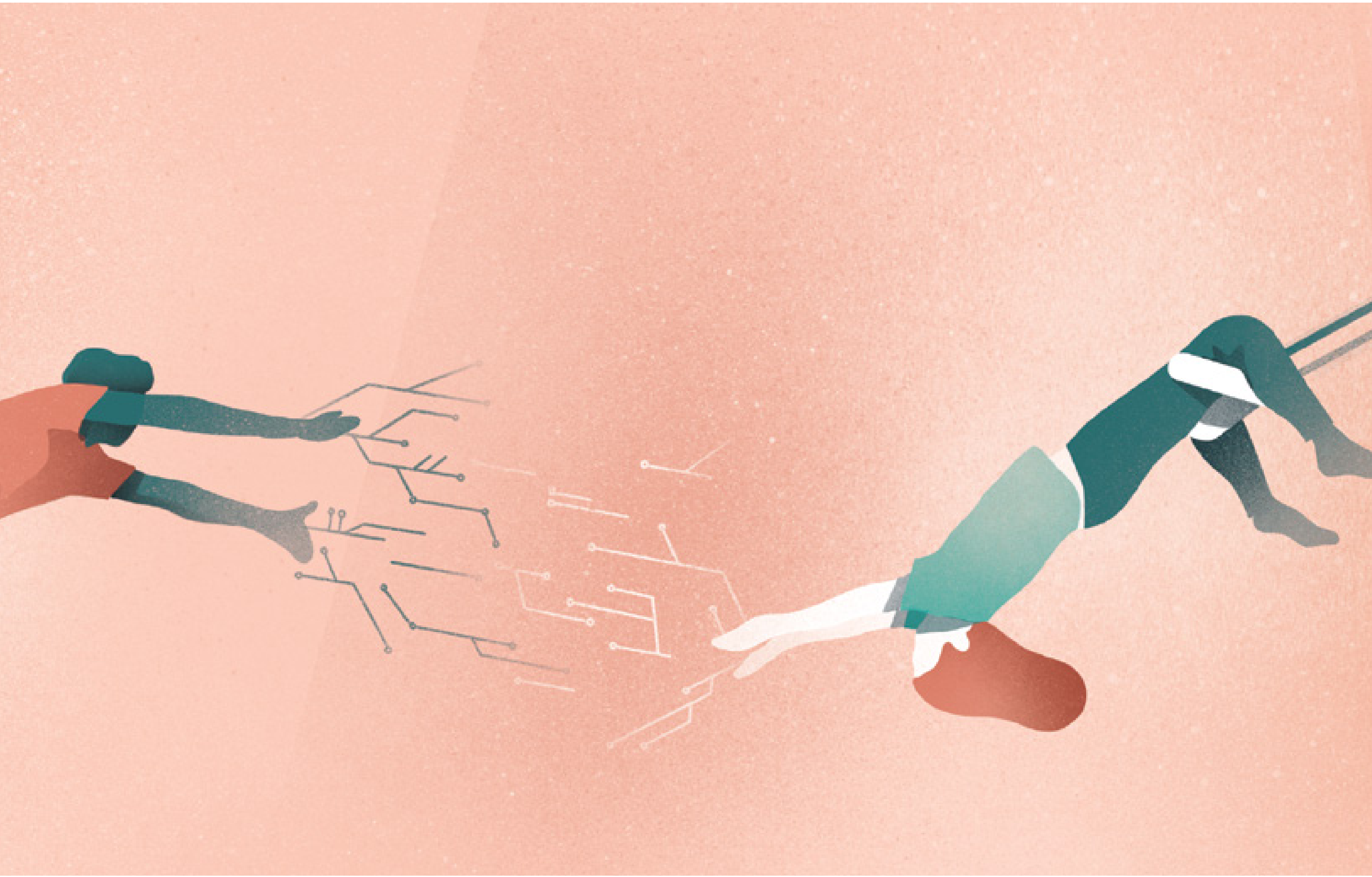
Banks and governments have in many ways failed to broker trust for the global economy, especially in the past few decades. Ordinary people have grown wary of centralized power and are seeking alternatives.

Bitcoin—and blockchain technology in general—allows the brokering of trust to be shifted toward machines and away from human intermediaries such as bankers. This technology could design exploitation out of the system instead of punishing it later.

Blockchains lend themselves both to human emancipation and to an unprecedented degree of surveillance and control. How they end up being used depends on how the software handles digital identity.

TO PARTICIPATE IN TODAY'S GLOBAL ECONOMY, ordinary people must accept an asymmetrical bargain: their lives are transparent to states, banks and corporations, whereas the behavior and inner workings of the powerful actors are kept hidden. The boundaries between the consumer and the citizen have irreversibly blurred. Harvard University social scientist Shoshana Zuboff has called this one-sided, extractive interaction "surveillance capitalism," and it is a major structural issue. The very institutions whose charter is brokering social trust—banks and governments—have in many parts of the world spectacularly failed to do so, especially during the lifetimes of those younger than 35.

The 2008 financial crash and its aftermath gave



shape to a kind of ambient helplessness. Of the legal cases that were brought to court, most were settled at shareholders' expense rather than resulting in jail time for high-ranking bankers, which convinced many that the wealthy and powerful collude for their own benefit. The issues run much deeper than the fallout from bad mortgages. An analysis of a 2007 database listing 37 million companies and investors across the world yielded the conclusion that 1 percent of these companies control 40 percent of the network, and most of the 1 percent are financial institutions. Over the past three decades investment earnings have become the chief source of economic growth in most countries, far outpacing income growth and making the top tier of wealthy people even wealthier. In the meantime, two billion people are still unbanked, excluded even from a far from perfect network that in principle facilitates access to capital. There is no agreement about whether or how these trends should be transformed to promote greater economic equality and inclusion without compromising individual autonomy.

That brings us to a historic moment in which mistrust of authority in the forms of power and wealth grows against a background of economic life that is inescapably global and mobile. If there's an impulse to retreat from it all in protest, there's also an acknowledgment that doing so is a recipe for economic self-sabotage. These constraints have led technologists around the world to imagine alterna-

Natalie Smolenski is a cultural anthropologist who writes and speaks about the intersections of identity, technology and government. She also leads business development for Learning Machine, a firm that makes applications for issuing and verifying official records on the blockchain using the Blockcerts open standard.

tives that simultaneously scale trust while making it more intimate and reciprocal. It's no coincidence that the world's first successful digital currency, Bitcoin, emerged on the scene in 2009: it represents a reaction to this growing desire for transparency, access and empowerment.

Bitcoin, of course, is a currency that is transacted via a blockchain—a new digital infrastructure that functions as a distributed ledger of transactions, validated according to mathematical consensus rather than by humans. It is revolutionizing the possibilities for direct exchange and individual ownership, not only of money but of any digital asset.

Bitcoin—and blockchains in general—is often referred to as "trustless." But this isn't quite accurate. Rather trust has been shifted away from human actors and toward a cryptographic system, with material incentives for participating in the network. In other words, trust is being depersonalized. At first, this may seem like a paradox. Haven't all forms of trust relied on humans to some extent? Throughout history, the momentum of global migration and commerce has driven trust networks to scale from the small group of people any given person knows to communities largely made of strangers and enemies. To expand across the earth, feed growing populations, wage wars, build empires and engage in knowledge exchange, people have used trust technologies that evolved out of one another in a more or less overlapping sequence: kinship and gift giving, division of labor, account keeping (the origin of credit and debt), hierarchy, currency, universalizing religions and, most recently, banking.

At the beginning of the 21st century, trust is undergoing yet another stage of evolution. The very banks that underwrote modern capitalism by acting as secure brokers of trust have in many ways become an impediment to its development. In our current financial system, policy and law tend to disincentivize exploitative practices through punishment. In the future, blockchains could simply design those practices out of the picture.

BUILDING FROM A BLOCKCHAIN

BITCOIN'S CONSENSUS PROTOCOL, which sets out the incentives and requirements that frame participation in the network, is exceptionally good at maintaining a distributed, open, peer-to-peer system of governance. Its transactions are public, though pseudonymous, and its code is open-source and maintained by a global network of volunteer core developers. The Bitcoin blockchain also doesn't store identity data; it uses public/private key pairs, rather than accounts, as addresses.

But blockchain-based transactions are more traceable than cash, which means that once a key pair is tied to a known identity, network analysis can, for example, aid police in tracking down criminal actors. This reality runs counter to the assumption that cryptocurrencies are more suited to criminal activity than other types of currency. In fact, it reintroduces the specter of surveillance capitalism. Interestingly, blockchains have properties that lend themselves both to human emancipation and to an unprecedented degree of surveillance and control. Whether they end up being used for the former or the latter depends on how the architecture of the "software stack"—the blockchain protocol and the application layer—handles digital identity.

When it comes to protocol, it's important to understand that there is more than one way to design a blockchain. Generally, "blockchain" is used to describe a type of system in which a single, universal record of transactions is replicated, although there is no absolute agreement on a set of necessary characteristics. Countless chains have now been introduced, and they are built to solve different things.

Take Ethereum, a public blockchain that aims to be a global, distributed computer called the Ethereum Virtual Machine. Its chain stores smart contracts that are executed when the conditions they specify are met. Unlike Bitcoin, the users most highly invested in the network—determined via cryptocurrency security deposits—get to collectively validate new blocks. Misbehaving users have their cryptocurrency automatically confiscated.

Some blockchains are designed for communities with a higher level of trust among their users. These "permissioned" chains generally rely on a central authority that grants specific users access to the system so they can serve as transaction validators. To make sure everyone behaves, permissioned chains tend to rely more on disciplining by the central authority rather than automated material incentives. One major example is Ripple, a blockchain designed specifically to serve as a settlement network for transactions between banks. Similarly, the Enterprise Ethereum Alliance is made up of nearly 200 corporate members who are building an open-source tool kit so businesses can design their own permissioned versions of the Ethereum blockchain.

Still other blockchainlike initiatives are referred to as distributed ledgers because they may lack one or all of the underlying features of blockchains. They are generally permissioned, with many of their transactions also kept private. A major distributed ledger is R3 Corda, developed by a consortium of banks to facilitate consensus regarding financial agreements.

Permissioned blockchains and distributed ledgers arose in part to include some type of identity vetting for validators and transactors on the network. (By design, there is no native identity validation in the Bitcoin blockchain protocol.) The field of identity is the terrain on which the emancipatory or oppressive characteristics of blockchains will be socially realized. The easier it is to tie someone's transactions to an identity—and the more centralized and externally controlled an individual's digital identity becomes—the more the possibilities for abuse multiply.

PROMISE AND PERIL

THE AVERAGE PERSON cannot use any blockchain directly, in the same way that the Internet cannot be used directly. Rather the individual uses applications that make use of the underlying blockchain in one way or another. The application layer is where untold confusion and often outright bad faith can reign. The history of Bitcoin, for example, is littered with cryptocurrency exchanges and wallet providers who left gaping security flaws in their applications, leading to high-profile hacks and accusations of embezzlement. In the case of the Ethereum network, vulnerabilities have resulted in the theft or loss of millions of dollars in its Ether cryptocurrency, with virtually no recourse for users. In general, using any application built by a trusted third party to hold your blockchain-based digital assets is still a highly insecure proposition.

This is the crux of blockchain's catch-22: the public won't use blockchains without user-friendly applications. But user-friendly applications often achieve that ease through centralization, which replicates the conditions of control that blockchains sought to circumvent.

If blockchains are to become widely useful, though, some correlation of identity with transactions is necessary. Perhaps identity will not require a full disclosure of who you are. As some in the Bitcoin community have argued, the current fixation on identity verification is largely misplaced; generally, what people want to know is whether a particular claim about you is true: Are you over 21? Did you really get a Ph.D. from M.I.T.? Are you a U.S. citizen? We are habituated by the incentive structures of surveillance capitalism to believe that giving up sweeping personal data is necessary to get by in the world. Changing that presupposition is one of the most radical influences that blockchain technologies may have.

Imagine, for instance, a future of digital voting. An election board must be able to correlate the casting of a vote to a registered voter so that person's vote is marked as "spent." But that process doesn't necessarily have to identify the individual to the board: it could simply verify that the voter is registered to participate in that election and record that he or she has cast a ballot after that person has done so—all without correlating the vote to the voter.

Projects that minimize the dispersal of so-called personally identifiable information are still rare, in part because they are not easy to monetize—either in financial currency or in the "currency" that is personal data. One example is Blockcerts, a series of free reference libraries developed by the M.I.T. Media Lab and Learning Machine, where I work. Blockcerts allows individuals to hold their digital assets in a private wallet that is hosted on their own device. The documents issued to a person are not associated with any identity profile unless the recipient chooses to do so. All the code is open-source, so it can be inspected for integrity and used by anyone to build his or her own applications for sending, storing, sharing and verifying official documents. This claims-based approach is a step toward what some in the digital identity space have called "self-sovereign identity," which means that individuals have administrative control over their own data.

Blockchains are indeed a disruptive trust technology. But if blockchain-based applications are not designed with a commitment to digital self-sovereignty, there is nothing, in principle, preventing human beings from being treated as so many objects in a supply chain, with every movement and activity recorded, perhaps permanently. Creating digital identities whose existence is independent from governments and corporations is the next grand challenge that blockchains both pose and could help solve.

We are habituated by the incentive structures of surveillance capitalism to believe that giving up sweeping personal data is necessary to get by in the world. Blockchain technologies may change that.

MORE TO EXPLORE

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FROM OUR ARCHIVES

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scientificamerican.com/magazine/sa

SUSTAINABILITY

Can We Save the

Scientists are urgently transplanting, fertilizing and enhancing corals to help them adapt to warmer oceans, but rebuilding entire reefs will be daunting

By Rebecca Albright

ACROPORA CORAL in the Great Barrier Reef releases bundles of sperm and eggs. Corals along the reef's thousands of kilometers spawn once a year, during the summer.

Corals?

Rebecca Albright is a coral biologist and curator at the California Academy of Sciences. She focuses on understanding how coral reef ecosystems cope with changing environmental conditions.

I'M STANDING ON A BEACH IN AUSTRALIA, TOES DIGGING INTO THE SAND, ZIPPING UP MY WET SUIT before I dive down to the Great Barrier Reef. As I stare out at the ocean, I'm excited by memories of my previous dive at this site a decade earlier. Growing up in Ohio, I had spent my childhood reading *A Day in the Life of a Marine Biologist* when I wasn't glued to the Discovery Channel. I got certified for scuba diving in one of Ohio's murky limestone quarries and made it to the Great Barrier Reef a year later. I'm remembering the anticipation squeezing my chest the day of that dive. My friend Emily, now an expert in marine algae, and I took bets on how long we could make our air last, which turned out to be about two magical hours. We were mesmerized by a forest of vibrant corals teaming with cuttlefish, giant purple clams and graceful sea turtles.

Now I am back, this time as a postdoctoral researcher at the Australian Institute of Marine Science. I wade in up to my chin, tip my head underwater and look through my mask. My heart drops. Gone are the cuttlefish. Gone are the giant clams. Gone are the turtles. The corals are drab. Most of the thriving life has been replaced by algae and sediment. Although I know senior scientists who shared gut-wrenching stories of how a particular reef had degraded over their long careers, I feel I am too young—barely 10 years in—to see this alarming degree of change. Shouldn't I be having this experience at the end of my tenure, not the beginning?

DIVERS secure new coral fragments raised onshore at Florida's Mote Marine Laboratory back onto a reef so they will grow and fill it in, a strategy similar to reforestation on land.

My shocked realization happened in 2014, as the third global mass-bleaching event began. Corals, often mistaken for rocks, are made of living animal tissue that contains microscopic algae, which provide the organism with food and give it color. When rising ocean temperature stresses corals, they expel the algae, causing the tissue to bleach—turn white—and leaving it vulnerable to starvation and disease. The mass bleaching has persisted for three years, ruining reefs and breaking hearts worldwide. Although coral reefs can be threatened by overfishing, pollution and ocean acidification, the rapid and widespread destruction from warming is the greatest concern today.

The first major global bleaching events hit in 1998 and 2010, each time triggered by warming seas worsened by El Niño conditions. The 2014–2017 event was by far the longest and most extensive, harming more than 70 percent of the world's coral reefs. Two thirds of the Great Barrier Reef were reported as dead or severely bleached, and the devastating effects continue. Reefs are disappearing before our eyes. In the past 30 years we have lost approximately 50 percent of corals globally, and researchers estimate that only about 10 percent will survive past 2050. We need solutions, and we need them fast.

Although reefs cover just 0.1 percent of the ocean floor, they support nearly 25 percent of all marine species, including fisheries that feed millions of people worldwide. They also provide natural breakwaters that protect coastal communities by reduc-

PRECEDING PAGES: GETTY IMAGES; THIS PAGE: COURTESY OF JOE BERG *Way Down Video*

IN BRIEF

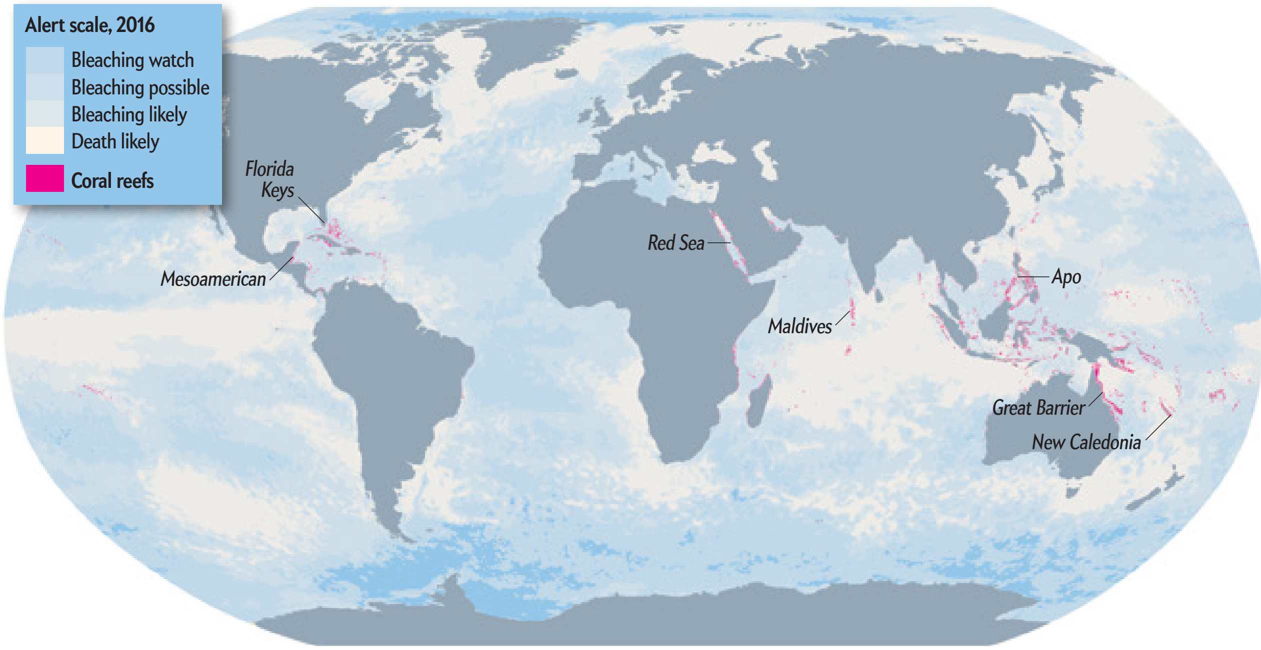
Ocean warming is killing corals. Scientists are trying several approaches to help them adapt, including transplanting lab-fertilized corals into the wild.

Researchers have found that stressing corals can turn on genes that lead to more resilient offspring, and enhancing certain algae can boost coral health.

These techniques could restore reefs on a regional scale, but a worldwide revival can occur only if humans slow global warming.

Worst Bleaching on Record

Relentlessly warm ocean water from 2014 to 2017 created the most extensive coral bleaching ever recorded. More than 70 percent of the earth's coral reefs were harmed. In 2016 alone (*map*), severe conditions spanned the globe (*white regions*). Hot water stresses corals, causing them to force algae out of their tissue, cutting off their food supply and leading to emaciation or death.



ing wave energy by up to 97 percent and wave height by up to 84 percent. And they generate vast tourism revenue. If we lose reefs, we jeopardize the livelihoods of 500 million people and more than $30 billion annually in goods and services. Even if you do not directly benefit from coral reefs, their destruction touches a chord in many people. As my colleague Luiz Rocha of the California Academy of Sciences puts it, "I may never live to see the *Mona Lisa,* but I still wouldn't want it to burn."

Driven by urgency, scientists are trying increasingly bold and creative ways to conserve and restore reef ecosystems. We are looking for techniques that are scalable and will not break the bank. Right now we are focusing on a handful of options that build on one another and can be integrated, including natural processes and human assistance. Together the steps might give corals the chance they need to make it through the coming decades, after which, it is hoped, the world will have drastically reduced its emissions, so warming will slow down.

I'm frequently asked: Will coral reefs survive? I think the answer is that they are resilient and might be able to cope, but they need breathing room—now.

NURSING CORALS BACK TO HEALTH

IF YOU WERE TO DIVE some seven kilometers off the coast of Florida, you might happen on one of several underwater forests of plastic trees with corals suspended from branches, like ornaments decorating a Christmas tree. Researchers are using such nurseries, as well as ones on land, to grow corals that can then be transplanted, or "outplanted," onto degraded reefs. Nurseries take advantage of the fact that all corals can reproduce sexually and asexually. Corals are clonal organisms—animals that are made up of hundreds to thousands of genetically identical polyps that are all clones of one another. They can reproduce sexually by creating eggs and sperm that fuse to create larvae and asexually when one polyp buds another.

When a coral is damaged by a storm, a piece of a colony might break off, tumble away, and eventually reattach to the bottom and continue to grow by cloning itself. Nursery practitioners can therefore deliberately fragment corals to create genetically identical clones. Today almost 90 species are successfully farmed around the world. Practitioners in the Caribbean and western Atlantic now grow and outplant tens of thousands of corals onto degraded reefs every year, often funded by private donors, grants or government restoration projects.

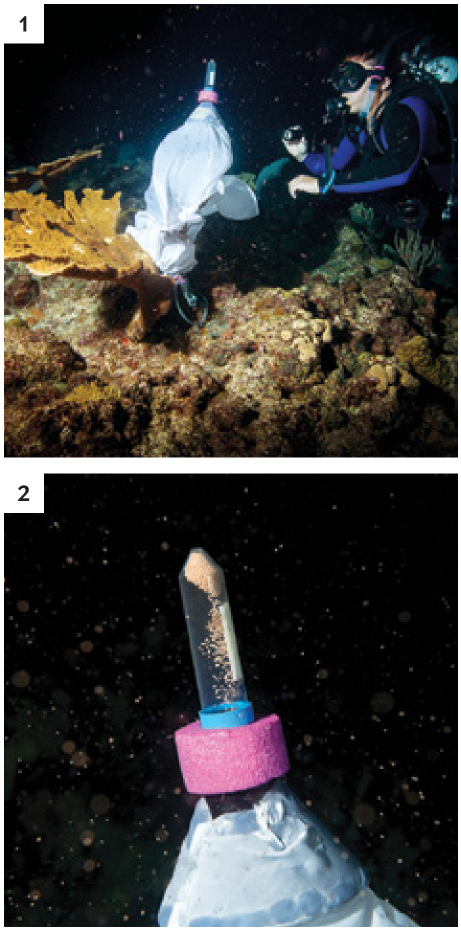
Scientists are looking to ramp up this restoration. Dave Vaughan of Florida's Mote Marine Laboratory recently discovered that because of a natural healing response, corals that are broken into tiny, eraser-size "micro fragments" can grow 25 to 50 times more quickly than corals in the wild. If pieces with the same genetic makeup (from the same parent) are placed a few centimeters apart, they will reconnect into a larger colony. In months, Vaughan's team can grow football-size corals that would have taken years to grow in the wild. After Vaughan began 12 years ago using older techniques, he produced 600 corals in six years. Now his team produces 600 corals in an afternoon

SOURCE: NOAA SATELLITE AND INFORMATION SERVICE

Map by Mapping Specialists

and has succeeded with all of the half a dozen species it has tried. Vaughan intends to produce and outplant 50,000 corals this year and 100,000 next year. He has vowed not to retire until he plants one million. When Vaughan first started, the price tag on a single coral was about $1,000. With improved technology and efficiency, his team is currently operating at less than $20 per coral. By integrating citizen scientists and volunteers, Vaughan is convinced that he can get the cost down to $2 per coral—$1 to reproduce it and $1 to plant it. Although the U.S. National Marine Fisheries Service says recovering the endangered Caribbean staghorn and elkhorn corals will require a minimum of $255 million and 400 years, Vaughan's goal is to remove them from the endangered species list in his lifetime.

We're now very good at growing corals, and we can, in many cases, successfully restore reefs to their historical range and function—at the local level. But a jump to the ecosystem level is massive. One of the toughest challenges is how to meaningfully scale to the big leagues. Most efforts cover less than a hectare, while reef degradation is occurring over hundreds to thousands of square kilometers. The price tag to replant the extensive Great Barrier Reef system, 2,300 kilometers in length, has been estimated at nearly $200 billion, using fragments at $5 apiece. But even that cost could be well worth it because the recovery would restore large fisheries that feed many people, create many jobs, and protect valuable coastlines and communities from storms.



ELKHORN CORAL'S sperm and eggs are collected underwater (*1*) in a tube (*2*). In the lab, researchers combine the gametes with those from other corals to make new varieties, which increases genetic diversity, improving resilience to ocean stresses.

COURTESY OF PAUL SELVAGGIO *SECORE International*

CORAL SEX

In addition to growing corals asexually in nurseries, scientists are having increasing success in helping corals reproduce sexually, which can broaden genetic variation. As populations decline, genetic diversity is lost, which lessens corals' ability to resist warming water. Many Caribbean reefs, for example, are dominated by a single clone, and both science and history teach us that relying on low genetic variation, particularly in times of environmental change, can lead to disaster. In the 1800s, for example, a single clone of the Irish lumper potato fed Ireland's growing population until a rot wiped it out, devastating the island's people and economy. A more diverse crop would have fared much better. As in potatoes and people, genetic diversity can make corals less susceptible to environmental stress.

Sexual reproduction is nature's way of building diversity. Corals are fixed to the ocean floor, so they cannot move around in search of a mate. To reproduce sexually, most corals release eggs and sperm into the water column where, fingers crossed, fertilization happens. In degraded areas, where corals are few and far between, this becomes increasingly unlikely.

At the California Academy of Sciences, we are partnering with The Nature Conservancy and SECORE International, a coral conservation organization, to help shepherd corals through this tricky process. We now have a good idea of when different coral species spawn. On predicted nights of spawning—after sunset, near a full moon in late summer (corals are surprisingly romantic)—coral colonies release eggs and sperm. We descend into the water with nets to harvest them and transfer these gametes to the laboratory, where we fertilize them in buckets of seawater. The resulting larvae are generally the size of sesame seeds and are vulnerable to being eaten in the wild until they settle and start to grow, so we raise them until they are big and healthy enough to be outplanted onto the reef. The goal is not to replant entire reefs but to maximize genetic variation and to rebuild enough of the population so the reef can then recover naturally and be more resilient to environmental change.

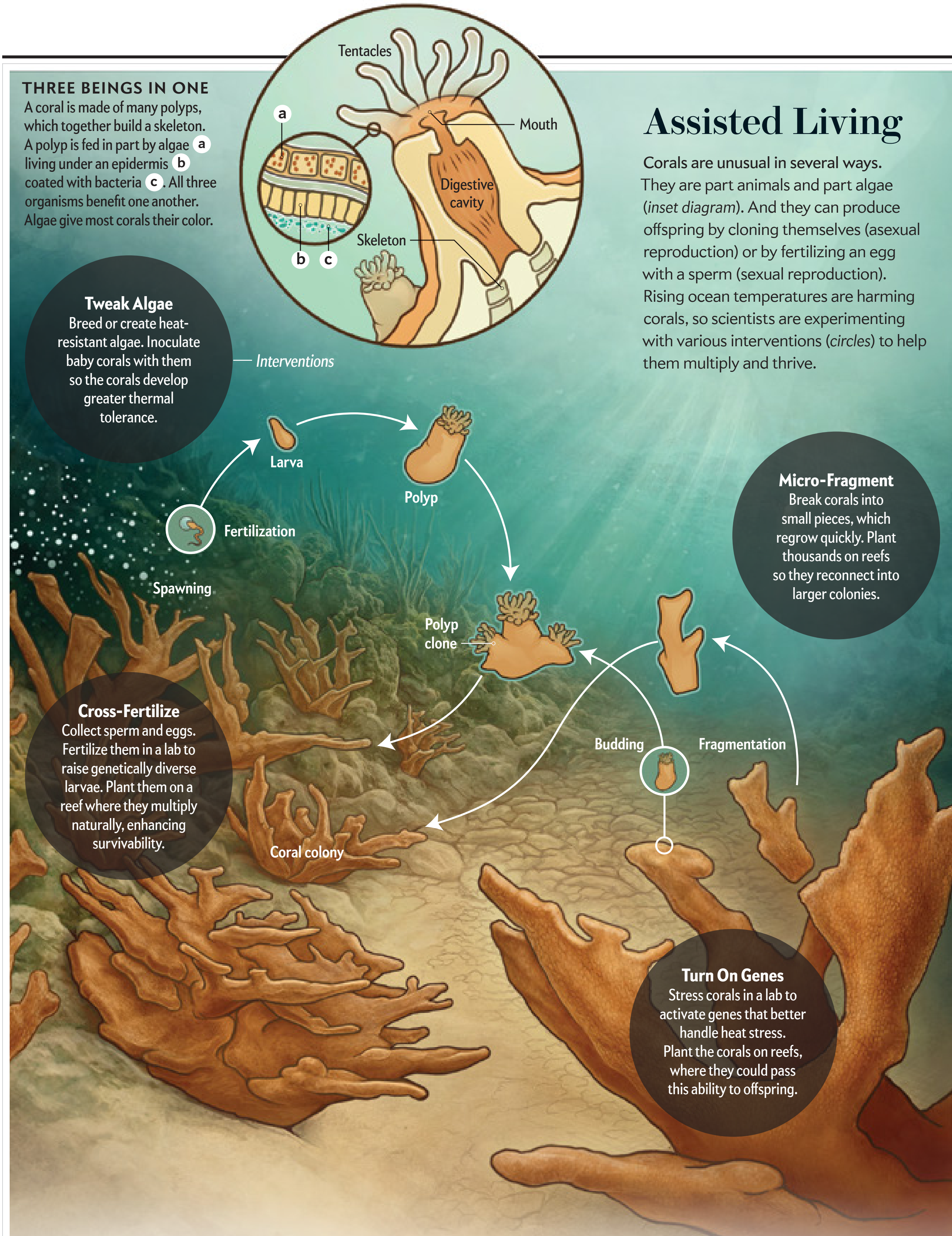
Many reefs have low genetic diversity, which prevents them from churning out coral babies. By combining asexual and sexual restoration techniques, we may be able to restore one reef to the point where it can rebuild healthy reefs nearby. The aim is to create something that has a life beyond itself.

In the wild, only about one in a million coral babies survive. We are doing everything we can to help them through the vulnerable early stages. We can now achieve almost 100 percent success in fertilizing corals in the lab and settling the larvae onto tiles that can be outplanted, increasing the number of sexually compatible individuals that can improve future reproduction without our help. At a spawning event in Curaçao in the Caribbean last year, I helped a team collect five million eggs from 25 colonies within two short days. This is a new record for SECORE "and shows the scales we could work with," says the organization's founder Dirk Petersen.

One of the biggest hurdles is keeping baby corals alive once we place them back in the sea. After all, degrading conditions are the main cause of coral decline in the first place, so until we tackle climate change, pollution and overfishing—through policy, awareness and global changes to the way we live—we are basically using a Band-Aid approach to buy reefs more time to try to survive. Along the way, we may be lucky enough to create

Assisted Living

Corals are unusual in several ways. They are part animals and part algae (*inset diagram*). And they can produce offspring by cloning themselves (asexual reproduction) or by fertilizing an egg with a sperm (sexual reproduction). Rising ocean temperatures are harming corals, so scientists are experimenting with various interventions (*circles*) to help them multiply and thrive.



SEXUAL REPRODUCTION

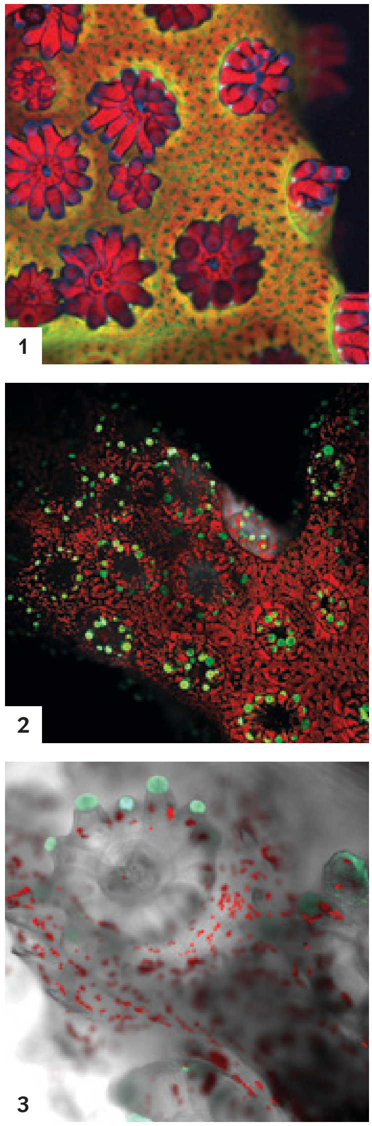
One night a year a coral colony releases millions of tiny translucent bundles that contain eggs and sperm. The bundles rise, dissolving near the ocean surface. If a sperm fertilizes an egg, the larva will grow, swim down to the seafloor, attach itself and metamorphose into a polyp that can branch out.

ASEXUAL REPRODUCTION

A polyp can clone itself by forming a bud that matures into a second identical polyp. Or if strong waves break a branch, the fragments can attach to the sea-floor and mature into adult clones of the original organism.

Illustration by Rebecca Konte

genotypes through sexual reproduction that we could mass-produce with asexual techniques. We could then outplant them so Mother Nature could select which species might thrive.



ALGAE (*red dots*) feed a healthy *Pocillopora* coral (*1*). Warming seas drive them off (*2*) until the coral is bleached (*3*), starving it of sugars. (Green dots are proteins.) Scientists hope to devise heat-tolerant algae that would persist.

COURTESY OF AMY EGGERS (1); COURTESY OF AMY EGGERS, KATIE BAROTT AND MINDY MIZOBE (2,3)

SUPERCORALS

WE CAN'T DEPEND ON good fortune for that scenario to happen. And because the ocean environment is changing too rapidly for many corals to adapt naturally, scientists are exploring other ways to accelerate the pace of adaptation. One approach is human-assisted evolution—enhancing traits that boost the capacity of corals, among other reef organisms, to tolerate stress and recover after bleaching events. Human-assisted evolution already surrounds our everyday lives. Most of the food we buy has been selectively bred or modified in some way (think "disease-resistant tomatoes"). Our pets have been selectively bred for certain aesthetics and personality traits. So why not breed or enhance corals to resist climate change?

Ruth Gates of the Hawaii Institute of Marine Biology and Madeleine van Oppen of the Australian Institute of Marine Science are collaborating to enhance stress resistance. Gates puts corals on "environmental treadmills" to condition them to handle stress. Exposing certain corals in the lab to sublethal temperature stress may actually prompt them to turn on certain genes that help them better handle greater thermal stress in the long run. This process, known as epigenetic tuning, might be even more exciting if the trained corals are transplanted onto reefs, where they can transfer this ability to offspring, creating a generation of "supercorals." In theory, epigenetic tuning could enhance corals' ability to resist bleaching.

We are only beginning to understand this process. Early lab tests are promising, but field trials have yet to be conducted. Once done, they will reveal whether transplanted corals confer enhanced abilities to subsequent generations, whether the approach can be scaled up and at what cost, and whether any inherent risks exist.

Van Oppen is exploring selective breeding. A certain amount of genetic diversity exists within each species, leaving some of them more or less resistant to bleaching or disease. As breeders do with pets to optimize desired traits, if we can identify resistant coral colonies and breed them to produce resistant offspring, we may be able to improve the temperature tolerance of an entire reef as subsequent generations pass down the useful genes.

Breeding corals is difficult because they can take up to a decade to fully mature. Adapting to environmental change is hard for the same reason. But microbes and algae that live in symbiosis with corals typically mature rapidly, and they can influence a coral's health tremendously. We are therefore trying to manipulate these organisms through artificial selection in ways that boost coral health. In recent years scientists have realized just how much our microbiome (the bacterial communities inside our body) influences our health, for better or for worse. Probiotics are now available in everything from yogurt to kombucha tea and even chocolate, claiming to boost digestion, immune function and overall health.

Van Oppen is currently developing strains of algae in the lab and inoculating baby corals with them to see whether they confer thermal tolerance. She and Gates are also attempting to see if epigenetic tuning, selective breeding and microbiome manipulations done on the same corals could possibly be even more effective in combination.

It is still early days for most of the techniques we are trying. But some evidence suggests that they could be combined for even greater success. This approach might look like the following: First, we would use sexual reproduction and assisted evolution to generate improved and new diversity among coral populations and to create individuals that have greater stress tolerance. Then we would mass-produce them in nurseries using asexual techniques and outplant them to reefs.

Could this happen soon? Not exactly. Some techniques, such as selective breeding, are immediately tractable, inexpensive and effective. But more work is needed to establish the viability and scalability of other techniques and to gauge the risks of unanticipated ecological consequences. It is possible, for example, that artificially enhanced organisms might possess novel traits that allow them to outcompete native populations rather than integrating with them, which would undermine the very goal of helping reefs thrive.

FROZEN FOR THE FUTURE

WHETHER WE BOOST CORALS using single or combined techniques, one other step is vital: preserving sperm, eggs, larvae and entire coral fragments in the equivalent of seed banks, which agronomists have used for decades to help raise crop yields, disease resistance and drought tolerance. The banks allow researchers to pull out biological bits and pieces as needed to further improve resilience and diversity.

RESEARCHER monitors transplanted corals in a bay surrounding the Gates Coral Lab in Hawaii to see how they are affected by acidic ocean water, another stressor imposed by climate change.

COURTESY OF THEOCEANAGENCY.ORG

Taking a page from the in vitro fertilization (IVF) handbook, Mary Hagedorn of the Smithsonian Conservation Biology Institute has established the first genome repository for endangered coral species. In IVF, sperm or eggs are cooled with liquid nitrogen to extremely low temperatures. The eggs can be thawed, fertilized in the lab and transferred to the uterus as embryos. Originally developed for humans, the cryopreservation concept has spread to help endangered species worldwide.

In 2004, some years after the first human baby generated from a cryopreserved egg was born, Hagedorn created the coral cryoconservation program. Her team has developed a freezing system for sperm that can be applied to a wide range of coral species. To date, the team has successfully banked 16 species from around the world (2 percent of the earth's estimated 800 species). Thawed sperm have fertilization rates comparable to fresh sperm, and the resulting embryos develop normally into healthy juveniles.

Hagedorn has distributed this germplasm, or living tissue, to cryobanks in various countries. Theoretically, it could remain frozen and alive for hundreds to thousands of years. The germ line cells could later be thawed and used in natural and captive breeding programs. For example, frozen sperm could fertilize eggs from places far beyond the sperm's natural range, introducing new genes into the coral gene pool. And of course, the banks can preserve species that may decline or disappear if reefs collapse.

Hagedorn hopes to cryopreserve eggs (in addition to sperm) and whole larvae within the next two years before moving on to entire micro fragments. She is also developing techniques to cryopreserve fish testes to help conserve reef fish biodiversity. Ultimately she envisions a future in which the germplasms of corals and other endangered reef organisms are deposited in highly secure facilities, making eggs, sperm and embryos available to broaden genetic diversity and rebuild reefs. "We have no idea what science will be able to do in 100 years," Hagedorn says.

Where do we go from here? Although some of these solutions may seem too unconventional by today's standards, we must invest in strategies for tomorrow. Many of these techniques have yet to be tested beyond the conceptual or lab stage, and questions remain about the scalability, costs and ecological consequences of manipulating reef systems. The consequences of doing nothing, however, threaten corals and the many species that rely on them.

What we know for sure is that there is no single fix to the problems plaguing coral reefs. Scientists are throwing everything we have at different options to buy reefs time. Although none of today's techniques is likely to salvage reefs at the global scale, many show promise on local or regional levels. The reefs of tomorrow may not resemble the reefs of today, but they can still provide important goods and services to ecosystems and to people. Climate change, pollution and overfishing are the larger challenges. We have to tackle them collectively to protect oceans overall and to give coral reefs the breathing room they need to survive. SA

MORE TO EXPLORE

Global Warming and Recurrent Mass Bleaching of Corals. Terry P. Hughes et al. in *Nature,* Vol. 543, pages 373–377; March 16, 2017.

California Academy of Sciences' reef program: www.calacademy.org/explore-science/hope-for-reefs

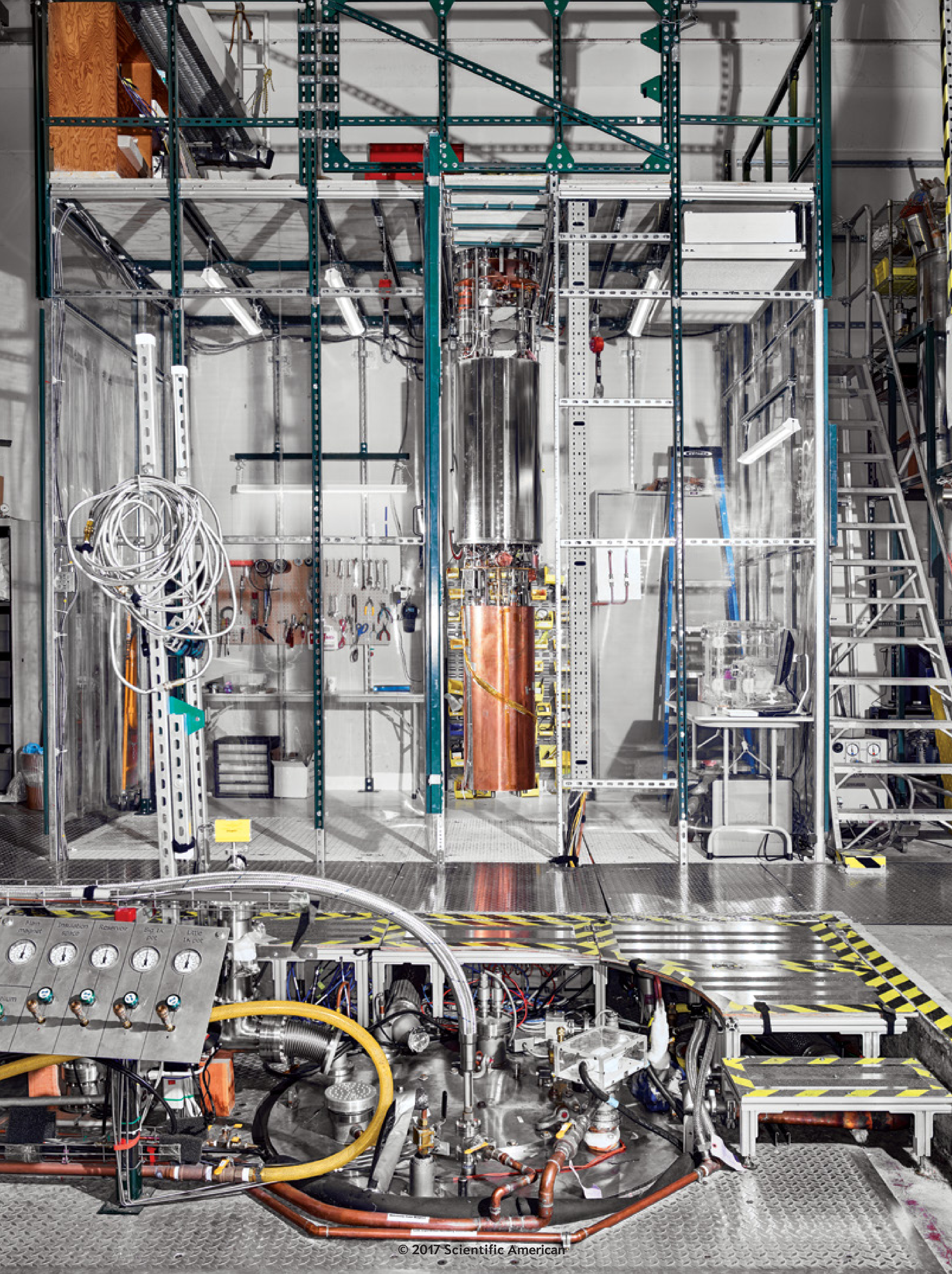
Mote Marine Laboratory's micro fragment program: https://mote.org/research/program/coral-reef-restoration

SECORE International's coral conservation program: www.secore.org

FROM OUR ARCHIVES

Corals as Paleontological Clocks. S. K. Runcorn; October 1966.

scientificamerican.com/magazine/sa



SEARCHING FOR THE DARK

ASTROPHYSICS

The Axion Dark Matter Experiment just entered the most sensitive phase yet in its search for invisible particles to explain the universe's hidden mass

By Leslie Rosenberg

IN THE BACKGROUND, the insert containing the heart of the ADMX experiment sits in a clean room. It will soon be lowered into a hole (*covered in this image*) in the foreground to begin a new run.

Photographs by Ian Allen

Leslie Rosenberg is a professor of physics at the University of Washington. He has been hunting for axion dark matter for more than two decades.

THE COSMOS IS MOSTLY MADE OF SOMETHING WE CANNOT SEE.

That was the conclusion astronomers started to reach in the 1930s by looking at galaxy clusters, which should have blown apart unless some "dark matter" was binding them together. Scientists started taking the idea more seriously in the 1970s, when astronomers studying how fast galaxies rotated found the same thing. Soon researchers realized that dark matter was unlikely to be made up of normal matter and radiation. By now it seems nearly inescapable that more than 90 percent of the stuff in the universe that clumps together under gravity is some exotic material, perhaps a new particle left over from the big bang.

For a long time the most popular dark matter candidate was the theoretical weakly interacting massive particle (WIMP), which fits into the much loved but speculative theory of supersymmetry. Yet sensitive terrestrial WIMP detectors have found no signs of such particles despite decades of searching. It is certainly too early to write off WIMPs, but these null results have raised the profile of non-WIMP dark matter candidates.

A less well-known candidate is the axion, another theorized particle that would weigh much less than the WIMP but would have a similar tendency to ignore normal matter. If axions are dark matter, they would abound everywhere—tens or even hundreds of trillions of them could be floating around in every cubic centimeter around you. Their only effects on the rest of the universe would be felt through gravity—their accumulated mass would be substantial enough to tug on the orbits of stars in galaxies and of galaxies in clusters.

For more than 20 years I have been part of the Axion Dark Matter Experiment (ADMX) search for these particles. Although we have not found them yet, we have been steadily improving our technology. In 2016 ADMX began a new phase. It is now sensitive enough that it should be able to either detect axions or rule out the most plausible versions of them over the next five to 10 years. We stand at an important threshold, and exciting news is coming soon, either way.

THE ORIGIN OF AXIONS

I WAS A GRADUATE STUDENT in the 1980s shortly after the idea of axions first arose from a problem with a theory called quantum chromodynamics (QCD). QCD governs the strong force, which holds together atomic nuclei. It has been remarkably consistent with experiments, except when it comes to something called the strong CP problem. (CP stands for "charge parity.") QCD suggests that if you were to flip a particle's charge parity—that is, flip its electric charge and view it in a mirror—it would no longer follow the same rules of physics. Yet researchers have found no evidence that this is the case. This conflict between theory and experiment presents a serious conundrum—a crack in our best model of particle physics. The crack is the strong CP problem, and it suggests we are missing something big.

In 1977, when physicists Helen Quinn and Roberto Peccei were both at Stanford University, they realized that they could attack the strong CP problem in a simple, elegant way using the idea of broken symmetries. This concept, one of the recurring ideas in physics, goes like this: Sometimes nature is not sym-

IN BRIEF

Scientists are searching for unseen particles to explain the "dark matter" that seems to be exerting a gravitational pull on everything else in the universe.

An underdog candidate is the axion, a theoretical particle that could explain dark matter *and* solve a mystery about the "strong force," which binds atomic nuclei together.

The Axion Dark Matter Experiment recently became sensitive enough to either detect the most plausible versions of axions or rule them out.

metrical when it seems that it should be. For instance, if you stand a pencil on its end, there is a rotational symmetry whereby it is equally likely to fall in any direction. But what if it always falls in one direction? We would say that nature has made a choice and has "broken" the symmetry. When this happens in the context of particle physics, a new particle arises to maintain the underlying symmetry even though it appears, on the surface, to be broken. (The symmetry does not have to be obvious; it can be some abstract symmetry of the underlying mathematics.)

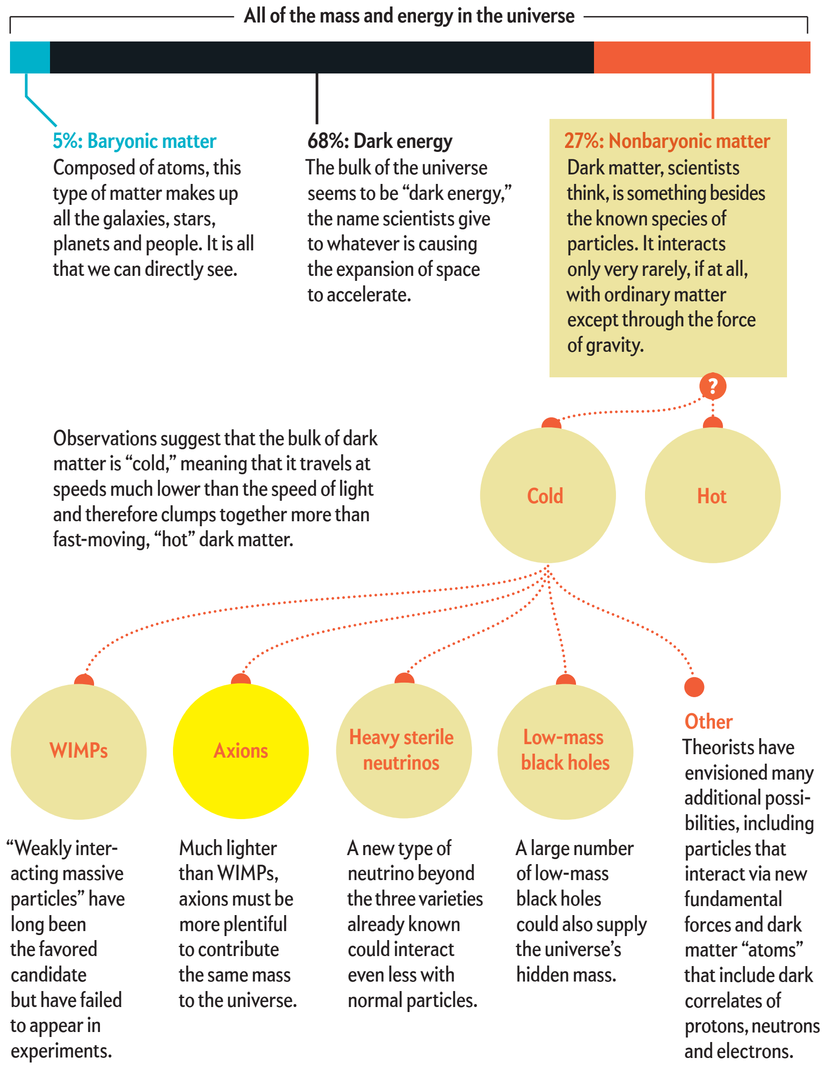
In what I thought was a brilliant insight, Quinn and Peccei applied this idea to the strong force. They speculated that a hidden type of symmetry related to this force has been broken. If this were the case, it would nullify the expected CP difference that theory predicted but that experiments failed to see. Problem solved. Shortly thereafter, in another brilliant insight, Steven Weinberg, now at the University of Texas at Austin, and Frank Wilczek, now at the Massachusetts Institute of Technology, realized this so-called Peccei-Quinn mechanism would result in a new particle: the axion. (Physics folklore says that the name was borrowed from that of a washing detergent because it "cleaned up" the strong CP problem.) By the mid-1980s theorists concluded that the big bang could have produced enough axions to account for dark matter.

The theory did not tell us how heavy axions would be or how likely they would be to interact with normal matter. We knew, though, that they had to be pretty inert because so far particle colliders and other experiments had not seen them. If they were extremely inert, they would also likely be very lightweight. And in 1987 a major cosmic event further limited the possibilities for the axion's mass. At that time a supernova exploded in the Large Magellanic Cloud, a nearby dwarf galaxy. Almost the entire gravitational binding energy of the star that collapsed escaped in the form of neutrinos, some of which made it to underground detectors here on Earth. If axions had a mass of even a few milli electron volts divided by the speed of light squared (meV/c^2) (somewhat more than one billionth the mass of the electron), they would have been produced in the explosion and distorted the escape time of the neutrinos on their way to Earth. Because experiments observed no such distortions, we knew the axions must have a smaller mass. Such light axions have extraordinarily feeble interactions with normal matter and radiation. For instance, a relatively mundane particle called the neutral pion decays into two photons roughly once every 10^{-16} second. A light axion would decay into two photons once every 10^{45} years—and that is many, many orders of magnitude longer than the age of the universe. The axion would be by far the least interactive particle known.

Interestingly, if the axion mass is too small, we have new problems. Because of the intricacies of the process by which we think axions were created near the beginning of the universe, the lower the axion mass, the greater the mass density of axions

Dark Matter Contenders

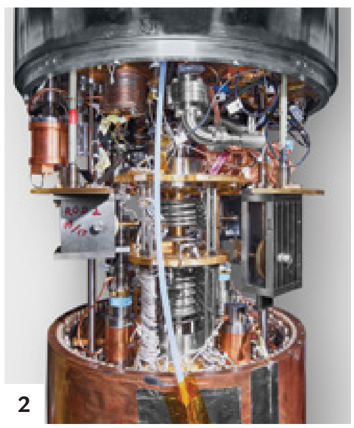
Something unseen appears to be exerting a gravitational pull on the normal matter in galaxies and clusters throughout the cosmos, but what is it? Scientists have theorized several potential explanations for the "dark matter" they think makes up about a quarter of the total mass and energy in the universe. These possibilities fall into various categories, as outlined.



Graphic by Jen Christiansen

that results. Should the axion mass be too small, the big bang would have produced way more axions than necessary to account for dark matter. There are substantial uncertainties about this mechanism, and theorists have come up with clever ways to evade the issue, but to me, it becomes increasingly implausible to have axions with masses much below one micro electron volt divided by c^2 (μeV/c^2).

To recap, axions cannot be too heavy, or else we would have seen them already, either through particle colliders or through their effects on the evolution of other stars. Moreover, axions cannot be too light, or else there would be too much dark matter. Determining exactly what these mass limits are is very challenging, but a reasonable range of allowed dark matter axion masses is in the neighborhood of around 1 μeV/c^2 to 1 meV/c^2. This range is the "sweet spot" for the axion mass, but such particles would be so unreactive to normal matter and radiation that they have been dubbed "invisible axions."



SCIENTISTS attach sensors to the experiment insert (*1*). Above the insert's copper-plated cavity is a liquid-helium reservoir surrounding electronics (*2*).

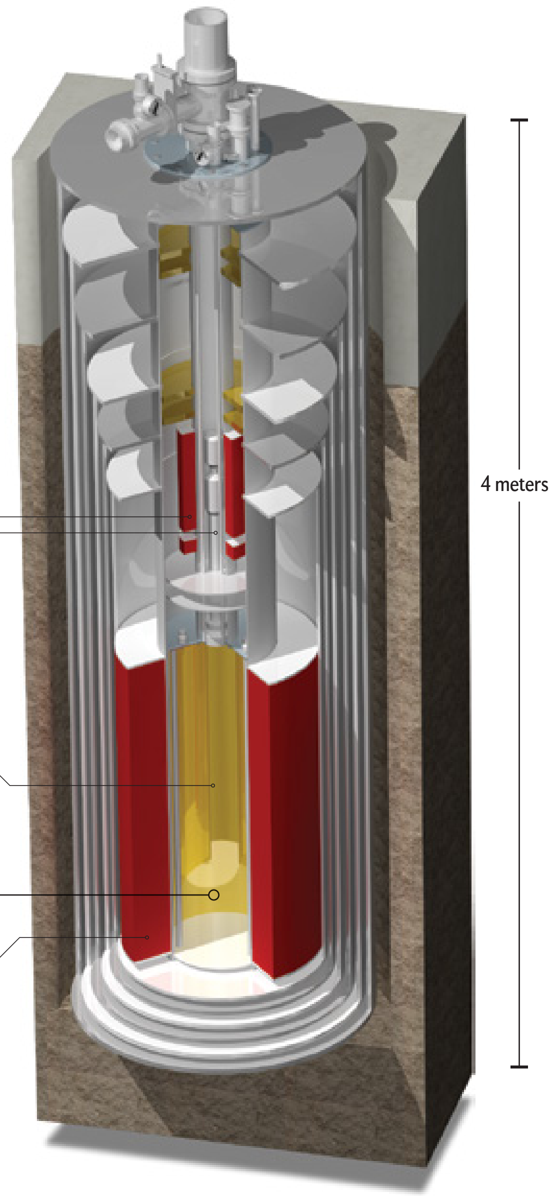
SIKIVIE'S GREAT IDEA

WHEN QUINN AND PECCEI first theorized the existence of axions, physicists at Stanford and elsewhere began searching for them in the explosions produced at particle colliders. Yet the very properties that make the axion an attractive dark matter candidate—its feeble interactions with ordinary matter and radiation—made these searches feel hopeless. It was frustrating to know that we may be bathed in a dense sea of particles—about 10 trillion axions or more per cubic centimeter—that are impossible to conjure up in the laboratory.

Then Pierre Sikivie of the University of Florida had a clever idea: rather than trying to create axions in accelerators, we could search for the cosmic axions that make up the vast, pervasive sea of dark matter around us. Sikivie imagined a magnetic field filling a cylindrical cavity that was devoid of everything except, presumably, the cosmic axions that flood all of space. When an axion interacted with the magnetic field, its total energy would be almost completely converted into a photon. This interaction would be much more likely to occur if the cavity was tuned to resonate with the same frequency as the photon produced by the axion. Because axions' mass is very small, and the cosmic ones near us are presumably moving at speeds similar to the rest of the Milky Way, their energy is tiny, so the resulting photon would be somewhere in the microwave frequency range. Exactly where, though, is a mystery until we know the precise axion mass. For this reason, experimenters would need

The Hardware

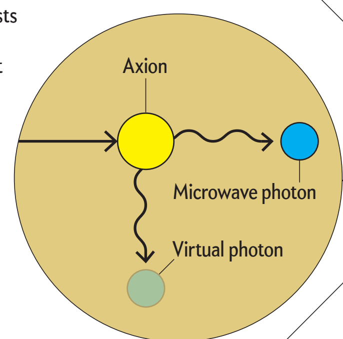
If axions are all around us, the Axion Dark Matter Experiment could find them on the rare occasions that they decay into microwave photons. To make this decay more likely, the experiment has a large magnetic field and a radio-frequency cavity that, if tuned to the same frequency as the photons produced by the axions, should encourage the transformation. In 2016 the project entered a new phase and began its most sensitive search yet.



Bucking Magnet
This smaller magnet cancels out, or "bucks," the magnetic field of the main magnet in the vicinity of the SQUID amplifier, which relies on a tiny magnetic field created by the photons to detect a signal.

SQUID Amplifier
This device uses quantum-mechanical effects to detect and amplify the minute signal created when an axion decays into a photon.

Microwave Cavity
The heart of the experiment, this empty cavity is where scientists expect ambient axions, which should be present throughout space if they constitute dark matter, to transform into microwave photons under the right conditions.



8-Tesla Magnet
The main magnet in the experiment fills the cavity with a magnetic field that encourages the axions to decay into photons.

to continually adjust the resonant frequency of the experiment's cavity to "scan" the possible range in hopes of hitting on the right match for the axion.

The resulting signal would be very small, perhaps 10^{-21} watt or less, with accompanying noise of around the same amount. But very sensitive microwave detectors, collecting a signal for a sufficiently long time, should be up to the job. Two of my great loves are radio electronics and particle physics, so in my mind, Sikivie's ideas fit together powerfully.

ADMX IS BORN

I RECEIVED MY PH.D. WHILE AT STANFORD in the 1980s, when the influence of Quinn and Peccei was still there, and axions made a big impression on me. They appeared to solve two huge mysteries in physics—the strong CP problem and the dark matter issue. And after Sikivie's paper, it seemed that there might be a way to detect them.

From Stanford, I moved to the University of Chicago, where I was privileged to work under the late James W. Cronin as an Enrico Fermi Fellow. There I became aware of the first attempts to put Sikivie's idea into practice, including the Rochester-Brookhaven-Fermilab experiment and a project at the University of Florida. Both lacked the sensitivity to detect axions in the plausible mass range, but they developed the basic hardware used by all subsequent experiments.

While in Chicago, I got to talking with Karl van Bibber, then at Lawrence Livermore National Laboratory, and David Tanner of the University of Florida, and we realized that we could improve on these efforts. We could begin by deploying a large cavity volume with a strong magnetic field—that would bring us

Illustration by Don Foley

EQUIPMENT RACKS house ADMX's room-temperature microwave electronics (*1*). Engineers study sensor data from the experiment (*2*).

partway to the sensitivity we wanted. To go the rest of the way, we knew we would need better microwave amplifiers. They were the key to being able to pick up and boost the extremely weak microwave signal we expected axions to produce—yet the transistor microwave amplifiers available at the time were too noisy by far. We wanted an amplifier that was limited only by the unavoidable noise produced by quantum-mechanical uncertainty, but they did not yet exist in our frequency range.

Thus was the ADMX program conceived: We would start with a large magnet, the best available microwave amplifiers and liquid helium to cool the experiment to 4.2 kelvins to reduce noise. In the intermediate term, we would focus on developing quantum-limited microwave amplifiers. In the long term, we would add a "dilution refrigerator"—a system that would cool the cavity and amplifiers to temperatures around 100 millikelvins, thus reducing noise. It was an ambitious program—each phase would take about a decade. Fortunately, we had the backing of the Department of Energy's High Energy Physics division and a vision to carry us through.

THE EARLY YEARS

IN 1993 I MOVED TO M.I.T. to be an assistant professor, and once I was there, we formed a collaboration to begin the experiment. Lawrence Livermore supplied a large superconducting magnet and the experiment site. The gifted Lawrence Livermore physicist Wolfgang Stoeffl made the initial cryogenic design, and we are still using much of his ingenious system today. Tanner largely conceived and developed the innards of the experiment based on the early University of Florida project, and our group at M.I.T. built an ultralow-noise microwave receiver to pick up the signal. In 1998 we published the initial results from this early ADMX "phase 0"—the first experiment sensitive to plausible dark matter axions. We had not found the elusive particles, but we were off to a good start.

Meanwhile we pushed forward on the quest for an amplifier that would be sensitive to the faint microwave signals we expect axions to produce. Around then, I heard a talk by John Clarke, a brilliant quantum-device physicist at the University of California, Berkeley, on quantum amplification. He had been working on so-called superconducting quantum-interference devices (SQUIDs), which take advantage of the phenomenon of quantum tunneling—the ability of a particle to pass through walls or traverse barriers that a macroscopic object cannot. If a photon arose in the experiment, it would induce a small magnetic field in the SQUID that would disrupt this tunneling in a measurable way. The devices were exquisitely sensitive, but they did not yet exist for use on microwave-frequency signals. For that application, Clarke developed what is called a microstrip DC SQUID amplifier. This gadget has a clever geometry that allows the SQUID to operate at higher frequencies.

The plan was promising, but there were still some issues. The tiny signal magnetic fields of the SQUID would be swamped by the larger field inside the ADMX cavity. The DOE reviewed our plan and flagged the SQUID issue as "high risk." At this point, in early 2002, I moved to Lawrence Livermore, and my collaborators and I decided to divide ADMX into two sequential phases: "phase 1a" would demonstrate that SQUIDs can work in the experiment's large magnetic field. A later "phase 1b" would then add the dilution refrigerator we needed to get the experiment down to the low temperatures we required.

We began phase 1a by developing a system to protect the SQUID's sensitive magnetic field from the huge field of the experiment. We did this with a series of nested shields and magnets surrounding a large magnet called a bucking coil that would cancel out, or "buck," the main magnetic field. By the mid-2000s we had demonstrated that this system works, and we began work on the dilution refrigerator—the major element needed for ADMX's phase 1b.

THE EXPERIMENT GROWS UP

AROUND THIS TIME, I MOVED to the University of Washington, and the ADMX experiment came with me to a new and substantially upgraded site. Meanwhile the DOE and the National Science Foundation were conceptualizing "Generation 2" dark matter detectors meant to be huge improvements on the sensitivity of existing searches. Most of the experiments they had in mind sought WIMPs, but they were also interested in axions. Our ADMX phase 1b plans slotted closely into the Generation 2 program, and ADMX Gen 2 was born. Scheduled to begin operations in 2016 and to run into 2021, ADMX Gen 2 finally adds the dilution refrigerator into our experiment. It also more than doubles our effective data-taking rate. We have added substantial features to improve the experiment's sensitivity, and it can now conduct what we call a "definitive search"—a sweep over a broad range of axion masses, from around 1 to 40 $\mu eV/c^2$, that includes the sweet spot for predicted dark matter axions.

ADMX is now sensitive enough that it should be able to either detect axions or rule out the most plausible versions of them over the next five to 10 years.

ADMX has many complicated parts that must all work in concert, but most of its systems are now highly refined and reliable. The collaboration has grown to include Lawrence Livermore, U.C. Berkeley, the University of Florida, the University of Washington, Washington University in St. Louis, Pacific Northwest National Laboratory, Los Alamos National Laboratory, Fermi National Accelerator Laboratory, the National Radio Astronomy Observatory and the University of Sheffield in England. A new ADMX leadership team has emerged, with co-spokespersons Gray Rybka of the University of Washington and Gianpaolo Carosi of Lawrence Livermore.

Although we are now surveying the most likely mass range for dark matter axions, there is always a chance nature could surprise us. Searching in a slightly lower mass range is not hugely difficult, but outfitting our experiment to look for even higher masses is a challenge. As the axion mass increases, the cavity's resonant frequency needs to increase as well, and thus the diameter of the cavity must decrease, thereby reducing the available volume to search for axions. We could pack a large number of cavities inside a single big magnet to maintain a large volume, but doing so becomes a "Swiss watch problem": the complexity of such a system is daunting. We may also be able to live with a small cavity as long as we can increase the strength of the magnetic field to compensate. Such an increase is expensive, but research into this possibility is under way. Perhaps within five to 10 years increased magnetic field strength—to 32 or even 40 tesla—could expand the mass range of our search. At much higher axion masses—those approaching 1 meV/c^2—we may even be able to see a signal from space. If axions exist in this range and form dark matter halos around galaxies, radio telescopes could spot very weak emission lines.

Eventually ADMX and other projects will be able to fully explore the theoretical window of possible dark matter axion masses. The fact that the full plausible mass range is totally accessible to experiments makes axions an attractive candidate for dark matter, compared with some alternatives that we may never be able to test completely.

As our experimental work marches on, theorists are also making progress on trying to understand the nature of dark matter. Sophisticated cosmological models running on supercomputers are working on more reliable predictions of the axion mass. It is also possible, for instance, that axions would clump together throughout the universe in a different pattern than WIMPs would, in ways both subtle and dramatic. Future astrophysical experiments, such as the Large Synoptic Survey Telescope due to begin observations in 2019, may be able to map out the large-scale structure in the universe accurately enough to allow scientists to discriminate among the dark matter candidates.

Another possibility is that the axions predicted by quantum chromodynamics are just a reflection of some greater theory of physics existing on a higher energy scale. One such theory contender, string theory, predicts axions with much smaller masses than those probed by ADMX. String theory, however, is highly speculative, as are its predictions.

Twenty years ago the comfortable consensus was that dark matter is made up of WIMPs. Since then, the appeal of axions has increased. In the not too distant future, we should know whether or not they are the solution to the mystery of the invisible side of the cosmos. SA

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MEDICINE

WAR AGAINST OURSELVES

Many new drugs trigger an immune reaction that cripples them—and the race is on to thwart the attack

By Michael Waldholz

Illustration by Bill Mayer

Journalist **Michael Waldholz** led a team of reporters who were awarded a Pulitzer Prize in 1997 for their coverage of AIDS. He lives in New York State's Hudson Valley.

EVER SINCE HE CAN REMEMBER, EVEN AS A BOY GROWING UP ON A SMALL FARM IN MICHIGAN, Ken Martin has battled betrayal by his own body. Now 50 years old, Martin was born with hemophilia, and he bleeds almost uncontrollably from a cut. If an internal vein or artery is injured, the blood it carries pools in an intensely painful balloon under Martin's skin. When that happens in his knees, as it frequently does, he must hobble on crutches or stay in a wheelchair until the bleeding slowly stops.

Worse, Martin's body has dealt him a double whammy. People have hemophilia because they lack a gene that makes an essential blood-clotting protein, and many of them get regular infusions of the missing molecule, which is called Factor VIII. But if Martin gets an injection of Factor VIII, his immune system launches a swarm of disease-fighting antibodies against the clotting protein, sweeping it away as if it were an infectious microbe. "I've never benefited from any regimen containing Factor VIII," says Martin, who is married with two boys and, despite the ailment, has had a successful career as a design engineer in the auto industry. Martin deals with his bleeds by elevating and icing the swollen area and resting—and with "a lot of patience," he says. There are about 20,000 people in the U.S. with hemophilia, and around 30 percent of those with Martin's type experience similar antibody attacks.

The problem of antidrug antibodies reaches far beyond blood-clotting disorders. ADAs, as they are called, threaten some of the newest drugs for treating cancer, heart disease and various autoimmune illnesses, such as rheumatoid arthritis. These medications, referred to as biologics, mimic naturally occurring proteins. That often makes them more effective than traditional drugs: the pills we swallow that contain small synthesized chemicals. But because our immune systems are built to detect foreign proteins, some patients react to biologics as if they were invading bacteria, and this sets off an antibody onslaught rarely seen with pills or tablets. The result is that biologic medicine can be blocked or destroyed before it can do any good.

Early biologic developers believed that because many of the drugs were based on human genes and proteins, the human immune system would not treat them as foreign. This turned out to be overly optimistic. When there are reactions, they are frequently big enough to ruin the drug. Awareness of this response has turned into alarm as biologics have become a major part of our medical arsenal. They have grown from 11 percent of the total global drug market in 2002 to between 19 and 20 percent in 2017, according to the IMS Institute for Healthcare Informatics, a research firm, and pharma companies keep making more. "With the explosion of biologic products on the market and in research pipelines, we've become very concerned about the effectiveness and safety of these drugs," says Amy

IN BRIEF

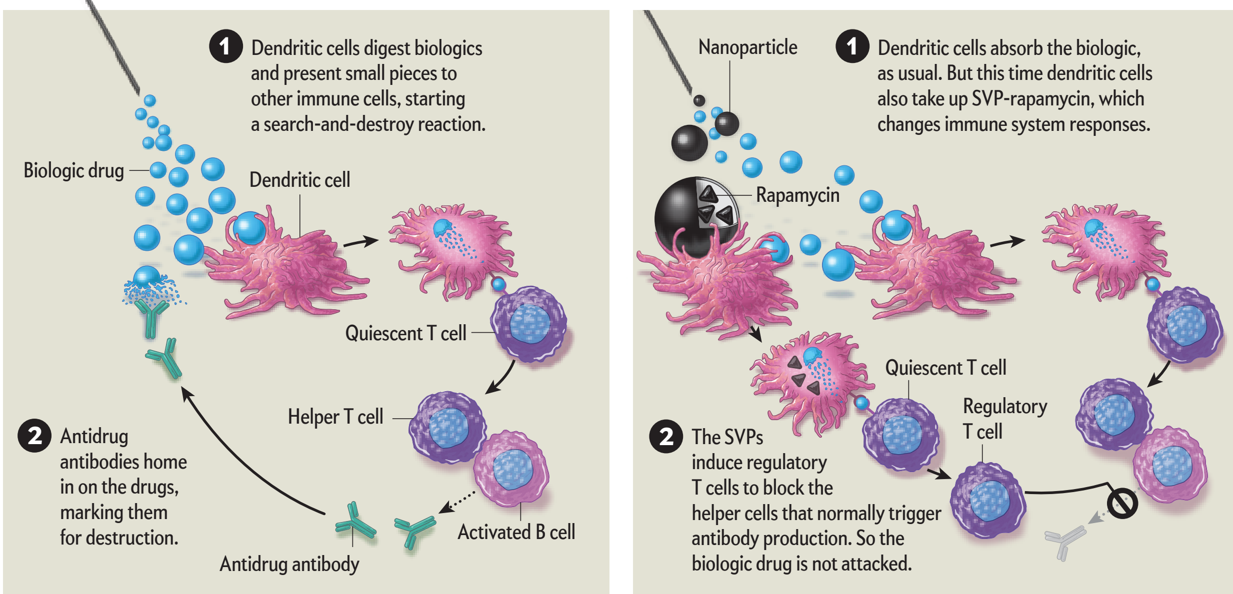
Antidrug antibodies are a growing and serious problem, an immune reaction that destroys lots of modern medications or ruins their effects.

Drugs for cancer, heart disease and other serious illnesses fail to work in patients when these antibodies attack.

New strategies to thwart antibodies include training the body to tolerate medicines with a vaccine-like technology.

Blocking a Bad Reaction

Biologics, the newest drugs to treat deadly illnesses such as cancer and heart disease, are based on proteins. But the body's immune system can react to these molecules by targeting them for destruction with antidrug antibodies. One company, Selecta Biosciences, is developing synthetic vaccine particles (SVPs) that reduce immune system antipathy toward these medicines.



When Antibodies Attack
Dendritic cells in the immune system react to protein-based drugs as if defending the body against invading bacteria. The cells carry small pieces of the drug to hitherto quiet helper T cells, activating them. The T cells then signal antidrug antibody (ADA) factories, called B cells, to turn on.

More Tolerance for Medicine
SVPs are nanoparticles containing rapamycin, an immune system modulator. They are injected at the same time as the biologic medicine. Both types of molecules are taken up by dendritic cells, which, because of the pairing, do not tell the body that the medicine is an invader.

Rosenberg, director of the U.S. Food and Drug Administration division that regulates therapeutic proteins.

An antibody response is the likely reason that AbbVie's Humira, a biologic that treats irritable bowel disease, psoriasis and rheumatoid arthritis, fails to work in one fifth of patients or more in some studies. Drugmaker Pfizer had to pull a promising anticholesterol medicine, a biologic named bococizumab, after testing it in more than 25,000 people. The drug lost its ability to help patients over time, and in six trials almost half the people who received medication developed ADAs. The antibodies were the probable reason for the drug failure, says Paul Ridker, a cardiologist at Brigham and Women's Hospital, who oversaw the tests.

In October 2016 researchers at the Netherlands Cancer Institute in Amsterdam reported that more than half the biological anticancer drugs being tested in 81 clinical trials worldwide were generating antibodies, although they could not determine if the activity always crippled the drug. Swiss drug company F. Hoffmann–La Roche recently stopped developing a protein that successfully treated breast and lung tumors after it triggered ADAs in initial human studies.

When these drugs failed, they cost patients dearly and also set back pharma companies hundreds of millions of dollars. So there is widespread worry. In 2016 Rosenberg's agency called on drugmakers to improve ADA-testing technologies, to look for the antibodies before and during clinical trials, and to report the incidence of such reactions and their effect on drug efficacy and patient safety. "It's important to get evidence we didn't ask for before," Rosenberg says.

Researchers themselves are asking for tolerance—but not for crippled drugs. They are devising ways to get greater tolerance from the immune system for biologic molecules. In one approach gaining wide interest, immunologists are testing new ways to "teach" the immune system to accept these new biologics, to perceive them as normal instead of as an unwanted intruder. Other biotech companies are building tolerance into the therapeutic molecules themselves, developing substances that lack the features that raise an immune alarm. One, in fact, is using antibodies themselves to develop medicine with a minimal antibody response.

TELLING FRIEND FROM FOE

SELECTA BIOSCIENCES, a biotech firm based outside Boston, is trying to foster tolerance based on new insights into how the

Illustration by Mesa Schumacher

immune system distinguishes pathogens it should destroy from human cells it must leave undisturbed. Selecta's most advanced therapy prevented ADA reactions that hinder a medicine for severe gout, a disabling form of arthritis, in a clinical trial. The technique is also showing promise in enhancing the effectiveness of treatments for cancer and genetic illnesses that have been inhibited by ADAs, the company says.

"We have found a way to manipulate the immune system in a very specific way," says Takashi Kei Kishimoto, Selecta's chief scientist. "It's something immunologists have been trying to do for a very long time."

Selecta's technology has its origins in the Harvard Medical School laboratory of Ulrich Von Andrian, who has spent years unraveling how the body's disease defenders signal the presence of a marauding infectious agent. After tracking how immune system cells move through the body to an infection site, he focused on dendritic cells, which appear to act like the commanding officers of the immune system's army. They are responsible for signaling an offensive against a marauding pathogen. When a dendritic cell encounters a virus or some other dangerous germ, it carries a unique fragment of the interloper, called an antigen, into one of a number of lymph nodes distributed throughout the body. "I wanted to study what goes on in the lymph nodes to understand the rules of this immune surveillance," Von Andrian says.

IF AN ANTAGONISTIC IMMUNE RESPONSE CANNOT BE TAMED, ANOTHER IDEA IS TO DESIGN MOLECULES THAT DO NOT SET OFF THE RESPONSE IN THE FIRST PLACE.

Beginning in 1994, Von Andrian employed increasingly powerful imaging techniques to track cellular traffic in and out of the lymph compartments in studies of mice. He and his colleagues were able to see the dendritic cells, like relay racers exchanging a baton, pass along the antigen identity of a threatening pathogen to other immune system constituents called T cells. Once activated, the T cells launched a barrage of disease-fighting mechanisms, including antibodies, against the unwelcome invader.

About 10 years ago Von Andrian's team was able to track the way that dendritic cells not only start immune system wars but also stop them. The researchers were looking at how rapamycin, a drug that can suppress immune activity, does so through the action of dendritic cells. They combined rapamycin with antigen from cells of healthy tissue, and the pairing was taken up, as usual, by dendritic cells. But this time the cells became "tolerogenic" instead of actively campaigning against marauders. They induced T cells that were not activated but actually heightened tolerance by preventing the formation of antibodies. These T cells could also suppress other immune system activity that can lead to tissue-damaging inflammation.

Because of this dual dendritic nature, Von Andrian thought that if he could figure out a reliable way to spark the cells' protective action, that process could suppress the hyperactive immune responses underlying autoimmune diseases such as rheumatoid arthritis, multiple sclerosis or type 1 diabetes. These ailments all result from the immune system mistakenly assaulting healthy tissue, much in the way ADAs fight off biologics.

Although Von Andrian did not know it at the time, a possible method to communicate with dendritic cells—to switch an immune response on or off—was being developed by researchers at the nearby Massachusetts Institute of Technology. In the lab of bioengineer Robert Langer, scientists were designing nanometer-scale biodegradable particles, about as small as a virus, that could be constructed to ferry anticancer agents through the bloodstream to the site of a tumor. Those particles became the seeds of Selecta technology.

Von Andrian—who had been asked by some of the scientists to consult about a venture to commercialize the particles—realized that the nanoparticles, composed of a soluble polymer called poly(lactic-*co*-glycolic) acid, most likely could be constructed to contain an antigen signature and ferry it to dendritic cells inside lymph nodes. But it was Kishimoto who hit on a new way this ferrying action could be used. "It struck me that [nanoparticles] could be used to prevent ADAs," he recalls.

A VACCINE APPROACH

THE SCIENTISTS had already formed Selecta and were working on synthetic vaccine particles, or SVPs. Kishimoto's idea was to insert a combination of rapamycin and the antigen of a particular biologic into the SVP. Once injected under the skin or into a muscle, the particles would eventually enter lymph nodes. There they would spur dendritic cells to generate a surge of tolerance, in the form of regulatory T cells that prevented the creation of antibodies against whatever drug that the company researchers combined with the nanoparticle.

Selecta tested the concept by tackling the hemophilia antibody problem. Researchers administered nanoparticles containing rapamycin and a Factor VIII antigen to mice that lacked the blood-clotting factor. And they gave the mice Factor VIII. The treatment cut down the number of Factor VIII antibodies after 10 weekly treatments, according to a 2015 paper in the *Proceedings of the National Academy of Sciences USA*. (At present, the company is partnering with investigators who are developing a gene therapy for clotting that will be delivered with a nanoparticle.)

Satisfied that the SVP approach was worthwhile, Selecta is now aiming it at gout, a particularly painful type of arthritis that if untreated can eat away at bone and joint tissue. About eight million people in the U.S. have the condition, which is caused when uric acid builds to very high levels in the blood and forms crystals. It can damage blood vessels and kidneys, and severe cases can be fatal.

There is a biologic gout treatment, a synthetic version of a crystal-degrading enzyme called uricase that is found in many mammals. People, however, do not make uricase. As a result, the human immune system perceives the enzyme as foreign. Just more than 40 percent of those treated with uricase generate ADAs that neutralize the drug's action.

The SVP therapy works similarly to the Factor VIII experiment. The nanoparticles contain the synthetic uricase, along with rapamycin, and head for dendritic cells to make peace. An early study in gout patients reported in the summer of 2017 that the treatment, administered once a month, reduced blood levels of uric acid to almost zero without inducing antibodies. "It's an exciting approach," says David W. Scott, an immunologist at Uniformed Services University. "It's especially important because it works by activating the immune system's own immune-suppressing process."

With a colleague, Scott is working on a way to avoid ADAs by genetically engineering regulatory T cells to protect a protein-based drug. In one experiment reported last year, these lab-designed T cells prevented antibodies against Factor VIII in healthy donor blood samples as well as in hemophilia-bred mice. A commercial product, though, is probably years off, Scott says.

REJECTING REJECTION

IF AN ANTAGONISTIC immune response cannot be tamed, another idea about tolerance is to design biologic molecules that do not set the response off in the first place. Hemophilia, again, is a target disease for this approach. Alnylam Pharmaceuticals in Cambridge, Mass., is developing a hemophilia medicine based on RNA interference, or RNAi, a discovery that garnered a Nobel Prize in medicine in 2006. The scientists who found it, Craig Mello of the University of Massachusetts Medical School and Andrew Fire of the Stanford University School of Medicine, learned that by injecting small molecules of double-stranded RNA, they could interfere with the longer RNA molecules that a cell sends to carry production orders to its protein factories. As a result, the cell stopped making certain proteins.

One of Alnylam's first drugs is Fitusiran, a lab-made chemical that mimics the action of an RNAi molecule. What Fitusiran interferes with is a protein that shuts off another key blood-clotting protein called thrombin. Knocking out the first protein means more thrombin is available in the body, which means more clotting and less hemophilia-driven bleeding. In July 2017 in the *New England Journal of Medicine,* Alnylam scientists reported that a once-monthly injection of the drug reduced bleeding events during a 20-month trial in 25 patients with hemophilia.

The immunological value of RNAi as a drug is that unlike proteins, RNA-based medicines generally do not elicit antidrug antibodies, says Akin Akinc, who runs Alnylam's Fitusiran project. And if a larger study proves successful, the therapy may be available by 2020. Alnylam is also making an RNAi molecule that hits the same target as Pfizer's troubled anticholesterol drug—the one abandoned because of frequent ADA responses—but does not trigger an antibody attack.

Antibodies can do more than attack invaders, and their other abilities hold different solutions to the drug problems they create. For instance, they can bind two proteins together. Scientists at Japanese drug company Chugai began taking advantage of this in another attempt to treat hemophilia, in this case to sidestep Factor VIII and all its problems. Factor VIII gets a lot of attention in hemophilia treatment design because it is an essential link in a chemical chain reaction called the coagulation cascade. It makes two other proteins—Factors IX and X—bind together, a key step in forming a clot. But of course, it also can attract destructive antibodies.

The researchers designed a synthetic humanlike antibody that acts like a chemical bridge, tying together Factors IX and X and thereby eliminating the need for Factor VIII. In this incarnation as a drug, the antibody is called emicizumab. In two clinical trials reported last year, it was administered once weekly to prevent bleeding episodes in hemophilia patients who had generated antibodies to Factor VIII. In adults, the drug reduced bleeding events by 87 percent. Antibodies against emicizumab did arise in a small number of patients, but those ADAs apparently did not interfere with the drug's effectiveness, says Gallia Levy of biotech company Genentech, which began developing the drug with Chugai after Roche bought both companies. The therapy is not perfect: some patients developed unintended clots, and one died from a bleeding event unrelated to the medicine. Even so, the FDA gave the drug a priority review and approved it in November 2017.

"It's a potential game changer," says Michael Callaghan, a hematologist at DMC Harper University Hospital and Children's Hospital of Michigan, who treats several patients enrolled in emicizumab trials. (Callaghan receives a fee from Genentech to discuss the drug with other doctors.) One of his patients is Ken Martin. "Mr. Martin has had a very long and challenging struggle," Callaghan says. "For him the drug has been life-altering."

Martin agrees. For several years he has kept a log documenting his bleeds. Before joining an emicizumab trial in July 2016, Martin says he had an average of 46 bleeding episodes a year. Since starting the drug, he has had only three. He still hurts, though. The years of blood pooling in his joints, along with inflammation, have left him with severe arthritis in his knees, ankles, elbows and shoulders. He hopes that if patients prone to ADAs start the drug when they are younger, they might avoid such problems. That has not yet been tested. But even at this late stage, Martin is happy to have found a remedy his body can live with. "I'm pretty fortunate," he says. SA

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PSYCHOLOGY

The Toxic
Lonel

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Isolation from others can lead to a range of illnesses and even premature death. New science is probing causes and solutions to the problem of social disconnection

By Francine Russo

Illustration by Bryan Christie Design

IN BRIEF

Evidence from numerous studies in fields as diverse as epidemiology and psychology has begun to link loneliness to a vulnerability to a host of psychological and physical ills, ranging from depression and cognitive decline to cardiovascular problems.

Research into loneliness has focused on the young, the old and those of any age with a negative self-outlook. Children may often experience it because of inadequate social skills. The elderly may be lonely because of a loss of loved ones.

Interventions to allay gnawing feelings of solitude have succeeded when they diminish negative thoughts for all age groups. For the elderly, mindfulness meditation, learning how to Skype and even proximity to a robot pet have also helped.

Francine Russo is a veteran journalist, specializing in psychology and behavior. She is also a speaker and author of *They're Your Parents, Too! How Siblings Can Survive Their Parents' Aging Without Driving Each Other Crazy* (Bantam, 2010).

CARRIE AULENBACHER GREW UP PAINFULLY LONELY IN RURAL Pennsylvania. Despite having a loving husband and friends, the 39-year-old administrative assistant and writer in Erie still battles her sense of aloneness.

In high school, she had feared approaching a group of girls. She felt she would not know what to say—and maybe they would turn on her. She constantly questions and judges herself. "Am I purposely making myself lonely by projecting things I don't realize?" she asks. "Am I trying so hard I'm pushing people away?"

Over the years Aulenbacher has grown and changed in many ways, but the loneliness remains. Recently she spoke at a seminar. "I arrived alone. I went to lunch alone," she reports. "No one invited me, and I didn't try to belong. Should I have? Yes."

"You learn to move through the world and reach out," she says through tears, "but loneliness stinks."

Loneliness like Aulenbacher's, which may seem to be the ordinary stuff of life and literature, has been attracting a torrent of scientific inquiry. From psychology to epidemiology to evolutionary biology, researchers have been probing the nature of different types of loneliness, their biological mechanisms and their effects on mind and body.

Growing evidence has linked loneliness to a marked vulnerability to a host of psychological and physiological ills, from depression and cognitive decline to heart problems and stroke. A 2015 meta-analysis (combining studies between 1980 and 2014) by psychologist Julianne Holt-Lunstad of Brigham Young University and her colleagues found that loneliness, social isolation and living alone—even more so than obesity—were all associated with a higher chance of early death. Reviewing the available evidence in 2017, Holt-Lunstad and her colleagues concluded that insufficient social connection, stemming not only from feelings of loneliness but also from isolation and poor-quality relationships, is a major public health concern.

How lonely are we exactly? Some scholars such as Holt-Lunstad cite indicators that social isolation, which can cause loneliness, is rising: more individuals living alone, falling marriage rates, fewer children, declining volunteerism and fewer Americans reporting a religious affiliation. In a 2006 study by researchers at Duke University and the University of Arizona, the number of Americans who said they had no close confidants tripled from 1985 to 2004. But other statistics depict a different picture. The subjective feelings of loneliness among adults, says sociologist Keming Yang of Durham University in England, who has analyzed European data from 2006 to 2014, are "quite stable" at about 7 to 10 percent. For the U.K., he says, it "is pretty stable at 5 to 6 percent."

Whether or not loneliness is growing—and that depends partly on what is being measured—the link to health problems has awakened a desire worldwide to find ways to reduce it. In 2011 Crown Princess Mary of Denmark launched a national effort to diminish loneliness. In the U.S., AARP is funding several loneliness-reduction efforts for older people. Age UK, a group similar to AARP, and other organizations unleashed the Campaign to End Loneliness in 2011, researching interventions for loneliness. In 2016 the BBC documentary *The Age of Loneliness* trumpeted the "loneliness epidemic" and helped to make the topic a national priority. "The message has gone out," says Brunel University London gerontologist Christina Victor. "If only you'd all go round and visit your granny, she wouldn't have to go to hospital."

WHAT IS IT EXACTLY?

WE HAVE ALL FELT "LONELY" at some point, but for most of us, that feeling depends on our situation and how we look at it. Loneliness is defined as perceived social isolation and the experience of being cut off from others. Among the majority of sufferers, it can change as our status shifts: when finding new friends, for example, or perhaps beginning a new romantic relationship. People whom researchers define as "chronically lonely" experience profound loneliness over long periods, despite changing circumstances.

What they feel is not the same as depression, social anxiety or shyness, although these conditions often overlap with chronic loneliness. According to psychologist Ken Rotenberg of Keele University in England, studies show that chronically lonely people are more likely than others to show dysfunctional styles of processing social information (hypervigilance for social threats), psychological problems (depression) and interpersonal maladjustment (social withdrawal).

Social isolation, which can cause loneliness, can be measured objectively by factors such as living alone and having few affiliations or neighbors. Some who are socially isolated may feel perfectly content. Others who are not at all isolated by objective standards—consider a married person with many friends—may feel profoundly lonely. Both loneliness and social isolation have been correlated with heightened health risks, albeit probably for different reasons. Loneliness may also be associated with physiological responses that affect health. For socially isolated people who do not feel lonely, Holt-Lunstad says, "there may be no one to remind you to take your medicine, no one to call 911."

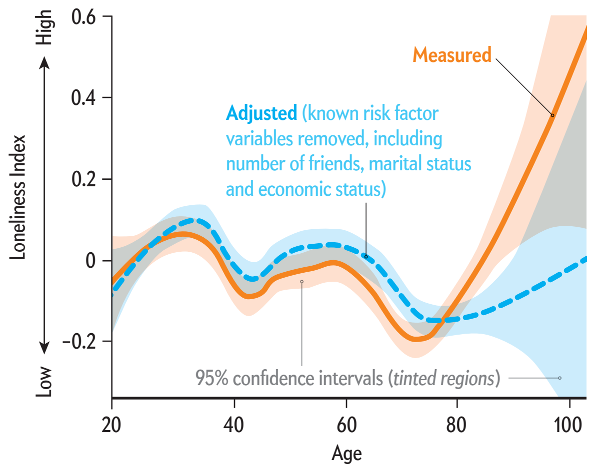
The data on how many people experience both social isolation and loneliness and whether this subgroup faces the greatest risk are complex. The overlap is hard to pin down.

Part of the problem in the scientific literature is that the standard tools for measuring loneliness do not necessarily gauge the same things. Often used in large European surveys, the De Jong Gierveld Loneliness Scale measures both loneliness and social isolation but not their duration. It simply asks people to answer "yes!" "yes," "more or less," "no" and "no!" to such statements as "I miss having a really close friend" and "There are many people I can trust completely."

The most commonly used measure of loneliness, the Revised UCLA Loneliness Scale, assesses individuals' perceived dissatisfaction with the quality or quantity of their relationships. People rate, for example, how often they feel close to others, lack companionship, or feel shy or alone. The measures are primarily cognitive—examining self-perception and other factors rather than delving into the actual feeling of loneliness. For some, Rotenberg says, "the emotional experience of loneliness, when your gut is in a knot, can be quite brutal and undermine mental health if it persists."

Age Matters

Loneliness rises temporarily around ages 30 and 60—and again for the oldest old (*orange line*). When the researchers adjusted the data for number of friends, marital status and other social variables (*blue line*), the ups and downs of loneliness remained unchanged from the measured observations until late old age, when they increased less dramatically. The precision of estimates lessens for the very old, as witnessed by the widening of the tinted regions (confidence intervals), suggesting that the degree of loneliness may vary from person to person for that group.



SOURCE: "AGE DIFFERENCES IN LONELINESS FROM LATE ADOLESCENCE TO OLDEST OLD AGE," BY MAIKE LUHMANN AND LOUISE C. HAWKLEY, IN *DEVELOPMENTAL PSYCHOLOGY*, VOL. 52, NO. 6; JUNE 2016

CLASSIC RESEARCH

SINCE THE MID-20TH CENTURY psychologists have focused on loneliness as separate from depression or other psychic ills—often proposing theories that have since been left aside. In a 1959 article entitled "Loneliness," German psychoanalyst Frieda Fromm-Reichmann referred to its "naked horror" and theorized that it arose from premature weaning. In the 1970s and 1980s, as research intensified, some scholars hypothesized that the primary cause was not being fully part of an accepting social network or community. Others focused on cognition, the negative and unrealistic way that lonely people see themselves and others.

University of Chicago neuroscientist John Cacioppo has more recently proposed an influential theory, positing that loneliness serves an evolutionary function. When people see themselves as excluded from a social group, they feel less safe from threats—individuals perceived as enemies, for instance.

In Cacioppo's evolutionary theory, the pain of loneliness triggers both a motivation to connect to others, known as the reaffiliation motive (RAM), and a hypervigilance to social threats, along with neural changes that increase physical stress. These traits are not unique to humans and function as a survival mechanism.

In everyday life, explains psychologist Pamela Qualter of the University of Central Lancashire in England, people will become quiet or withdraw as a way of observing the social world and will try to work out ways to reconnect. "Let's say I'm at a party," she says, "and I don't know anyone well. I'm feeling unsure and lonely. I'd observe [the situation] and try to identify people I might connect with and people I might want to avoid."

Stephanie Cacioppo, a University of Chicago neuroscientist who researches loneliness with her husband, John Cacioppo, explains that people will find a way to connect, and the adjustments triggered by loneliness are reversed. But when efforts to repair or form new social connections repeatedly fail, people may stay in a hyperalert mode that stresses the body and brain. Such a person's mind, Stephanie Cacioppo says, is always on the lookout, searching for threats before they face harm. But this response is often counterproductive because of the difficulty of differentiating a real threat from an ambiguous social cue.

HOW LONELY?

PEOPLE TEND TO BE MORE VULNERABLE to loneliness, it turns out, at certain times of life—and this understanding has focused research. Increasingly, scientists are looking at two age groups of the lonely: the young (under 30) and the old (over 60).

The need to channel efforts at both ends of the age spectrum emerges from various findings. In looking at 2,393 British subjects aged 15 to 97, Brunel's Victor and Durham's Yang reported in 2012 that the highest levels of loneliness occurred before age 25 and after age 65. Similarly, a large German population study published in 2016 by psychologists Maike Luhmann, then at the University of Cologne in Germany, and Louise C. Hawkley of the University of Chicago found that the loneliest groups were younger than 30 and older than 80 [*see box above*].

These reports of people's feelings, Luhmann and Hawkley speculate, are influenced by what is perceived as "normal" at each life stage. Study after study, for example, has found that being married or cohabiting protects against loneliness, but that factor may have less impact on young people who do not yet expect to be married and may be less critical to the very old, for whom widowhood is common. Being employed can make a crucial difference for adults in midlife but less so for older people who have chosen to retire. Meanwhile certain fairly predictable factors—social engagement, number of friends and frequency of contacts—appear to be universal predictors of loneliness at any age.

WHY ARE CHILDREN LONELY?

A MAJOR EMPHASIS of research spotlights children and adolescents because of the lingering effect that loneliness can have throughout a lifetime. Studies have shown that it can lead to depression, and lonely children are at an increased risk of becoming lonely and depressed adolescents and adults. A 2010 British study of nearly 300 children ages five to 13 found that lonely children were likelier to be depressed as adolescents.

Some children in the study were lonely in relationships with their parents, others in relationships with their peers. The work of Marlies Maes of KU Leuven in Belgium and her colleagues shows that adolescents who felt lonely with their peers but not with their parents were seen as more shy and were likelier to be identified as victims of bullying.

Some kids are lonely because they have inadequate social skills. In a 2016 study, 1,342 adolescents rated themselves and their classmates on how well they dealt with others. By comparing the subjects' self-evaluations with those of their classmates, says lead author and behavioral scientist Gerine M. A. Lodder of the University of Groningen in the Netherlands, the researchers found that lonely children fell into two groups. The ones whose classmates agreed that they had poor social skills very likely did, but they might still be capable of change. Relationships entail different social tasks, says Duke developmental psychologist Steven R. Asher. They include taking the initiative to make social contacts, being a reliable partner and resolving conflicts. Although some children are worse than others at handling these tasks, kids can potentially learn to improve their interactions and become less lonely.

The other group in Lodder's study had a pervasive negative view of themselves, their social environment and their social relations—and at times might need a different approach. "There is no one-size-fits-all solution," Lodder says.

Many intensely lonely kids have fine social skills. Qualter has observed a group of children ranging from ages eight through 14 in their dealings on the playground and in other interactions. The loneliest of them, she says, behave much like other children but interpret their interactions differently.

She has found the same with college students. With a best friend, lonely students appear to behave just like everyone else. But afterward, Qualter explains, they say, "I talk too much" or "too little." On average, they underestimate their performance.

Findings from these studies with children and adolescents fit with John Cacioppo's model of faulty RAM and intense hypervigilance. The research indicates that severely lonely children and young adults respond differently to images and situations of social inclusion and exclusion.

A 2015 study of 730 adolescents by developmental psychologist Janne Vanhalst of KU Leuven and her colleagues suggested that chronically lonely adolescents may stay lonely because of their negative interpretations of social situations. Testing them annually over four years, the investigators found that those who stayed lonely responded more negatively to scenarios describing social exclusion, such as not being invited to a new lunch place. Strikingly, they also responded less enthusiastically to scenarios describing being included, such as being invited to a party. They were more likely to attribute the invitation to coincidence than to being likable. "Not taking as much pleasure in being included, as well as getting more upset about being excluded, is a kind of double whammy," says Asher, a co-author of the study.

> Chronically lonely adolescents may be unable to set aside feeling solitary in scenarios in which they are included in group activities, such as being invited to lunch.

One idea in the search for the roots of loneliness in the young holds that low trust issues cause or maintain loneliness. In 2010 studies by Rotenberg and his colleagues of children in age groups of five to seven, nine to 11, and 18 to 21 who had diminished trust exhibited increases in loneliness in each age group over time.

In one of the studies, the researchers asked young adults to learn a series of "trusting" or "distrusting" words ("loyal" versus "dishonest," for example) before having an interaction with another person that was carefully structured by the researchers. Those "primed" for trust were likelier to pick more intimate topics to discuss and to report that they "hit it off" with the other person.

DIFFERENT IN THE OLD

DO ALL THE LESSONS from studying young people apply to later life? Probably not. The elderly are not in fact really lonely, says Victor, who has done stereotype-busting research on the old. Yet, she says, "in Britain, it's seen as normal for aging people to be lonely."

In a study conducted in 2000 and 2008 with almost 1,000 people older than 65, she and her colleague found that 9 percent reported severe loneliness. Of the individuals in the study, 30 percent said they were sometimes lonely, and an impressive 61 percent reported they were never lonely. Greater levels of loneliness, Victor notes, were linked to life changes: losing a partner or having impaired physical health. Victor and her colleague also found, in a 2015 study, that contrary to popular belief, the loneliest time for older people was not Christmas but summer, when family routines change. She says she had thought of calling the study "No One Invites Granny to the Beach."

SOLITUDE REDUCTION

AS THE SCIENTIFIC CONSENSUS has grown that loneliness and social isolation are linked to physical and emotional decline, researchers have tested an array of remedies. In 2011 internist Christopher Masi, then working with John Cacioppo at Chicago and now at NorthShore University HealthSystem and other researchers, analyzed 20 well-designed loneliness interventions out of a total of 50 studies published between 1970 and 2009. They fell into four main categories: improving lonely people's social skills, increasing social support, encouraging interactions with other people, and providing cognitive-behavioral therapy (CBT), a form of talk therapy that tries to dispel or reframe negative interpretations of an individual's experiences. "On average," Masi says, "for all 20, the overall effect was reducing loneliness." But the intervention that really stood out, he reports, was CBT.

Given that lonely children become lonely (and depressed) adolescents and adults, you might think that scientists would be focusing their intervention efforts on the youngest sufferers. Alas, Groningen's Lodder says, "for kids, there's not much out there."

The barriers to helping children are clear to Ami Rokach, a clinical psychologist who teaches at York University in Toronto. In his private practice, he treats chronically lonely adults using CBT. For teenagers as young as 16, he uses a variety of approaches, and CBT is frequently one part of the therapy. "CBT works for them," he says, "if I can get their parents onboard. It's very difficult if they go home and get the message that they're unlikable or that you can't trust people."

The other end of the age spectrum has witnessed a burst of innovation. Mindfulness training, robot pets and teaching the elderly how to use Skype have all been tried. Pairing elderly people with similar-aged volunteers for a series of visits, reports Trinity College Dublin psychiatrist Brian Lawlor, showed some effectiveness in reducing loneliness. But interventions that include CBT have shown more impressive gains.

A 2016 study by West Virginia University gerontological nursing professor Laurie Theeke and her colleagues, for example, demonstrated the effectiveness of CBT. The 27 lonely volunteers (screened with the full UCLA scale) received either five weeks of a structured group therapy program called LISTEN or heard lectures on healthy aging.

The therapy groups, made up of three to five older men and women, discussed and wrote about such topics as "belonging" or "relationships." They learned to revise some of their negative assumptions. An 83-year-old retired executive who had felt useless heard from the others that his skills as a businessperson could still be used; afterward, he created a newsletter for seniors in his building. A 65-year-old woman who felt no man would enjoy her company heard from men in her group that they did like being with her.

Twelve weeks after the program the LISTEN participants had reduced loneliness levels—"almost to the nonlonely range," Theeke says—and they also experienced enhanced social support and decreased systolic blood pressure. The control group reported decreased functional ability and quality of life.

The LISTEN participants admitted, both to themselves and to others, that they were lonely. Not all lonely people can do this. Some of the best interventions, Victor says, do not tackle loneliness head on but the underlying circumstances. If people's health keeps them indoors, she suggests, walking groups should be created. If they lack transit, it should be provided. She recalls a shopping service her mother used that took a group of elderly women to the market weekly. They began exchanging phone numbers and making friends. "They would not have dreamed of talking to one another in the street," Victor says.

Many people, experts say, worry that if they acknowledge being lonely, others will think there is something wrong with them. Public campaigns to bring loneliness to the attention of others may help, so may exploding myths about loneliness, especially for older people.

The myth that it is typical for old people to be lonely, Victor says, can itself be harmful. In 2016 she and her colleagues reported on a study of people older than 50. When initially tested, those who expected to be lonely were in fact likelier to be lonely eight years later than those who did not.

THE FUTURE OF LONELINESS RESEARCH

THE MORE SCIENTISTS LEARN about loneliness, the better they are able to identify groups at risk because of specific issues. A 2016 Danish population-based study by psychologist Mathias Lasgaard of DEFACTUM and the University of Southern Denmark and his colleagues, for example, identified certain high-risk groups, including those who are ethnic minorities, unemployed, on disability, suffering from a long-term mental illness and living alone. Interventions might be developed specifically for these groups.

For chronically lonely people, CBT remains the treatment of choice, but drug therapy with allopregnanolone, a neurosteroid, is showing promise in animal studies in reducing perceived social isolation and may eventually become a useful adjunct to CBT, Chicago's Stephanie Cacioppo says. New approaches for the loneliness of the old continue to proliferate.

The biggest challenge is alleviating the plight of chronically lonely children. It may be eventually possible to craft interventions, York's Rokach says. "It is doable, but it takes work and dedication by both teachers and parents. Many are not enlightened. They tell the kids, 'Just go out and play.'" SA

MORE TO EXPLORE

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FROM OUR ARCHIVES

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EVOLUTION

HOW SNAKES CAME TO SLITHER

New fossil analyses and insights from evolutionary developmental biology elucidate the long-sought origin of serpents

By Hongyu Yi

A CHINESE RIDDLE INVITES ONE TO GUESS THE IDENTITY OF RUNNERS WITHOUT A LEG, SWIMMERS without a flipper, gliders without a wing. The answer, of course, is snakes. Today more than 3,000 species share a long, limbless body that can negotiate land, water and even the air between trees. Their ancient ancestors, however, had limbs of various shapes. How, scientists have wondered, did snakes lose their legs?

Special forms of appendages are often tied to certain habitats. Whales evolved flippers as adaptations to the aquatic realm. Birds evolved wings as they transitioned to life in the air. But for decades evolutionary biologists have struggled to ascertain what kind of environment helped to forge the distinctive body plan of snakes, in part because today's snakes are so widespread and because the fossil record of early snakes is sparse. Debate has centered on two competing hypotheses. One holds that snakes lost their legs on land while adapting to subterranean

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environments; the other posits that snakes evolved their telltale traits in the sea. Both these settings favor a streamlined body.

If only we could travel back in time to the Cretaceous period, between 145 million and 66 million years ago, when snakes got their start. Then we could observe ancestral snakes in their actual habitats and see whether they excelled at burrowing or swimming. In reality, we have only their fossilized remains to go on, and it can be difficult to reconstruct the ecology of an animal and how it behaved based on its bones alone, particularly when they are damaged or fragmentary, as fossils often are.

Over the past 10 years, however, advances in imaging technology have enabled scientists to break through previous limits in understanding snake origins. High-energy x-ray imaging of fossil skulls has revealed hidden features that hint at the ecology of ancient snakes. Meanwhile studies of developmental biology have elucidated the genetic mechanisms underlying the loss of limbs, as well as the gain of vertebrae.

Our knowledge is far from complete. But these insights are at last allowing scientists to start piecing together the long-standing puzzle of how snakes underwent their extraordinary evolutionary transformation.

EVOLUTIONARY EXPERIMENTS

SNAKES DID NOT LOSE functional limbs in one fell swoop. The fossil record indicates that the first snake with no legs, *Dinilysia patagonica,* emerged about 85 million years ago during the Late Cretaceous period, when dinosaurs reigned supreme. Researchers recovered the remarkably well-preserved remains of *Dinilysia* from rust-colored sandstones on the Patagonia plateau. The almost complete skeleton of this animal, which was about as long as a human adult, shows that not only did it not have legs, but it also lacked the shoulder or pelvic girdles to support such appendages. Because the fossil was found in terrestrial sedimentary deposits, we know it lived on land.

Yet other snakes from this time period retained legs. *Najash rionegrina,* a roughly 92-million-year-old terrestrial snake from Argentina that was only as long as a strand of spaghetti, possessed a pair of tiny hind limbs composed of bony elements from the hip to the ankle. *Najash*'s limbs were far too small and delicate to bear the animal's weight. Instead they may have functioned as claspers during mating.

Other Late Cretaceous snakes with legs lived in the ocean. Fossils from marine deposits near what is now Jerusalem reveal sea snakes that swam among sharks. Two such creatures, *Pachyrhachis* and *Haasiophis,* display almost complete hind limbs made up of bones from the thigh, shin and foot. The function of these legs remains unclear. Both *Pachyrhachis* and *Haasiophis* lack a pelvic girdle to attach the leg to the trunk of the body, so their legs would have been of little use for swimming.

All told, these fossils indicate that by the Late Cretaceous snake evolution was already well under way. The long, sinuous body with highly reduced limbs was established, and snakes were undergoing an adaptive radiation, rapidly diversifying into a multitude of forms that could exploit a variety of ecological niches. To probe the origin of the snake's characteristic body plan, then, scientists need to look to even older fossils.

Until recently, researchers had few snake fossils predating the Late Cretaceous to study. But over the past five years several new candidates from the Early Cretaceous and the even earlier Jurassic period have come to light. The remains, which hail from terrestrial deposits in Europe and the U.S., are quite fragmentary and do not reveal much about the body proportions of these animals. If they are in fact snakes, however, these specimens would extend the fossil record of this group by another 70 million years and show that the oldest known members were small and lived on land, not in the sea.

Still, the mounting fossil evidence pointing to a terrestrial origin for snakes did not address the question of why they evolved a streamlined body. A subterranean way of life would benefit from limb reduction. Modern burrowing snakes and lizards simply push their head through soft earth to tunnel underground—legs would only get in the way. But establishing that any given fossil snake actually did burrow underground is tricky. The Jurassic and Early Cretaceous fossils are too scrappy to even guess their behavior. *Najash* might have been a burrower, judging from its short tail, which resembles those of living snakes that burrow. For its part, *Dinilysia,* the earliest known snake to lack legs altogether, was much larger than modern burrowing reptiles. Could it have burrowed anyway? I decided to find out.

CLUES IN THE EAR

ON CHRISTMAS DAY 2014, I flew from Buenos Aires to New York City, carrying skulls of *Dinilysia* with me in a shoebox. It had taken almost a year for my Argentine colleagues and me to prepare the paperwork needed to borrow the specimens for computed tomographic scanning in the U.S.—all so that we could study the animal's ear.

Why the ear? Working with Mark A. Norell at the American Museum of Natural History, I had developed a method to distinguish modern burrowing snakes from marine species based on that anatomical region, and we wanted to try it on *Dinilysia*.

Using a state-of-the-art imaging technique, we had obtained high-resolution x-ray images of the skulls of dozens of modern-day snakes and lizards. We then stacked these images to create three-dimensional virtual models of their inner ears. We focused on a structure called the vestibule, which holds lymphatic fluid and the

PRECEDING PAGES: JOEL SARTORE *Getty Images*

IN BRIEF

The snake body plan represents a radical departure from the vertebrate norm. Researchers have long wondered how snakes evolved their extreme traits.

New fossil analyses have illuminated the roles that environment and behavior play in shaping the snake form.

Evolutionary developmental biology studies have revealed some of the genetic mechanisms underlying limb loss and other aspects of snake evolution.

so-called ear stones that aid in sensing gravity and movement.

Statistical shape analyses of the virtual models revealed significant differences in the vestibules of burrowing specialists, terrestrial generalists and aquatic forms. In marine snakes and lizards, the vestibule has shrunk to nearly nothing. In burrowers, however—particularly those that do their own digging, as opposed to taking another animal's burrow for shelter—the vestibule has blown up like a balloon, enabling better hearing underground. This trend holds true regardless of the size and limb structure of the burrower: we observed vestibular expansion in a three-foot sand boa and a 10-inch Asian pipe snake, as well as in the bizarre burrowing lizard *Bipes,* which has a pair of front limbs but no hind limbs.

I had reason to suspect that *Dinilysia* would align with the burrowers: a study published in 2012 presented an x-ray image of its skull, in which a large vestibule was visible. But no one knew what the vestibule looked like in three dimensions. I was confident that subjecting the fossil to our method would settle the question of this ancient snake's locomotor behavior.

Our study confirmed that *Dinilysia*'s vestibule is indeed large, with the same balloonlike shape seen in today's burrowers. In fact, it is nearly indistinguishable from that of the modern sunbeam snake, a large burrower from Southeast Asia that eats mainly small rodents and smaller snakes. Our model predicted *Dinilysia* to be a burrower with nearly 95 percent probability. We speculate that it lived much like the sunbeam snake, hunting on the ground surface and digging into loose soil for shelter.

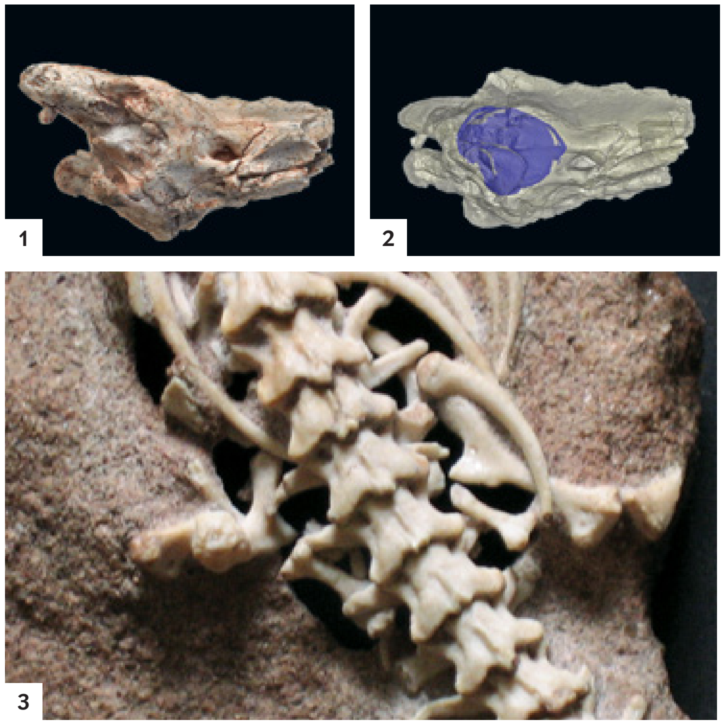
When mapped onto an evolutionary tree, these findings illuminate the role of habitat shift in the transition from lizard to snakes. *Dinilysia* was not among the first lineages to split off from lizards. Instead it is closely related to the ancestor of today's snakes—more advanced than *Najash,* with its functional hind limbs, but more ancestral than modern species. The revelation that *Dinilysia* was a burrower strengthens the hypothesis that the lineages leading to modern snakes lost their limbs while adapting to life underground.

The fact that burrowing, rather than swimming, became the predominant modus operandi in the ancestors of present-day snakes does not imply that in the Cretaceous, a group of lizards decided to live underground and gradually lost their limbs to become snakes. Rather evolution works in a stochastic fashion. Going subterranean was one of many influential events that took place in the millions of years over which the unique body plan of snakes took shape. This new way of life probably lifted certain constraints on the genomes of primitive snakes that had previously been essential for survival. Freed from these limitations, the limbs and trunk could change. Hence, a wide array of limb types and body lengths is evident in the fossil record of snakes.

STRETCH THE BODY

WHOLE-GENOME SEQUENCING and experimental gene editing of modern snakes have further enhanced scientists' understanding of snake evolution. All vertebrate species share a great number of genes. The dramatic differences in the body plans of creatures ranging from birds to fish actually stem from mutations in just a small portion of the genome. In theory, the evolution of the snake's long, limbless body from a lizard's short, sprawling form may have involved changes in just a handful of key regions of the genome.

A closer look at the embryonic development of vertebrates hints at the steps needed to evolve one of the snake's hallmark traits: its long spinal column, which is made up of more than 300 vertebrae compared with 33 in humans and 65 in a typical lizard. The head and trunk of limbed vertebrates form from blocks of cells called somites. Each somite gives rise to one vertebra. Somites initially appear similar, then differentiate to create the neck, chest, waist, hip and tail regions of the spine.



SKULL OF *DINILYSIA* (*1*), the earliest known snake with no legs, had an enlarged inner-ear vestibule, as revealed by high-resolution x-ray imaging (*2*). This trait is associated with animals that specialize in burrowing. Other similarly ancient snakes, including *Najash,* had tiny hind limbs (*3*).

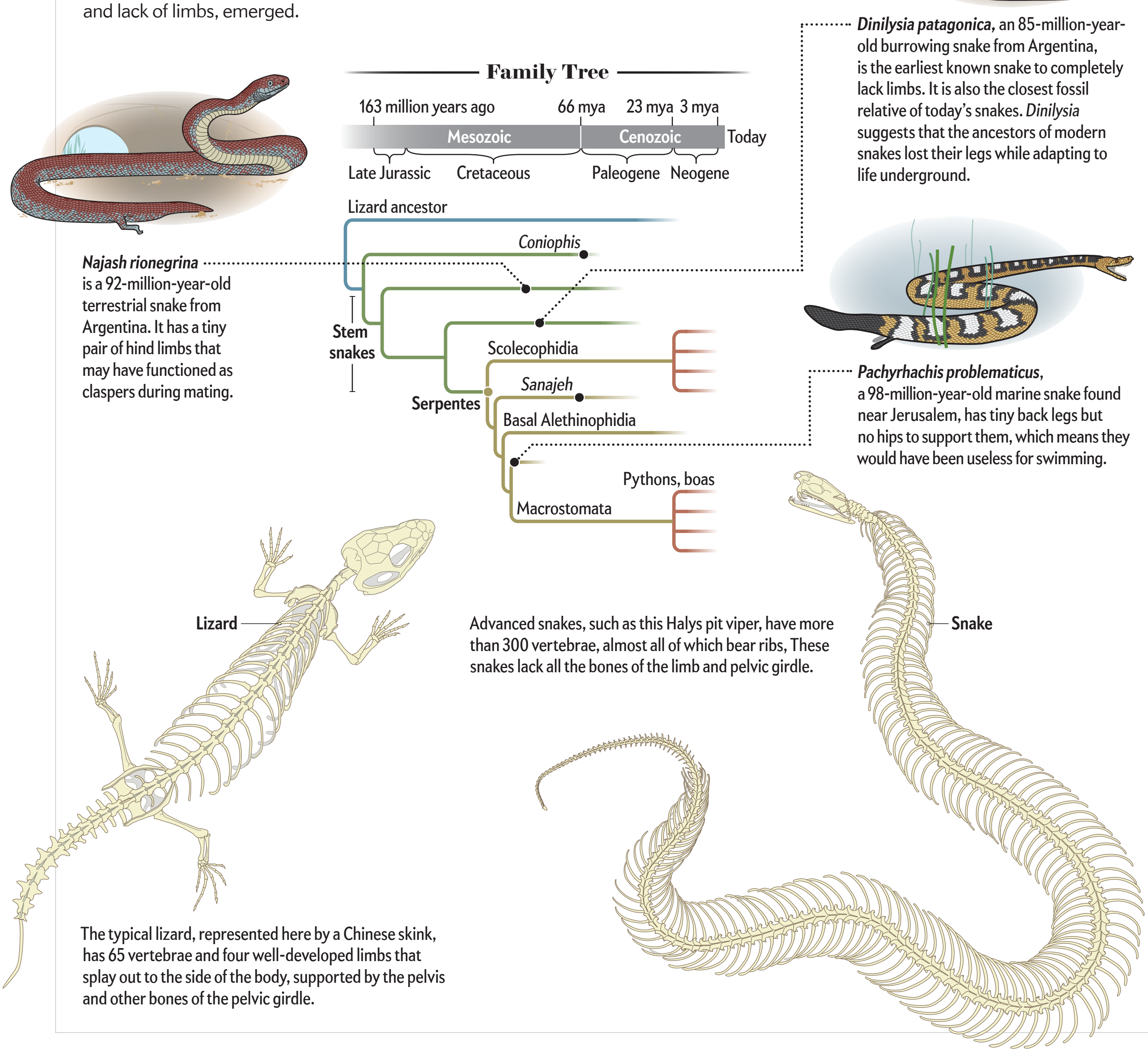
FROM "THE BURROWING ORIGIN OF MODERN SNAKES," BY HONGYU YI AND MARK A. NORELL IN *SCIENCE ADVANCES,* VOL. 1, NO. 10, ARTICLE NO. E1500743; NOVEMBER 27, 2015 (*1, 2*); COURTESY OF PALEONINJA *Wikipedia* (*3*)

A gene whimsically dubbed *Lunatic Fringe* helps to increase the number of vertebrae in snakes. It works with other so-called somite-generating genes to create clusters of cells at the tail end of the embryo. Once a certain number of cells accumulate, a somite forms and moves up the body, like a bead on a string. Together the somite-generating genes are known as the somitogenesis clock because they turn on and off at regular intervals to make the somites. The faster the clock ticks, the more somites are produced from the same number of cells. Céline Gomez, now at the Wellcome Trust Sanger Institute in England, and her colleagues showed that the *Lunatic Fringe* gene is expressed more frequently in corn snakes, whose somitogenesis clock ticks far faster than that of lizards.

The vertebrae are not the only bones that have gone wild in

Shape Shifters

The evolution of snakes from their lizard ancestors is one of the most dramatic transformations in the history of vertebrates. Recent discoveries have allowed researchers to start to reconstruct how the distinctive snake body plan, with its extremely long trunk and lack of limbs, emerged.



snakes. The ribs have, too. Consider the mouse and alligator, for example. In these creatures, only the chest (thoracic) vertebrae bear ribs. No ribs attach to the neck (cervical) and waist (lumbar) vertebrae because a gene called *Hox10* suppresses rib formation in these regions. In snakes, however, all the vertebrae except for the first three closest to the head and those in the tail bear ribs.

Researchers have long assumed that the mouse and alligator are good models for what the trunk skeleton of ancestral limbed animals looked like, with neck and waist vertebrae that are distinct from the chest vertebrae. The conventional wisdom was that snakes evolved their homogenized vertebral column from that ancestral form, a specialization possibly associated with limb loss. Scientists suspected that the *Hox* genes that typically govern the differentiation of vertebrae in other animals had somehow gotten disrupted in snakes.

A recent fossil analysis points to a different scenario. In 2015 Jason J. Head, then at the University of Nebraska–Lincoln, and P. David Polly of Indiana University Bloomington modeled the evolution of the trunk skeleton in four-limbed animals, also known as tetrapods. First, they predicted statistically that snakes

Illustration by Portia Sloan Rollings

actually have just as many distinct regions in the vertebral column as lizards do. The snake's *Hox* genes may simply be directing subtler changes in shape to the various types of vertebrae. Second, the researchers determined that contrary to the conventional wisdom, ancestral tetrapods actually had ribs associated with most of the vertebrae above the hip. Fossils of ancient relatives of mammals and alligators exhibit ribs attached to vertebrae of the neck and waist. Thus, the absence or reduction of ribs in these regions in modern alligators, birds and mammals evolved independently rather than being inherited from their ancient common ancestor.

Looking at fossils and recent species together has revealed which aspect of the trunk skeleton snakes inherited from their limbed ancestors (the rib distribution) and which is truly unique (the extremely elongate body).

DITCH THE LEGS

RECENTLY SCIENTISTS HAVE MADE new inroads into understanding the genetic mechanisms underlying limb loss. In 2016 Evgeny Z. Kvon of Lawrence Berkeley National Laboratory and his colleagues reported that they had identified a genetic "switch" for limb development in the snake and mouse. In their study, the researchers stitched a piece of a snake gene into the genome of a lab mouse. What emerged from the experiment was a science-fiction animal: a "serpentized" mouse, which had a normal mouse body and truncated limbs.

The snake gene in the serpentized mouse consists of a DNA segment referred to as the ZRS regulatory sequence. Active ZRS is critical for normal hind-limb formation in a mouse, yet it takes only a single mutation in this gene to cause limb abnormality. Because it is so important for survival, the ZRS regulatory sequence has remained mostly unchanged over the course of tetrapod evolution, but it is highly variable in snakes.

The ZRS variants found in snakes are consistent with the morphological diversity of their limb development. Primitive modern snakes, including the python and boa, retain a ZRS limb-enhancer sequence, albeit one that is shorter than that in other limbed vertebrates. Correspondingly, both species possess rudimentary, spurlike hind limbs. In contrast, advanced serpents such as the corn snake have lost the ZRS segment entirely and have no limb bones whatsoever.

Finding genetic variants that align with variations in limb development provides new understanding of fossil snakes. *Najash* preserves a pelvic girdle, femur, truncated tibia and fibula, but no toe bones. *Pachyrhachis* lacks toes, too. *Najash* and *Pachyrhachis* indicate that in the transition from lizard to snake, limb-specific regulatory genes were modified yet still functional in several ancestral snakes. For its part, *Dinilysia* had no limb bones or pelvic girdle at all, which marks the first complete loss of function in the evolution of a snake limb-enhancer sequence.

In the last chapter of the dinosaur era—the Late Cretaceous—snakes underwent dramatic change in their body plan and perhaps rapid evolution in their genome. We have only just begun to probe the genetic basis of the traits seen in the fossil record. *Haasiophis* had no pelvic girdle, but it did possess a complete femur and well-developed tibia and fibula, along with anklebones and foot bones. No living snake exhibits such an arrangement, but its existence in the fossil record hints at the interplay of multiple limb-regulatory sequences similar to the ZRS in the ancient past.

MISSING LINKS

NEW CLUES TO THE ORIGINS of snakes continue to surface. In 2015 researchers led by David M. Martill of the University of Portsmouth in England announced their discovery of a 120-million-year-old four-legged snake from Brazil. *Tetrapodophis amplectus* had four complete limbs preserving digits and toes. The limbs would have been strong enough to function as claspers during mating. Though shorter than a chopstick from head to tail, this animal has more than 200 vertebrae. The creature's long trunk and short tail suggest it was a burrower, supporting the hypothesis that snakes originated on land. Given its geologic age, ecology and the state of its legs, *Tetrapodophis* seems to have all the characteristics paleontologists have been searching for in their quest for transitional snakes.

But at a meeting of the Society of Vertebrate Paleontology in Salt Lake City, Utah, in 2016, some researchers questioned the discovery team's description of the fossil. These critics suggested that *Tetrapodophis* is not a snake but rather a marine lizard. The specimen could rekindle the debate over whether snakes originated on land or in the sea. At that same meeting, however, a group of scientists reported that the private owner of *Tetrapodophis* removed it from the public museum where the fossils were housed, violating the convention that all named species, fossil or extant, should be available to other researchers and the public for further study. The debate over *Tetrapodophis* ground to a halt as a result.

Tetrapodophis aside, scientists are currently investigating unsolved mysteries of snake evolution. We are eager to determine, for instance, whether snakes first appeared on the northern continents or in the south and whether the founding members of this group were nocturnal or diurnal. We also want to know how snakes evolved jaws large enough to swallow prey larger than their head and how they acquired venom.

Answers to these questions will enhance an already riveting tale. Popular cultures and religions have offered up all manner of stories to explain how certain parts of the body can be lost or otherwise transformed. The biblical account of snakes holds that God cursed the serpent to crawl on its belly for leading Adam and Eve to eat the apple in the Garden of Eden. In Chinese legend, the heavenly Jade Emperor punished the snake for hurting humans by ordering its legs to be cut off and given to the frog. But as the fossil and genetic evidence from snakes underscores, natural selection is not goal-oriented. Evolutionary novelties do not originate by design. They emerge from never-ending interactions between animals and their world. SA

MORE TO EXPLORE

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Progressive Loss of Function in a Limb Enhancer during Snake Evolution. Evgeny Z. Kvon et al. in *Cell,* Vol. 167, No. 3, pages 633–642; October 20, 2016.

FROM OUR ARCHIVES

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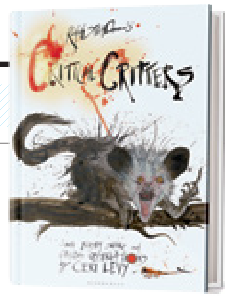
scientificamerican.com/magazine/sa

RECOMMENDED

By Andrea Gawrylewski



Critical Critters

by Ralph Steadman and Ceri Levy.
Bloomsbury Natural History,
2017 ($50)

After collaborating on two books showcasing extinct and endangered birds, legendary cartoonist Steadman and filmmaker Levy have paired up again to create this eccentric, wildly imaginative collection of illustrations of other critically endangered animals. Steadman's drawings are nonconformist, splotched with color and a delightful overlay of finger-painting-like splashes and precise ink drawings. Levy's descriptions detail each creature's environment and the threats to its survival. The depictions of insects—the little mother moth, the Greek red damsel, the monarch butterfly—are particularly lavish, and an eerie bleakness is infused in the portraits of the snow leopard and giant panda. Humorous correspondences between the two authors accompany the drawings, adding some lightheartedness to heavy subject matter.

The Stowaway: A Young Man's Extraordinary Adventure to Antarctica

by Laurie Gwen Shapiro.
Simon & Schuster, 2018 ($26)

Eager to escape the family upholstery business, 17-year-old Billy Gawronski snuck onboard the ship *City of New York* in 1928. He was determined to stow away on a daring expedition—the first American journey to Antarctica in the 20th century. Journalist Shapiro tells his story alongside the ship's commander, Richard Evelyn Byrd, and his crew. Discovered after several attempts and finally allowed to remain onboard, Gawronski takes on the role of messboy, penguin catcher and crowd favorite for the New York newspapers. The journey achieved many scientific successes: the geologic mapping of certain regions of Antarctica, photographic documentation of the mysterious land and the testing of long-distance radio signals. After they reached the icy continent, the explorers unloaded a three-engine Ford transport plane, on which they would become the first ever to fly over the South Pole. —*Yasemin Saplakoglu*

The Many Lives of Carbon

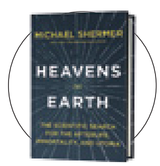
by Dag Olav Hessen. Reaktion Books,
2018 ($29)

One of the most familiar elements of the periodic table, carbon now plays diverging roles on our planet. It is essential to all living things on the earth, yet in the form of carbon dioxide, it threatens their existence by warming our world to dangerous levels. "Carbon, life's element, has become our greatest threat," writes Hessen, a biologist who studies the life cycle of carbon. He profiles the many vital contributions the element makes to human life and gives a fascinating explanation of how its structure renders it so useful in diverse materials and situations, from fire to photosynthesis.

Hessen also describes how carbon's chemistry turns it into such a menace to our climate by trapping heat via the greenhouse effect, and he eloquently highlights the need to use our carbon wisely, lest we irreversibly disrupt the delicate balance it has enjoyed on our globe for the past 4.5 billion years. —*Clara Moskowitz*

Heavens on Earth: The Scientific Search for the Afterlife, Immortality, and Utopia

by Michael Shermer. Henry Holt,
2018 ($30)



Author Shermer (who is a columnist for *Scientific American* and a member of its advisory board) uses a scientific lens to examine how the cultures and religions of the world view human mortality and what comes after death. He shines scientific skepticism on near-death experiences (most likely hallucinations, in his estimation), the afterlife (no evidence found) and efforts to extend human lives through technological endeavors—such as uploading minds into computers (technologically unfeasible). He recognizes that finding meaning in a meaningless universe can be troublesome, especially without the postlife end goal that many religions and philosophies promise. As Shermer writes, "there are scientific answers to such deep questions, if we reflect upon them with reason, honesty, and courage."

RALPH STEADMAN

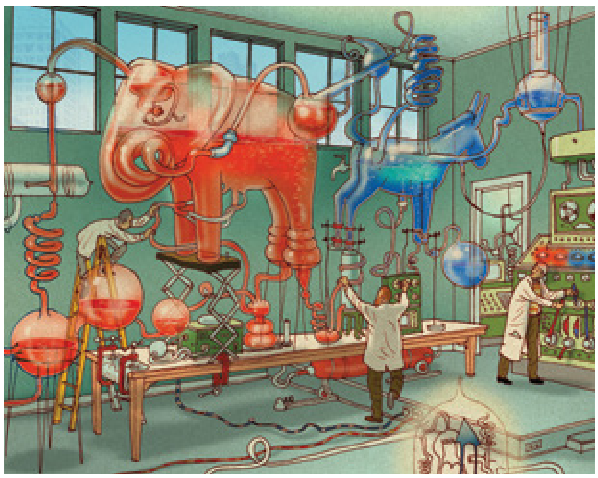
Michael Shermer is publisher of *Skeptic* magazine (www.skeptic.com) and a Presidential Fellow at Chapman University. His new book is *Heavens on Earth* (Henry Holt, 2018). Follow him on Twitter @michaelshermer

For the Love of Science

Combating science denial with science pleasure

By Michael Shermer

That conservatives doubt scientific findings and theories that conflict with their political and religious beliefs is evident from even a cursory scan of right-leaning media. The denial of evolution and of global warming and the pushback against stem cell research are the most egregious examples in recent decades. It is not surprising, because we expect those on the right to let their politics trump science—tantamount to a dog-bites-man story.



That liberals are just as guilty of antiscience bias comports more with accounts of humans chomping canines, and yet those on the left are just as skeptical of well-established science when findings clash with their political ideologies, such as with GMOs, nuclear power, genetic engineering and evolutionary psychology—skepticism of the last I call "cognitive creationism" for its endorsement of a blank-slate model of the mind in which natural selection operated on humans only from the neck down.

In reality, antiscience attitudes are formed in very narrow cognitive windows—those in which science appears to oppose certain political or religious views. Most people embrace most of science most of the time.

Who is skeptical of science, then, and when?

That question was the title of an October 2017 talk I attended by Asheley R. Landrum, a psychologist at Texas Tech University, who studies factors influencing the public understanding and perception of science, health and emerging technologies. She began by citing surveys that found more than 90 percent of both Republicans and Democrats agreed that "science and technology give more opportunities" and that "science makes our lives better." She also reviewed modest evidence in support of the "knowledge deficit hypothesis," which posits that public skepticism of science is the result of inadequate scientific knowledge. Those who know more about climate science, for example, are slightly more likely to accept that global warming is real and caused by humans than those who know less on the subject.

But that modest effect not only is erased when political ideology is factored in, it has an opposite effect on one end of the political spectrum. For Republicans, the more knowledge they have about climate science the *less likely* they are to accept the theory of anthropogenic global warming (whereas Democrats' confidence goes up). "People with more knowledge only accept science when it doesn't conflict with their preexisting beliefs and values," Landrum explained. "Otherwise, they use that knowledge to more strongly justify their own positions."

Landrum and her colleagues demonstrated the effect experimentally and reported the results in a 2017 paper in the *Journal of Risk Research* entitled "Culturally Antagonistic Memes and the Zika Virus: An Experimental Test," in which participants read a news story on Zika public health risks that was linked to either climate change or immigration. Predictably, when Zika was connected to climate change, there was an increase in concern among Democrats and a decrease in concern among Republicans, but when Zika was associated with immigration, the effects were reversed. Skepticism, it would seem, is context-dependent. "We are good at being skeptical when information conflicts with our preexisting beliefs and values," Landrum noted. "We are bad at being skeptical when information is compatible with our preexisting beliefs and values."

In another 2017 study published in *Advances in Political Psychology,* "Science Curiosity and Political Information Processing," Landrum and her colleagues found that liberal Democrats were far less likely than strong Republicans to voluntarily read a "surprising climate-skeptical story," whereas a "surprising climate-concerned story" was far more likely to be read by those on the left than on the right. One encouraging mitigating factor was "science curiosity," or the "motivation to seek out and consume scientific information for personal pleasure," which "seems to counteract rather than aggravate the signature characteristics of politically motivated reasoning."

The authors concluded that "individuals who have an appetite to be *surprised* by scientific information—who find it pleasurable to discover that the world does not work as they expected—do not turn this feature of their personality *off* when they engage political information but rather indulge it in that setting as well, exposing themselves more readily to information that defies their expectations about facts on contested issues. The result is that these citizens, unlike their less curious counterparts, react more open-mindedly and respond more uniformly across the political spectrum to the best available evidence."

In other words, valuing science for pure pleasure is more of a bulwark against the politicization of science than facts alone. 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.

Is Anybody Anywhere?

SETI is still scanning the skies for other galactic citizens

By Steve Mirsky

Fourteen years ago in Bremen, Germany, astronomer Seth Shostak gave a lecture that included a wager. "I bet everybody in the audience a cup of Starbucks that we would find E.T. within two dozen years," he told a new audience in October. You don't have to be a Klaatu-level math whiz to calculate that Shostak has 10 years left before he'd have to shell out for a lot of tall drips. I'm talking about the coffee.

Shostak is senior astronomer at the Center for SETI Research based in Mountain View, Calif. SETI stands for "Search for Extraterrestrial Intelligence," of course, as the millions who have loaned out their home computer time for the SETI@home project know. He mentioned the wager at a session on the current state of the search for any signs of alien intelligence at the World Conference of Science Journalists in the San Francisco Bay Area. The SETI conversation in question took place on the University of California, Berkeley, campus. No protesters or extraterrestrials attended. Probably.

"To have some reasonable chance of success," Shostak said, "you'd have to look at at least a million star systems." Which may be possible within the coffee challenge's time parameter, thanks to $100 million from Russian physicist and entrepreneur Yuri Milner in 2015 to establish what is called Breakthrough Listen—an effort to use multiple radio and optical telescopes to survey the million stars closest to us. (It recently came out that in 2015 Milner had invested in a start-up co-owned by Donald Trump's son-in-law, Jared Kushner, who is a senior White House adviser. Perhaps Milner's SETI funding represented his realization that looking for intelligent life in outer space was a better bet.)

Shostak thinks his Bremen audience comes out ahead either way. "Because either [by 2027] a signal has been found and you have something to talk about at lunch—or you get a cup of coffee. You can't lose."

But what about sending out messages inviting contact with intelligent aliens rather than just listening for incoming missives from faraway smarty-pants or whatever clothing may be appropriate for their anatomy? "I think the risks outweigh the benefits," said Dan Werthimer, chief scientist at the Berkeley SETI Research Center, which oversees Breakthrough Listen. "When advanced civilizations come in contact with less advanced civilizations, it hasn't been good on Earth. So I think there's a lot of risk."

But Shostak thinks we already might have attracted somebody's attention: "The kind of equipment that we have today is within four orders of magnitude of being able to detect radars on nearby worlds, within a few tens of light-years. Now this speed of increase in the collecting area of radio telescopes on Earth is roughly two orders of magnitude per century.... That means that any society that's at least 200 years more advanced than we are has equipment that can pick up SFO, alright? That's the local airport for those of you from out of town. So ... if you really think there's a potential of killing seven billion people because the aliens get ticked off by hearing *I Love Lucy* and send their interstellar battlewagons here to wipe us out..., you better turn off all the radars. Not for the weekend, not for this year, you better turn them off forever. And to me, that doesn't sound like a good idea."

Shostak also brought up a less frightening but perhaps more existentially dreadful possibility about some future first contact: what if we finally hear from aliens broadcasting their presence as sentient beings, and the big announcement is their understanding of well-known mathematical phenomena such as the Fibonacci sequence. "That would be a real bummer, wouldn't it?" he asked. "I mean, we finally hear from E.T., and he tells us something you learned in 10th grade."

Actually I'd be okay with it—and with them watching Lucy gobble chocolates off the conveyor belt. What I worry about is them catching the iconic *Twilight Zone* episode where the aliens show up with a manuscript entitled "To Serve Man," and it ends up being a cookbook. Why give advanced carnivores any cravings? 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

JANUARY

1968 The Weakness of Polls

"A strong caution against attaching too much weight to polls of public opinion, particularly concerning political issues, has been expressed by Leo Bogart, president of the American Association for Public Opinion Research. '"Don't know" in response to a survey question,' he writes, 'often means "Don't want to know," which is another way of saying, "I don't want to get involved."' In many such cases the attitude reflects the respondent's feeling that the issue is no responsibility of his. Bogart sees a valuable role for surveys in ascertaining the extent of public ignorance on matters of fact. 'Often what we should be doing … is measuring the degrees of apathy, indecision or conflict on the part of the great majority, with the opinionated as the residual left over.'"

1918 Gods of Egypt

"The question of the character and origin of the local gods of Egypt is still obscure; but a paper by Prof. Flinders Petrie does much to clear it up. By marking the headquarters of each deity, he arrives at important results. Ra appears in only one southern city, and his cult seems to have come from the north-east. The distribution of Mut, the mother-goddess, is decidedly eastern, while that of Amen is western. Set was certainly brought into Egypt by the desert road, as he had there two centers of the first class, and he was introduced by the Red Sea way to the Eastern Delta. The distribution of the Osiride triad indicates a settlement so early in the land that the worship was generally diffused."

Auto Dreams

"It's more or less true—no one really knows anything about the future. So here goes, for a try. The automobile of the future will be weather-tight. Probably it will be all glass—sides, front, rear and roof. If malleable glass is ever made, the frame may be dispensed with, but nobody has discovered malleable glass, to date! In the future the car with the steering wheel will be as obsolete as the car with the hand pump for gas or oil is today! Driving will be done from a small control board, which can be held in the lap. It will be connected to the mechanism by a flexible electric cable. A small *finger* lever, not a wheel, will guide the car."

Whale Steak

"I have joined with the crowd in another attempt to shoot a torpedo into the ribs of the high cost of living. Let me tell you that from an epicurean standpoint, whale meat isn't so awful bad. It is better than crow, not so tough as alligator, nor so rank as buzzard. Buzzard? 'Yes, stew it with red pepper and lots of garlic and you can never tell.' This is particularly true if the pepper is of the Mexican variety—real hot. The University of California and several other institutions of wise heads are attesting to the value of whale beef for food, but its own cheapness, 12 cents a pound, is the best drawing card."

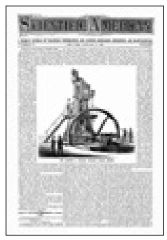
1868 Killing the Vector

"Dispatches from Commander Chandler of the United States steamer *Don,* dated Vera Cruz, Dec. 16, state that the yellow fever broke out on board of his vessel on the 25th of November. It proved to be of a most malignant type. Commander Chandler caused the hatches of the berth-deck and ward-room to be securely closed. One joint of the steam-heater on the berth-deck was disconnected, and the same operation performed in the ward-room. After two hours' steaming in the ward-room, a thermometer indicated 205 degrees, and on the berth-deck 170 degrees. No cases of fever occurred afterward. Commander Chandler is fully persuaded that heat eradicated the disease as effectually as a severe frost could have done."

Yellow fever was not definitively shown to be transmitted by mosquitoes for another three decades.

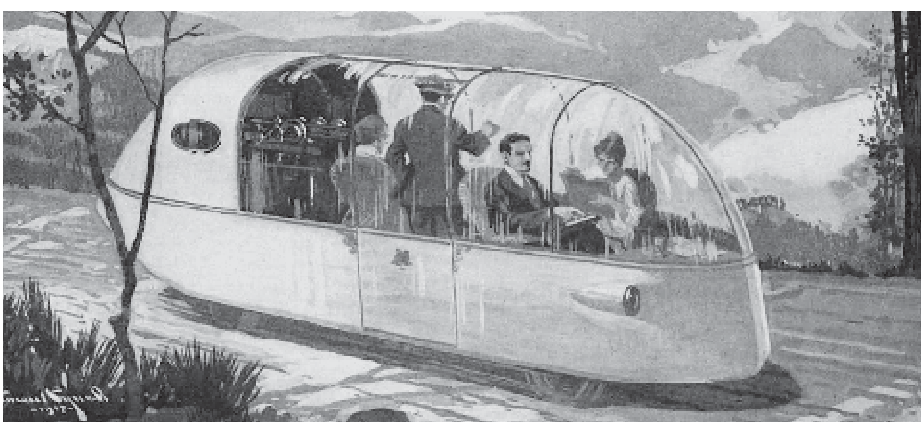

1968


1918


1868

Rubber Tire Invented

"Mr. R. W. Thomson, of Edinburgh, has invented a new locomotive for common roads, which was lately tried in the neighborhood of Edinburgh. The tires are made of bands of vulcanized india-rubber, about twelve inches wide and five inches thick. Incredible as it may appear, this soft and elastic substance not only carries the great weight of the road steamer without injury, but it passes over newly broken road metal, broken flints, and all kinds of sharp things without leaving even a mark on the india-rubber. The engine is destined for Java."


What cars ought to look like, steered by a finger lever, as imagined in 1918.

SCIENTIFIC AMERICAN, VOL. CXVIII, NO. 1; JANUARY 5, 1918

Text by Mark Fischetti | Graphic by Jen Christiansen

Killer Seas

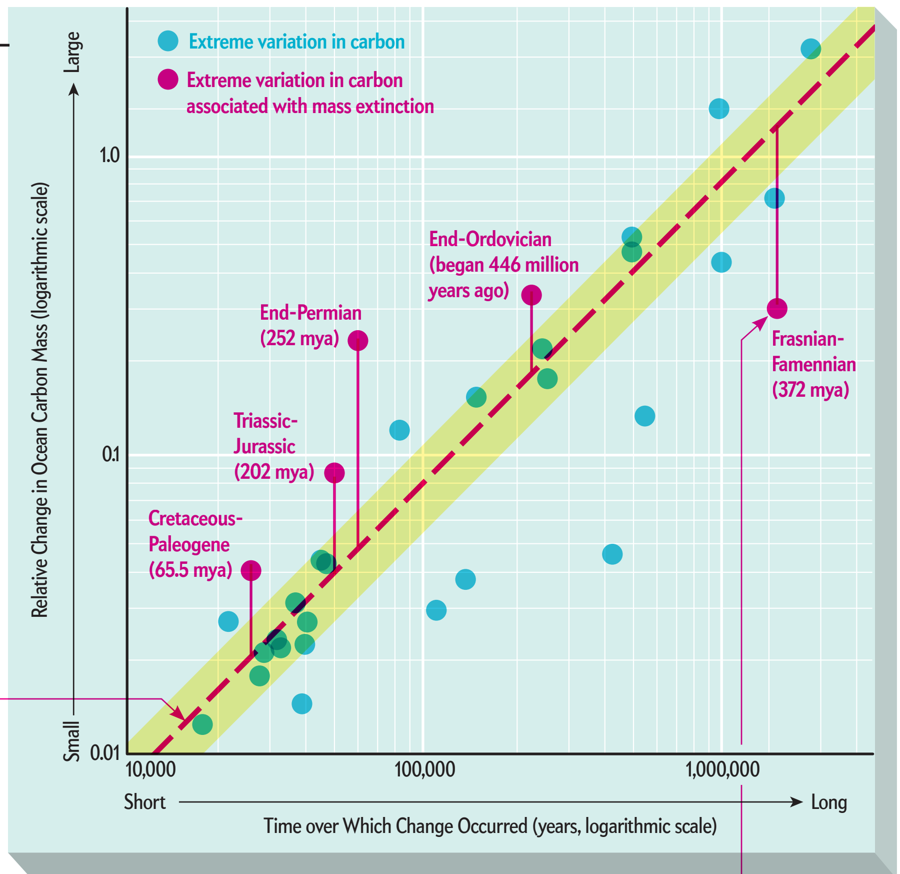
Mass extinction could begin by 2100

The amount of carbon in our planet's oceans has varied slowly over the ages. But 31 times in the past 542 million years the carbon level has deviated either much more than normal or much faster than usual (*dots in main graph*). Each of the five great mass extinctions occurred during the same time as the most extreme carbon events (*pink dots*). In each case, more than 75 percent of marine animal species vanished. Earth may enter a similar danger zone soon. In 1850 the modern oceans contained about 38,000 gigatons of carbon, and a new study by geophysics professor Daniel H. Rothman of the Massachusetts Institute of Technology indicates that if 310 gigatons or more are added, the deviation will again become acute. Humans have already contributed about 155 gigatons since then, and the world is on course to reach 400 gigatons by 2100 (*small graph*). Does that raise the chance for a mass extinction? "Yes, by a lot," Rothman says.

Five Mass Extinctions

Oceans hold about 50 times more carbon than the atmosphere. The concentration has gone up or down significantly 31 times (*dots*) but typically no faster than a critical rate (*pink line; yellow is margin of error*). Four of history's five mass extinctions occurred when the amount of carbon changed much faster than this rate (*pink dots above line*). The fifth was when the variation occurred very slowly (*pink dot below line*).

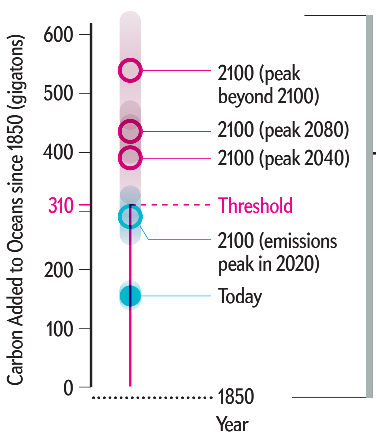
Threshold of Volatility
Events below the dashed line reflect modest changes in the global carbon cycle. Events above the line reflect unusual additions of carbon and suggest unstable, runaway change.



New Species Missing
This large, slow aberration in ocean carbon seems to have been accompanied by a strange anomaly: more than a million years during which few new species arose. Other species died out during that time, lowering the overall number significantly.

Sixth Extinction by 2100?

The world has added 155 gigatons of carbon to the oceans since 1850—so fast that catastrophic change could result from surpassing a critical mass. If additions reach 310 gigatons, the world could cross that threshold into a danger zone for a sixth mass extinction. Only one scenario—reducing global emissions starting in 2020—barely avoids the threshold. Other scenarios—hitting peak emissions, then reducing that beginning in 2040 or 2080 or beyond 2100—risk making mass extinction likely.



SOURCE: "THRESHOLDS OF CATASTROPHE IN THE EARTH SYSTEM," BY DANIEL H. ROTHMAN, IN *SCIENCE ADVANCES*, VOL. 3, NO. 9, ARTICLE NO. E1700906; SEPTEMBER 20, 2017