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JOSH EDELSON Getty Images

ON THE COVER
Neutron stars form when stars of certain masses die in supernova explosions, leaving behind dense remnants made mostly of neutrons. Inside these remnants, the neutrons themselves may break down, or they might form a frictionless "superfluid." New experiments should help scientists sort through the possibilities. Illustration by FOREAL.

SCIENTIFIC AMERICAN


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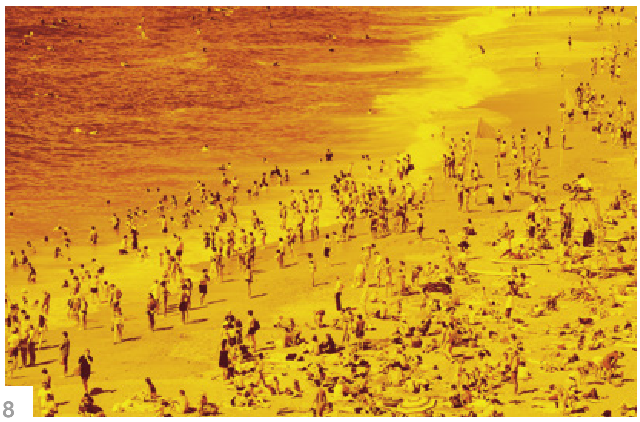
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ON THE WEB

Revisiting Fukushima
Scientific American looks at the legacy of the Fukushima nuclear disaster of March 11, 2011, and the science still being done to grapple with its continuing effects.
Go to www.ScientificAmerican.com/mar2019/fukushima

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

"Outrageous" Objects and Other Adventures in Science

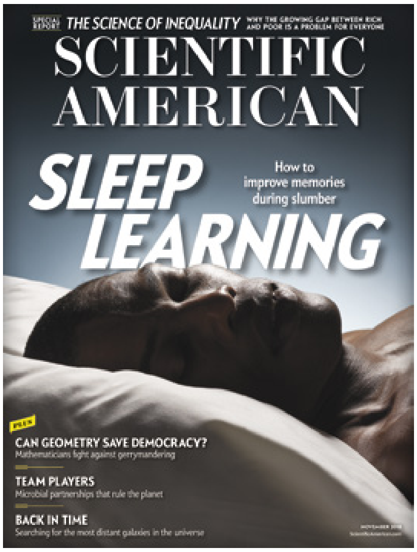
"The most outrageous object that most people have never heard of," as one scientist calls it, is the subject of our cover story—and, to my mind at least, such amazing adventures in discovery make up a theme that resounds throughout this *Scientific American* issue, among many others.

What's this intriguing object? In "The Inner Lives of Neutron Stars," senior editor Clara Moskowitz writes about these strange cosmic things, which pack the mass of roughly two suns into a space no wider than a city. They are born when stars die and collapse on themselves. The extreme density created by stellar cataclysms is the greatest amount allowed naturally in our universe and impossible to come close to approximating in any laboratory on Earth. Understanding the phenomena that result under such conditions is the tantalizing challenge of researchers, who are positioned to gain new insights from detectors capable of measuring gravitational waves from neutron star collisions, along with experiments focusing on these unusual objects. Dive in, starting on page 24.

The human genome's DNA forms some 10,000 wiggling minuscule loops in our cells, which somehow avoid "tangling into a mess" that would disrupt crucial genetic messages. These loops, which turn out to be ancient structures in biology, are involved in gene regulation and may hold clues to how many diseases arise. As geneticist Erez Lieberman Aiden writes, "We and others have figured out how these loops form, dancing an elegant tango that keeps the genome tangle-free." Beginning on page 50, you can unspool the mystery in his feature, "Untangling the Genome."

Several stories will take you on fascinating intellectual voyages into the mind and behavior—and not just those of humans. Contributing editor Melinda Wenner Moyer looks at why some people refuse to accept facts and data in "Why We Believe Conspiracy Theories" (*page 58*). "The Undiscovered Illness," by journalist Simon Makin, explores the question of whether some bipolar patients who experience only mania should have a separate diagnosis (*page 36*). Two articles look at cognitive areas at least partly shared among animals. "The Orca's Sorrow," by science writer Barbara J. King, finds evidence that a wide variety of animals are capable of mourning (*page 30*). "The Other Tool Users," by independent researcher Michael Haslam (*page 64*), looks at excavations of stone tools left behind by nonhuman primates and the origin of innovation. And get ready for more extreme summer weather, as expert Michael E. Mann takes us on a tour of the jet stream (*page 42*). SA

Illustration by Nick Higgins



November 2018

"The problems with slavery would not have been fixed simply by calling for more regulation and stiffer penalties."

MARIANNE HILL *SOUTH PORTLAND, ME.*

INEQUALITY CONTROL

Economist Joseph E. Stiglitz's article ("A Rigged Economy" [The Science of Inequality]) on how we got to today's lamentable economic state in the U.S. is spot on. Yet let me give my own, more simple explanation: When I was a young man, during the three decades after FDR and the New Deal, the maximum federal tax rate (applied at the time to income exceeding an amount that has ranged between $100,000 and $500,000) was between 70 and 91 percent. As such, federal taxation was highly progressive; the rich were few and were not so obscenely wealthy, and most important, the middle class was dominant. In 1981, shortly after taking office, Ronald Reagan slashed the top bracket's rate to 50 percent and then, in 1986, to 28 percent—a tremendous windfall for the rich that continues unabated (today's top rate is 37 percent on income exceeding $500,000).

One has only to look at Stiglitz's graphs, in which everything takes a turn for the worse after 1980, to see how our current tax code lines the pockets of the rich and steadily erodes the middle class. We either return to a progressive tax policy or continue the descent into plutocracy.

R. C. GIBSON *Irvine, Calif.*

I agree with the points that Stiglitz (who is my former professor) makes about the causes of inequality, as well as those that James K. Boyce makes about the links between environmental degradation and inequality in "The Environmental Cost of Inequality" [The Science of Inequality]. But Stiglitz's list of needed policy changes falls short, as does Boyce's reliance on environmental activists to save flora, fauna and natural resources.

We know that the problems with slavery would not have been fixed simply by calling for more regulation and stiffer penalties. Our laws today ensure that a few can claim excessive wealth and power. By what right do those owning firms have the power to decide how the income and wealth generated by the talent and labor of many are used? Stakeholders—employees, customers, the communities affected by a company's decisions—have rights that require greater recognition. Stakeholders' interests should be represented on the boards of big firms. Those with revenues exceeding $1 billion should be required to have a national charter that would lay out obligations and penalties.

Where would the power to institute such changes originate? My fellow economists are very reluctant to talk about political parties, yet we want to influence political platforms. We can at least begin to identify not only where the public interest lies but also what kind of political group is most likely to represent those interests.

MARIANNE HILL *South Portland, Me.*

REDISTRICT JUDGE

In "Geometry *v.* Gerrymandering," Moon Duchin describes mathematicians' efforts to create statistical methods to detect and replace biased voting district maps.

Last November's election in Missouri had an amendment on the ballot, approved by about 62 percent of the vote, to change "the process and criteria for redrawing state legislative districts during reapportionment." (While many argued that the ballot wording was deceptive, one needs examine the details. The full statement can be found here: www.sos.mo.gov/elections/petitions/2018BallotMeasures)

I wonder if any of the ideas or analyses Duchin presents could be used toward validating the method outlined in the constitutional amendment before actual redistricting maps are constructed.

MORITZ FARBSTEIN *St. Louis, Mo.*

The Markov chain Monte Carlo (MCMC) process for redistricting that Duchin describes requires the public to trust both the mathematics and the mathematicians. The possible configurations are so enormous that it reminds me of all the possible outcomes in a game of chess. And yet even beginners play chess without being overwhelmed by the vast number of moves.

Perhaps the entire process could be treated more like chess, with the two sides taking turns choosing a district to maximize its number of voters instead of letting one side make all the moves for both. If one side outnumbers the other, that side may be given proportionally more choices. The final result would be approved by a judge or a redistricting committee.

There is no need to resort to the massive computations in MCMC as long as the process of choosing the districts is fair.

BENJAMIN JONES *via e-mail*

DUCHIN REPLIES: The Missouri amendment that Farbstein refers to belongs to a crop of state-level reform measures approved by voters in 2018 (joining Colorado, Utah, Ohio and Michigan). Missouri's was especially detailed: specific criteria were laid out, including a formula to define "partisan fairness" and a precise way to measure "competitiveness." A legitimate worry for such reforms is that tradeoffs in redistricting priorities are so complicated that well-meaning rules might actually conflict or have unintended consequences. This raises scientific questions, and they are approachable! Sampling from the universe of plans can illustrate the cost to one priority as another is introduced and can give a state-specific base-

line or normal range for metrics used to evaluate a commission's proposals.

Regarding Jones's letter: One of the problems caused by rampant redistricting abuse is precisely the erosion of public trust, and restoring it will require transparency. MCMC for redistricting needs to be open-source, peer-reviewed and fully auditable. In terms of the problem's complexity, strategy games like chess—or Go—are great examples. The rules are simple, but mastery is elusive.

Note that advocates of outlier analysis propose to use MCMC only to evaluate plans and not to select them. There must still be a role for local knowledge, community input and all things human. But a bird's-eye view of the possibilities can help ensure that no group's interests are trampled, no matter what process is used.

CORRELATION TO MURDER

Maia Szalavitz's story "Income Inequality and Homicide" [Forum] refers to psychologist Martin Daly's assertion that income inequality predicts murder rates better than other variables do.

I am perplexed by Daly's use of murder rates alone to nail down his conclusions rather than looking at a more relevant tally of violent assaults overall. Death rates alone are often used in discussions of gun violence and highway speed limits. And yet death is just one of several possible outcomes of a violent assault. The end-of-year murder rate is more dependent on the access and actions of responding EMTs and hospital trauma teams. The impact of trauma center success stories in high-crime areas may be ignored in statistical studies and yet might be the primary reason for drops in regional murder rates.

John Andrews *Milford, N.J.*

ERRATA

"Back in Time," by Dan Coe, should have referred to galaxies likely at a redshift of around two as being three billion years old, or nearly a quarter of the universe's age, rather than 10 billion years old.

"A Rigged Economy," by Joseph E. Stiglitz [The Science of Inequality], should have referred to the "North American Free Trade Agreement," not the "North Atlantic Free Trade Agreement."

LETTERS TO THE EDITOR

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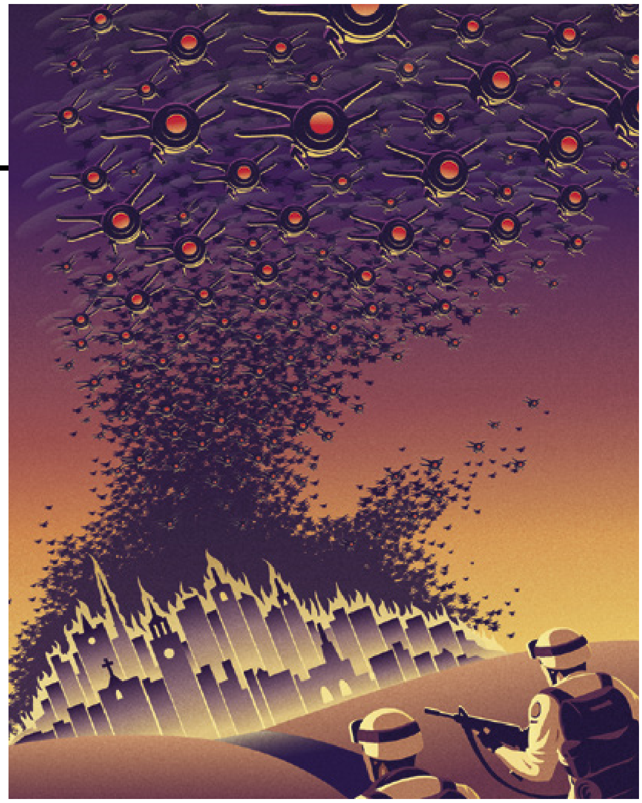
Don't Let Bots Pull the Trigger

Weapons that kill enemies on their own threaten civilians and soldiers alike

By the Editors



The killer machines are coming. Robotic weapons that target and destroy without human supervision are poised to start a revolution in warfare comparable to the invention of gunpowder or the atomic bomb. The prospect poses a dire threat to civilians—and could lead to some of the bleakest scenarios in which artificial intelligence runs amok. A prohibition on killer robots, akin to bans on chemical and biological weapons, is badly needed. But some major military powers oppose it.

The robots are no technophobic fantasy. In July 2017, for example, Russia's Kalashnikov Group announced that it had begun development of a camera-equipped 7.62-millimeter machine gun that uses a neural network to make "shoot/no-shoot" decisions. An entire generation of self-controlled armaments, including drones, ships and tanks, is edging toward varying levels of autonomous operation. The U.S. appears to hold a lead in R&D on autonomous systems—with $18 billion slated for investment from 2016 to 2020. But other countries with substantial arms industries are also making their own investments.

Military planners contend that "lethal autonomous weapons systems"—a more anodyne term—could, in theory, bring a detached precision to war fighting. Such automatons could diminish the need for troops and reduce casualties by leaving the machines to battle it out. Yet control by algorithm can potentially morph into "out of control." Existing AI cannot deduce the intentions of others or make critical decisions by generalizing from past experience in the chaos of war. The inability to read behavioral subtleties to distinguish civilian from combatant or friend versus foe should call into question whether AIs should replace GIs in a foreseeable future mission. A killer robot of any kind would be a trained assassin, not unlike Arnold Schwarzenegger in *The Terminator*. After the battle is done, moreover, who would be held responsible when a machine does the killing? The robot? Its owner? Its maker?

With all these drawbacks, a fully autonomous robot fashioned using near-term technology could create a novel threat wielded by smaller nations or terrorists with scant expertise or financial resources. Swarms of tiny, weaponized drones, perhaps even made using 3-D printers, could wreak havoc in densely populated areas. Prototypes are already being tested: the U.S. Department of Defense demonstrated a nonweaponized swarm of more than 100 micro drones in 2016. Stuart Russell of the University of California, Berkeley, a prominent figure in AI research, has suggested that "antipersonnel micro robots" deployed by just a single individual could kill many thousands and constitute a potential weapon of mass destruction.

Since 2013 the United Nations Convention on Certain Conventional Weapons (CCW), which regulates incendiary devices, blinding lasers and other armaments thought to be overly harmful, has debated what to do about lethal autonomous weapons systems. Because of opposition from the U.S., Russia and a few others, the discussions have not advanced to the stage of drafting formal language for a ban. The U.S., for one, has argued that its policy already stipulates that military personnel retain control over autonomous weapons and that premature regulation could put a damper on vital AI research.

A ban need not be overly restrictive. The Campaign to Stop Killer Robots, a coalition of 89 nongovernmental organizations from 50 countries that has pressed for a such a prohibition, emphasizes that it would be limited to offensive weaponry and not extend to antimissile and other defensive systems that automatically fire in response to an incoming warhead.

The current impasse has prompted the campaign to consider rallying at least some nations to agree to a ban outside the forum provided by the CCW, an option used before to kick-start multinational agreements that prohibit land mines and cluster munitions. A preemptive ban on autonomous killing machines, with clear requirements for compliance, would stigmatize the technology and help keep killer robots out of military arsenals.

Since it was first presented at the International Joint Conference on Artificial Intelligence in Stockholm in July, 244 organizations and 3,187 individuals have signed a pledge to "neither participate in nor support the development, manufacture, trade, or use of lethal autonomous weapons." The rationale for making such a pledge was that laws had yet to be passed to bar killer robots. Without such a legal framework, the day may soon come when an algorithm makes the fateful decision to take a human life. SA

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Illustration by Chris Whetzel

Jonas Korlach is chief scientific officer at Pacific Biosciences of California. He holds a Ph.D. in biochemistry and molecular and cell biology from Cornell University.

Genomic Studies Need Diversity

A heavy skew toward white people makes precision medicine imprecise

By Jonas Korlach

Underrepresentation of nonwhite ethnic groups in scientific research and clinical trials has been a disturbing trend. One particularly troubling aspect is that human genomic databases are heavily skewed toward people of European descent. If left unaddressed, this inherent bias will continue to contribute to uneven success rates in so-called precision medicine.

The problem stems from the underlying structure of science. In the early days of genomics, funding for sequencing projects was often highest among mostly white countries, so those populations are better represented in public databases. Also, some minorities have been historically mistreated by scientists—the Tuskegee syphilis experiment is one glaring example—and many members of those groups can be understandably reluctant to enter studies.

Early studies were also biased by the types of genetic variation the research focused on. Initially scientists looked at only tiny, single-base-pair DNA differences between populations, ignoring larger variations that were more difficult to assess but that turned out to be more significant than anyone expected. These are now known to cause genetic disease and influence the way drugs are metabolized by different ethnic populations, not just individuals—and advanced technologies allow scientists to identify variations that in many cases have never been seen before.

This is an exciting step forward: we are finding that some of these structural differences can explain diseases for which no cause had previously been found—such as Carney complex, a rare disorder that causes tumors to appear in various parts of the body, for example, or a mutation that may contribute to bipolar disorder and schizophrenia. And here, too, the effects may well vary from one ethnic group to another.

I am pleased to say that the genomics community is starting to tackle the challenge of improving the ethnic diversity in our databases. As chief scientist at a DNA-sequencing technology company, I witness these efforts every day. For instance, a number of countries have launched population-specific projects that aim to produce high-quality reference genomes. Excellent results in Korea, China and Japan have led to genomic resources that more accurately capture the natural diversity present in those populations, with positive clinical implications. Such sequences are also enabling large-scale studies of specific ethnic groups to dramatically improve their representation in genomic databases.

Already these projects have led to discoveries that can make clinical trials and medical care more successful for participants with these genetic backgrounds. For example, the Korean genome project found a population-specific variant in a gene that regulates how some medications are metabolized by the body. This is essential information for dosing and for gauging the likelihood that a patient will respond to a particular therapy.

In places with less developed infrastructure, including parts of Latin America and Africa, such efforts have lagged: the National Human Genome Research Institute has begun gathering data from these areas, but sequencing and analysis are usually done elsewhere. Still, as more such projects move forward, there will be important discoveries that will be relevant to any number of ethnic groups. One such program—a National Institutes of Health effort called "All of Us"—aims to sequence a diverse sampling of Americans across gender, sexual orientation, ethnicity and race. Being inclusive is its fundamental goal, and participation is free.

In the field of rare diseases, genome sequencing has proved remarkable at increasing the diagnosis rate, giving answers to patients who might otherwise have gone undiagnosed. Today that approach remains most effective for Caucasian patients because more of their DNA can be interpreted using current genomic data repositories. But as we build up data for people of other ethnicities, we can expect such successes to extend rapidly to patients of any background, which stands to dramatically improve health care for hundreds of millions of people.

Achieving the vision of precision medicine for individuals of any ethnic group requires more diverse representation in the biological repositories that underlie clinical programs. Advanced DNA-sequencing technology is one tool of many needed to help generate better information about people from all ethnicities for the equitable application of those data in clinical practice. SA

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Illustration by Alexandra Bowman

ADVANCES

Prolonged and deadly heat waves are becoming more common, leaving millions at risk.

MATTEO COLOMBO *Getty Images*

CLIMATE AND HEALTH

Feverish Planet

A sobering report links climate change to labor loss, disease and death worldwide

A devastating heat wave swept across Europe in 2003, killing tens of thousands of people, scientists estimate. Many were elderly, with limited mobility, and some already suffered from chronic diseases. But climate change is making such extreme weather more common—and the effects will not be limited to the old and sick. Warming temperatures do not only threaten lives directly. They also cause billions of hours of lost labor, enhance conditions for the spread of infectious diseases and reduce crop yields, according to a recent report.

The report, published last December in the *Lancet,* represents the latest findings of the Lancet Countdown—a coalition of international research organizations collaborating with the World Health Organization and the World Meteorological Organization. The group tracks the health impacts of—and government responses to—climate change.

"It affects everyone around the world—every single person, every single population. No country is immune," says Nick Watts, executive director of the Lancet Countdown and one of many co-authors of the report. "We've been seeing these impacts for some time now."

The report found that millions of people worldwide are vulnerable to heat-related disease and death and that populations in Europe and the eastern Mediterranean are especially susceptible—most likely because they have more elderly people living in urban areas. Adults older than 65 are particularly at risk, as are those with chronic illnesses such as heart disease or diabetes. Places where humans tend to live are exposed to an average temperature change that is more than twice the global average—0.8 versus 0.3 degree Celsius (*graphic*). There were 157 million more "heat wave exposure events" (one heat wave experienced by one person) in 2017 than in 2000. Compared with 1986 to 2005, each person was exposed to, on average, 1.4 more days of heat wave per year from 2000 to 2017. That may not seem like a lot, but as Watts notes, "someone who is 75 and suffers from kidney disease can probably survive three to four days of heat wave but not five or six."

Sweltering temperatures also affect productivity. A staggering 153 billion hours of labor—80 percent of them in agriculture—were lost to excessive heat in 2017, the new report found, with the most vulnerable areas being in India, Southeast Asia, sub-Saharan Africa and South America. The first stage of heat's impact is discomfort, says report co-author Tord Kjellstrom, director of the Health and Environment International Trust in New Zealand and a consultant on environmental and occupational health. But there comes a point at which it is simply too hot for the body to function. For example, sweating heavily without replenishing water can result in chronic kidney disease, Kjellstrom notes. News reports have documented farm workers in Central America dying from kidney problems after years of working in the hot fields. Richer countries such as the U.S. may avoid the worst effects because of better access to drinking water and, in the case of indoor work, air-conditioning. But these solutions can be expensive, Kjellstrom says.

Then there are indirect effects. For example, warmer temperatures have increased the geographical ranges of organisms that spread dengue fever, malaria and cholera. The "vectorial capacity"—a measure of how easily a disease carrier can transmit a pathogen—of dengue virus, which is spread by the *Aedes aegypti* and *Aedes albopictus* mosquitoes, reached a record high in 2016. The percentage of coastline suitable for bacteria in the *Vibrio* genus (which includes the species that causes cholera) increased from the 1980s to the 2010s in the Baltic region and northeastern U.S. by 24 and 27 percent, respectively. In Africa's highlands, environmental suitability for the malaria-causing *Plasmodium falciparum* parasite increased by nearly 21 percent from the 1950s to the 2010s.

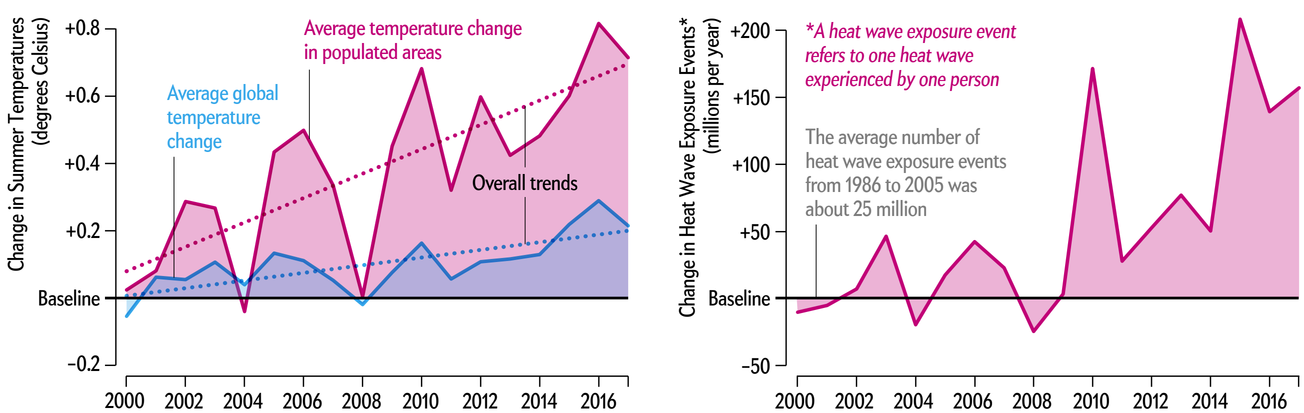
Climate change also threatens food security. Our planet still produces more than enough food for the world, but 30 countries have seen crop yields decline as a result of extreme weather, the report found.

"Overall, the report does suggest very serious concerns about the way in which climate change is evolving and its potential implications for human health," says Andy Haines, a professor of environmental change and public health at the London School of Hygiene & Tropical Medicine, who was not involved in the 2018 report but has co-authored previous Lancet Countdown assessments. "One of the problems is that we don't have enough data on the actual impacts, particularly in the low-income countries," which will likely be most affected, he says.

The report did find some bright spots: in 2015, 30 of 40 countries surveyed by the WHO reported having climate change health adaptation plans, and 65 percent of cities have undertaken (or are undertaking) risk assessments that address threats to public health infrastructure. But worldwide spending on health adaptation is still under 5 percent of all climate adaptation spending. And funding has not matched that pledged in the Paris Agreement, the global climate accord that is set to take effect in 2020.

Among the biggest steps countries can take to mitigate these health effects are phasing out coal-fired power and shifting to greener forms of transportation, Watts says. Electric vehicles are making inroads in places, he notes—and "active" transport, such as walking or cycling, is also important. Tallying up the costs of climate change, Watts says, makes it clear that "our response or lack of response is going to determine our health over the next century." —*Tanya Lewis*

A Hotter Planet Puts More People at Risk



The graphs compare temperatures and heat wave events since 2000 with baseline values from the reference period 1986–2005.

SOURCE: "THE 2018 REPORT OF THE LANCET COUNTDOWN ON HEALTH AND CLIMATE CHANGE: SHAPING THE HEALTH OF NATIONS FOR CENTURIES TO COME," BY NICK WATTS ET AL., IN *LANCET*, VOL. 392; DECEMBER 8, 2018

Graphic by Amanda Montañez

VANESSA MIGNON *Getty Images*

ANIMAL COMMUNICATION

Whale Chatter

Many humpback calls have remained the same over decades

Recently coined words such as "selfie" and "hangry" reflect humans' evolving language. The communication patterns of other social animals, including whales, also vary over time. The "songs" adult male humpback whales produce during the breeding season, for example, are constantly changing.

But in a new study, researchers investigated the permanence of nonsong whale vocalizations known as calls and found that the majority have remained stable over multiple decades. This surprising result suggests that calls may function as important tools for conveying information about foraging, social behaviors and whale identity.

Scientists have studied humpback whale songs extensively—but there is probably a lot more to these creatures' communication than we know, says Michelle Fournet, a marine ecologist now at Cornell University and lead author of the new study. "The running hypothesis is that any time the whales are talking about something other than breeding, they're using calls," explains Fournet, who completed the work while at Oregon State University. These vocalizations, which typically last only a few seconds, are extremely diverse and have evocative names such as "moans," "squeegies," "shrieks" and "growls." They can be heard by other whales several kilometers away.

Fournet and her collaborators amassed nearly 115 hours of archival recordings collected in southeastern Alaska between 1976 and 2012. "No one had listened to them in years," Fournet says of the older recordings, which likely include vocalizations of the great-grandmothers and great-grandfathers of juvenile whales alive today.

By analyzing the duration and frequency of the calls, the researchers grouped them into 16 types. Fournet and her team detected 12 of them in both the earliest and most recent recordings—and each of the 16 call types recurred over at least three decades, the scientists reported last September in *Scientific Reports.* This finding led Fournet to conclude that these particular vocalizations most likely are essential to the whales' survival, ensuring foraging success and social contact. "For calls to stay in the [collective] conversation for so long is an indication that these call types are vital to the life histories of humpback whales," she says.

This work provides "rare and very valuable insights into the evolution of animal communication systems," says Volker Deecke, a biologist at the University of Cumbria in England, who was not involved in the research.

Next summer Fournet plans to travel to southeastern Alaska to play back recordings of calls to humpbacks there. The goal is to test theories about the functions of different calls, she says, adding, "We're going to go and start the conversation."

—Katherine Kornei

GROUP DYNAMICS

Eyes of the Peloton

Visual cues govern cyclists' pack behavior

Like a school of fish or flock of birds, a pack of bicycle riders (technically called a "peloton") often behaves like a unified entity. When individuals engage in simple small-scale behaviors, a collective pattern emerges that helps the whole. But in densely packed groups, it can be unclear what determines each individual's behavior. Mathematicians and biologists have argued that cyclists' movements within a peloton are primarily driven by optimizing aerodynamics, but new research suggests a different explanation.

Jesse Belden of the U.S. Naval Undersea Warfare Center and Tadd Truscott of Utah State University have found that visual input plays a critical role in how cyclists position themselves within the pack: individuals subconsciously form a diamond-shaped pattern that optimizes their peripheral vision, helping them quickly respond to others' changes in motion.

Pairs of cyclists save the most energy when one rider follows closely behind another. But for pelotons, Belden says, "we don't see that pattern inside a group. Aerodynamics only matters at the outside edge—you save energy wherever you are inside a pack." Previous studies in animals ranging from locusts to birds suggested that vision helps to shape the group as a whole, but they did not explain how it shapes individual behavior. To find out, researchers decided to study professional cyclists.

While examining helicopter footage of Tour de France races, Belden, Truscott and their colleagues noticed two behaviors that caused fluidlike ripples through the peloton. In one, a rider would brake and other riders would slow to avoid a collision. In the other, a rider would move sideways

JEFF PACHOUD *Getty Images*

ECOLOGY

Zombie Spiders

Parasitic wasp larvae make arachnid hosts build their own tombs

Talk about a raw deal: deadly parasitic wasps ruin the lives of adolescent spiders by taking over their minds, forcing them to become hermits and then eating them alive.

A remarkable species of social spider lives in parts of Latin America, in colonies of thousands. *Anelosimus eximius* spiders dwell in basket-shaped webs up to 25 feet wide attached to vegetation near the jungle floor, where they protect their eggs and raise broods cooperatively. A colony works together to take down much larger prey, such as grasshoppers, which sometimes fall into a web after blundering into silk lines that stick out of it vertically. "It could be someone's nightmare," says Philippe Fernandez-Fournier, now a doctoral student at Simon Fraser University in British Columbia.

But Fernandez-Fournier recently observed a wasp species—not previously named or described in the scientific literature—that can bend these social spiders to its will in an even more nightmarish way. This parasitic puppet master camps out beside the web, apparently waiting for a young spider to stray from its colony. The wasps may prefer juveniles because of their softer shells and "less feisty" natures, according to Fernandez-Fournier, lead author of a study describing the strange parasitism, published online last November in *Ecological Entomology.*

Scientists do not know how a wasp larva

ALAMY

to skirt an obstacle or fill a gap. These movements produced waves moving forward and backward or left and right through the peloton, respectively. The left-right waves propagated relatively slowly—at the speed it takes a human to respond to an immediate neighbor's motions. The forward-backward waves, however, propagated much faster, implying that individuals had anticipated changes in response to the motion of someone two riders ahead.

These wave findings suggest that vision is the main influence on individual rider behavior because riders want to keep neighbors within the range of peripheral vision most sensitive to motion. Apart from long-term race goals, each cyclist's main objective is to avoid crashing; riders do so by maintaining a position that lets them focus on what is in front while keeping more space between side-flanking neighbors. The work was presented last November at the 71st Annual Meeting of the American Physical Society Division of Fluid Dynamics.

The researchers say their findings could be applied to explain collective animal behavior, help optimize exit plans in crowded spaces or program collections of autonomous robots.

—*Rachel Berkowitz*

ends up on the spider—but once there it starts feeding on the arachnid's abdomen. As the larva grows, it starts to control the spider's brain, inducing it to leave the safety of its colony. Then the young spider weaves a ball of silk that seals it off from the outside world. The larva completes its life cycle by eating the rest of the spider, using the conveniently surrounding web to build its own cocoon and pupate into an adult wasp.

Fernandez-Fournier believes the wasp larvae most likely release a chemical that activates specific genes in their hosts, triggering antisocial behavior. Other related spiders are less social, leaving their colonies when they are young. Andrew Forbes, an associate professor of biology at the University of Iowa, who was not involved in Fernandez-Fournier's research, says the mind-controlling wasp larvae may be tapping into this latent genetic pathway. The spiders may have evolved toward social living for protection from predators, but the parasites could be pulling the genetic strings in their favor. "You can think of it," Forbes says, "as an evolutionary arms race between the spider and the parasitoid." —*Joshua Rapp Learn*

BIOLOGY

Microbial Dark Matter

Most microorganisms have never been studied in a laboratory

Just as most of the matter in the universe is thought to be "dark matter," much of Earth is populated by a kind of microbial analogue: microorganisms that are known to exist but have never been grown in a laboratory.

A new study, published last September in *mSystems,* suggests such microbes could account for up to 81 percent of all bacterial genera that live outside the human body. These little-known organisms could hold the secrets to new tools for treating disease and could help us understand life in extreme environments, such as those on other planets.

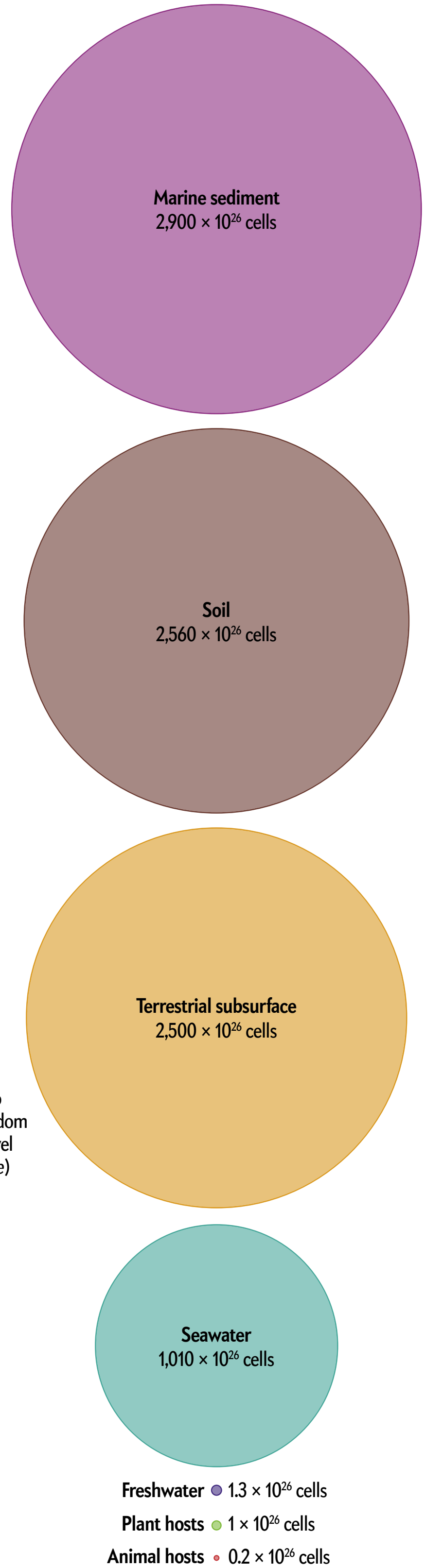
Microbes are the most abundant life-form on Earth. Researchers have sequenced the DNA of many species out in the field, but they can be difficult to culture in the lab, and scientists usually grow only one species at a time to study them in a controlled setting. To determine how much microbial dark matter exists, Karen Lloyd, a microbiologist at the University of Tennessee, Knoxville, and her colleagues compared all known microbial DNA sequences with the subset from species that have already been cultured. They then inferred the fraction of microbes that have been sequenced but never cultured (*graphic*). "We're discovering numerically that so many of the microbes on Earth are things we have never really learned anything about," Lloyd says.

The sheer number of microbial species—possibly close to a trillion—means that scientists cannot possibly collect them all. Many species exist in hard-to-reach places, such as at the bottom of the ocean or under frozen Arctic soil. Furthermore, not all microbes can survive in cultures designed to nurture just one strain. Some can grow only in a far more complex, natural environment, notes environmental microbiologist Laura Hug of the University of Waterloo in Ontario, who was not involved in the study. "They get what they need from their community," she says, "so that means you can't really grow them on their own."

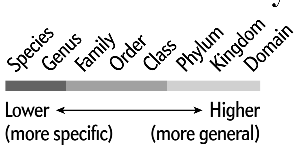
But Lloyd is optimistic. "We have made great strides with just the known microbes, and there are potentially even more discoveries hidden in these [unknown ones]," she says. "It leaves open the possibility for really grand discoveries."

—*Dana Najjar*

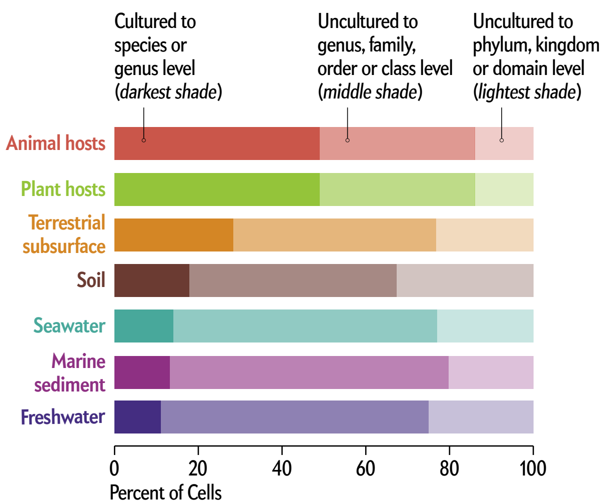
Estimated Abundances of Microbial Cells by Environment



Taxonomic Hierarchy



Scientists have pinpointed the evolutionary identities of about half of animal- or plant-dwelling microbes to at least the genus level of specificity. But the comparatively enormous populations of microbes inhabiting other environments remain largely mysterious. The phylum- or higher-level classifications of a third of microbes living in soil, for example, are unknown.



SOURCE: "PHYLOGENETICALLY NOVEL UNCULTURED MICROBIAL CELLS DOMINATE EARTH MICROBIOMES," BY KAREN G. LLOYD ET AL., IN *MSYSTEMS,* VOL. 3, NO. 5; SEPTEMBER/OCTOBER 2018

Graphic by Amanda Montañez


BECAUSE SOMEDAY
I'll throw out the syllabus.
Every someday needs a plan.®
Together, we'll help you achieve what matters most for retirement.
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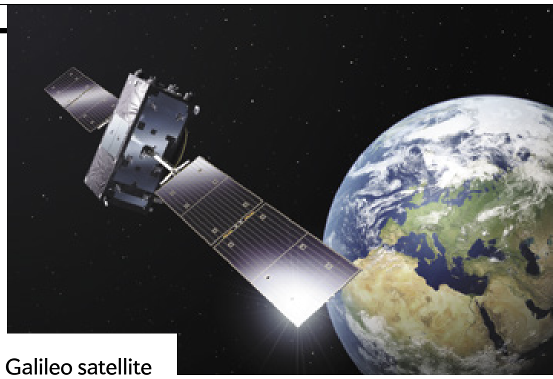
PHYSICS

Galileo's Loss, Einstein's Win

A satellite launch mishap tests general relativity


Galileo satellite

In August 2014 a rocket launched the fifth and sixth satellites of the Galileo global navigation system, the European Union's $11-billion answer to the U.S.'s GPS. But celebration turned to disappointment when it became clear that the satellites had been dropped off at the wrong cosmic "bus stops." Instead of being placed in circular orbits at stable altitudes, they were stranded in elliptical orbits useless for navigation.

The mishap, however, offered a rare opportunity for a fundamental physics experiment. Two independent research teams—one led by Pacôme Delva of the Paris Observatory in France, the other by Sven Herrmann of the University of Bremen in Germany—monitored the wayward satellites to look for holes in Einstein's general theory of relativity.

"General relativity continues to be the most accurate description of gravity, and so far it has withstood a huge number of experimental and observational tests," says Eric Poisson, a physicist at the University of Guelph in Ontario, who was not involved in the new research. Nevertheless, physicists have not been able to merge general relativity with the laws of quantum mechanics, which explain the behavior of energy and matter at a very small scale. "That's one reason to suspect that gravity is not what Einstein gave us," Poisson says. "It's probably a good approximation, but there's more to the story."

Einstein's theory predicts time will pass more slowly close to a massive object, which means that a clock on Earth's surface should tick at a more sluggish rate relative to one on a satellite in orbit. This time dilation is known as gravitational redshift. Any subtle deviation from this pattern might give physicists clues for a new theory that unifies gravity and quantum physics.

Even after the Galileo satellites were nudged closer to circular orbits, they were still climbing and falling about 8,500 kilometers twice a day. Over the course of three years Delva's and Herrmann's teams watched how the resulting shifts in gravity altered the frequency of the satellites' superaccurate atomic clocks. In a previous gravitational redshift test, conducted in 1976, when the Gravity Probe-A suborbital rocket was launched into space with an atomic clock onboard, researchers observed that general relativity predicted the clock's frequency shift with an uncertainty of 1.4×10^{-4}.

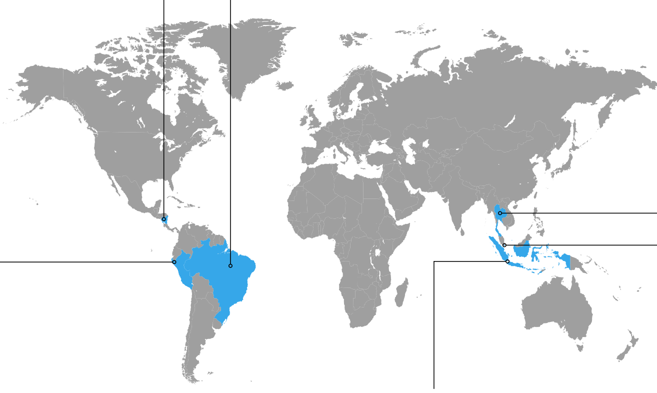
The new studies, published last December in *Physical Review Letters,* again verified Einstein's prediction—and increased that precision by a factor of 5.6. So, for now, the century-old theory still reigns. —*Megan Gannon*

P. CARRIL AND ESA

IN THE NEWS

Quick Hits

By Emiliano Rodríguez Mega



NICARAGUA
Government authorities used deadly force against students who were protesting social security tax increases and reduced pensions; they also fired professors and scientists who criticized the crackdown. The president of the Nicaraguan Academy of Sciences was forced to flee the country.

BRAZIL
A metropolis of at least 200 million active termite mounds—covering an area the size of Great Britain—was discovered in northeastern Brazil. The cone-shaped structures, connected by vast tunnel networks and hidden by scrubby forests, date from about 700 to nearly 4,000 years ago.

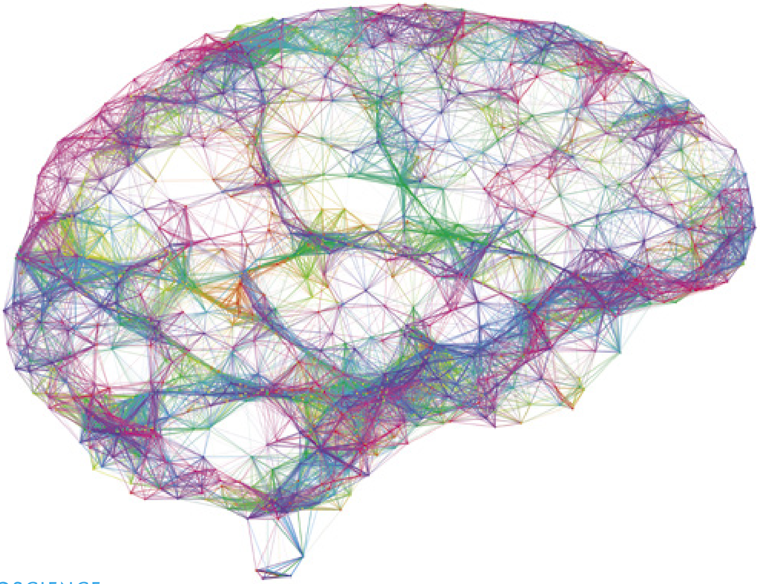
PERU
Scientists excavated the skeletons of more than 140 children and 200 baby llamas from part of Peru's northern coast, in what they think may have been the world's largest known child sacrifice. They believe the ritual slaughter took place 550 years ago in an attempt to combat rising sea temperatures and coastal flooding.

THAILAND
Thai lawmakers voted to pass an amendment that legalizes the medical use of marijuana and kratom, a tropical tree native to Southeast Asia that is traditionally consumed for its stimulant and painkiller properties.

SINGAPORE
Researchers used a bacteria-infecting virus to manufacture tiny wires in a computer's memory. This advance makes it possible to move data from memory to a hard drive in nanoseconds instead of milliseconds, which could help create faster supercomputers.

INDONESIA
Before-and-after radar images show that a flank of Indonesia's Anak Krakatau volcano disappeared—possibly in a landslide—during an eruption. This may have triggered the tsunami that killed hundreds of people last December.

For more details, visit www.ScientificAmerican.com/mar2019/advances



NANOSCIENCE

Ultrasonic Brain Beam

New technique delivers medication to specific regions within the organ

Neuroscientists have limited tools for understanding the human brain and treating its illnesses. Surgery or inserted electrodes are too invasive for most situations. Existing noninvasive technology, such as magnetic stimulation, is imprecise. Now neuroradiologist Raag Airan of Stanford University and his colleagues have demonstrated a method that could enable researchers to manipulate small, highly targeted brain areas noninvasively.

The study, published last November in *Neuron,* uses technology Airan has been developing for years—but this is the first time it has been shown to work with the necessary precision. The technique involves injecting nanoparticle "cages" filled with drug molecules into the bloodstream. Researchers then use a focused ultrasound beam to shake the drug particles loose from their cages in the desired location. There they cross the blood-brain barrier (a membrane between arteries and the brain that admits only tiny molecules), directly affecting brain function in only that spot.

Results from experiments in rats showed the action of the drug—an anesthetic—was limited to a three-millimeter cube where the beam was focused. The scientists aimed the ultrasound at the rats' visual cortices while flashing light in their eyes. Brain activity in the targeted region dropped when the beam was switched on, then recovered within 10 seconds after stimulation stopped, as the anesthetic wore off. "A spatially and temporally precise technology that allows us to intervene very focally in the brain is a tremendous goal," says neurosurgeon Nir Lipsman of Sunnybrook Research Institute in Toronto, who was not involved in the study. The team also saw metabolic activity reduced in distant parts of the brain connected to target areas, suggesting the method could be used to map brain circuitry.

The researchers found no evidence of tissue damage from the procedure. "They did a good job of demonstrating safety," Lipsman says. The study is only a proof-of-concept, but Airan says translation to clinical use should be rapid. Ultrasound is already commonly used in medicine, and the nanoparticles are made from chemicals routinely used in radiology and cancer treatment. "We just have to show their combination isn't unsafe," Airan says. "We're talking a first-in-human trial within a year or two."

Next up: testing whether the technology can simulate the effects of planned neurosurgeries, by anesthetizing the surgical target area to confirm it can be disabled safely. The approach could also be used to deliver psychiatric drugs to specific brain areas, potentially reducing side effects and improving efficacy. "The mind boggles with the range of possibilities," Airan says. —*Simon Makin*

ALFRED PASIEKA *Getty Images*

KRIS KESIAK *Getty Images*

NEUROSCIENCE

Boozy Recall

Conventional wisdom about drinking and memory may be wrong

Police officers investigating a crime may hesitate to interview drunk witnesses. But waiting until they sober up may not be the best strategy; people remember more while they are still inebriated than they do a week later, a new study finds.

Malin Hildebrand Karlén, a senior psychology lecturer at Sweden's University of Gothenburg, and her colleagues recruited 136 people and gave half of them vodka mixed with orange juice. The others drank only juice. In 15 minutes women in the alcohol group consumed 0.75 gram of alcohol per kilogram of body weight, and men drank 0.8 gram (that is equivalent to 3.75 glasses of wine for a 70-kilogram woman or four glasses for a man of the same weight, Hildebrand Karlén says).

All participants then watched a short film depicting a verbal and physical altercation between a man and a woman. The researchers next asked half the people in each group to freely recall what they remembered from the film. The remaining participants were sent home and interviewed a week later.

The investigators found that both the inebriated and sober people who were interviewed immediately demonstrated better recollection of the film events than their drunk or sober counterparts who were questioned later. The effect held even for people with blood alcohol concentrations of 0.08 or higher—the legal limit for driving in most of the U.S. (Intoxication levels varied because different people metabolize alcohol at different speeds.) The results suggest that intoxicated witnesses should be interviewed sooner rather than later, according to the study, which was published online last October in *Psychology, Crime & Law.*

The findings are in line with previous research, says Jacqueline Evans, an assistant professor of psychology at Florida International University, who was not involved in the new work. Evans co-authored and published a 2017 study in *Law and Human Behavior* that found similar results for moderately drunk witnesses. "Any effect of intoxication is not as big as the effect of waiting a week to question somebody," she says.

The new study also found that some aspects of the drunk people's recollections were not that different from those of the sober participants. For instance, both groups seemed particularly attuned to the details of the physical aggression portrayed in the film. "This research should at least make us more interested in what intoxicated witnesses have to say," Hildebrand Karlén says, "and perhaps take them a bit more seriously." —*Agata Boxe*

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

Vital Organs?

From the appendix to the tonsils, there are no truly expendable body parts

By Claudia Wallis

Medicine has not always shown a lot of respect for the human body. Just think about the ghoulish disregard early surgeons had for our corporeal integrity. They poked holes in the skull and copiously drained blood with leeches or lancets—a practice that remained a medical mainstay through the late 19th century. Even today many of the most popular surgeries involve the wholesale removal of body parts—the appendix, gallbladder, tonsils, uterus (usually after the childbearing years)—with an assurance that patients will do just fine without them. There are many valid reasons for these "ectomies," but what has become increasingly less defensible is the idea that losing these organs is of little or no consequence.

Take the appendix. Or rather leave it be, if possible. Many of us learned in school that this tiny, fingerlike projection off the colon is a useless, vestigial remnant of our evolution, much like the puny leg bones found in some snakes. But that idea has been debunked, says evolutionary biologist Heather Smith, director of Anatomical Laboratories at Midwestern University in Arizona. A 2017 study led by Smith reviewed data on 533 species of mammals and found that the appendix appears across multiple, unrelated species. "This suggests there's some good reason to have it," she says.

The reason appears to be immunological and gastrointestinal. In all species that have an appendix, Smith notes, it either contains or is closely associated with lymphoid tissue, which plays a role in supporting the immune system. In humans, the appendix also harbors a layer of helpful gut bacteria—a fact discovered by scientists at Duke University. In a 2007 paper, they proposed that it serves as a "safe house" to preserve these microbes, so that when the gut microbiome is hit hard by illness, we can replenish it with good guys holed up in the appendix. Some evidence for this idea surfaced in 2011, when a study showed that people without an appendix are two and half times more likely to suffer a recurrence of infection with *Clostridium difficile,* a dangerous strain of gut bacteria that thrives in the absence of friendlier types.

The appendix may have more far-flung roles in the body—including some that can go awry. A study published last October found that misfolded alpha-synuclein—an abnormal protein found in the brain of Parkinson's disease patients—can accumulate in the appendix. Intriguingly, the study found that people who had the organ removed as young adults appear to have some modest protection against Parkinson's.

New research has also shed light on the value of our tonsils and adenoids. In a study published last July, an international team assessed the long-term impact of removing these structures, or leaving them, in 1.2 million Danish children. Over a follow-up period of 10 to 30 years, the 5 percent or so who had one or both sets of organs extracted before age nine were found to have a twofold to threefold higher rate of upper respiratory diseases and higher rates of allergies and asthma. Notably they suffered more frequently from ear infections and, in the case of adenotonsillectomies, sinus infections—conditions thought to be helped by surgery.

We have known for a long time that the adenoids and tonsils "act as a first line of defense against pathogens that enter through the airways or eating," says Sean Byars, a senior research fellow at the Melbourne School of Population and Global Health and lead author of the paper. The fact that these tissues are most prominent in children, with the adenoids nearly gone by adulthood, has bolstered the view that they are not essential, but as Byars points out, "maybe there's a reason they are largest in childhood." Perhaps they play a developmental role, helping to shape the immune system in ways that have lasting consequences.

Byars cautions that his study, large though it is, awaits confirmation by others and that the decision to treat any given child must be made on an individual basis. Still, he says, "Given these are some of the most common surgeries in childhood, our results suggest a conservative approach would be wise."

It is worth noting that tonsillectomy rates have declined in the U.S., especially since the heyday in the mid-20th century. Surgeons are also doing fewer hysterectomies, reflecting a growing view that the uterus does not outlive its usefulness once childbearing is done and that there are less drastic ways to address common issues such as fibroid tumors.

So are any human body parts truly useless or vestigial? Perhaps the best case can be made for the wisdom teeth. "Our faces are so flat, compared with other primates, that there's often not room for them," Smith observes. And given how we butcher and cook our food, "we really don't need them." SA

Illustration by Celia Krampien

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

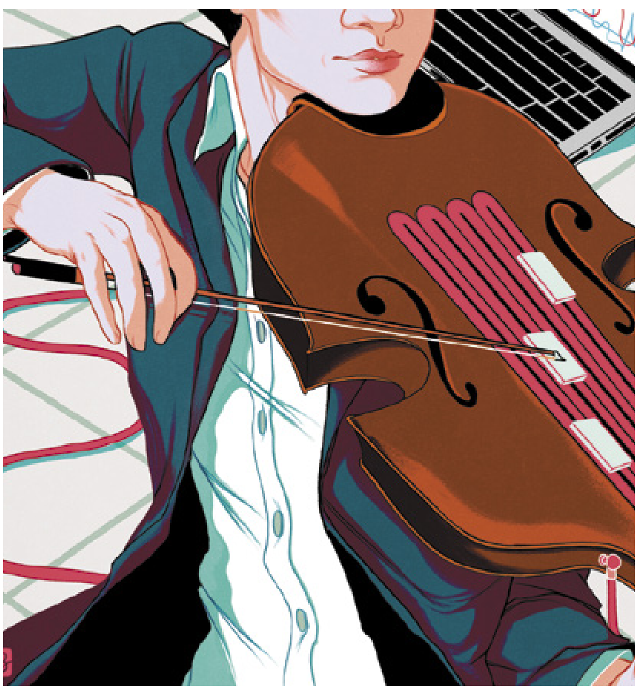
And the Laptop Played On

Technology is upending how music gets made

By Wade Roush

Even for Jimi Hendrix, the guitarist who used feedback and distortion to build sounds the world had never heard before, it wasn't easy to break into the music business. He joined his first band in 1958 and spent years as a touring and backup musician before releasing his first hit record in 1966. By the late 1960s Hendrix was headlining top music festivals such as Woodstock, where he earned more than any other performer. He died in 1970, but by then he had blazed a path to stardom and wealth that other pop artists would follow for three decades.

Next came the Napster Apocalypse. U.S. music revenues peaked at $15 billion in 1999 and then contracted as peer-to-peer sharing of MP3s undercut the need to buy music. The bleeding slowed, beginning in 2003, when Apple introduced the iTunes Store, and streaming services such as Spotify, Apple Music and Pandora finally stopped it in 2016. But today, unless your name is Drake or Beyoncé, you have to make do with literal micropayments for your music. Drummer Damon Krukowski (of the bands Galaxie 500 and Damon & Naomi) has written that "it would take songwriting royalties for roughly 312,000 plays on Pandora to earn us the profit of one—*one*—LP sale."



If there was ever a path to business success in music, it would seem that technology has closed it off. But here's the thing: technology is *always* roiling the music world. At the end of the 19th century, publishers worried that the phonograph would slash sales of sheet music, and it eventually did. But music flourished anyway, as the phonograph itself helped give birth to new genres, such as jazz. Today changes in the technology of music production and distribution are once again forcing musicians to find new ways to make money. But they're not impeding music creation—just the opposite.

I saw that at Mmmmaven, an electronic music academy in my hometown of Cambridge, Mass. When I visited this year, students were abuzz over recent upgrades to a popular sequencer program called Ableton Live. It was born in the early 2000s as a tool for live looping, or repeating a sampled section of music during a live performance. But today, in combination with its chessboardlike Push controller, it's changing what it means to write, record and perform music. DJs use Ableton to orchestrate all-night sets of electronic dance music, or EDM. And producers such as Jon Hopkins use it to synthesize haunting new sounds and assemble them into full songs. Hopkins's 2018 release "Luminous Beings" opens with "a kind of psychedelic feedback experience..., bounced down and pitched and distorted" in Ableton, he told the podcast Song Exploder.

What really had Mmmmaven students "freaking out," according to the academy's co-founder, David Day, was a collaboration feature called Link. "You can work on the same piece of music at the same time, in real time," from different computers, Day explained. "So if I'm working with another user, and they up the tempo, it ups my tempo. If they add a bass line, it adds it to my bass line. That is your future of music, right there. Everyone's a musician. All we hear is new music, and it's from *us*."

Thanks to these user-friendly digital tools, there's more new music to sample than ever. The EDM club scene is booming in cities around the world. And the emergence of online platforms such as SoundCloud, Beatport, YouTube and Bandcamp is helping more independent music producers find fans, who then buy digital tracks, merchandise and tickets to live gigs. Bandcamp alone reports that 600,000 artists have sold tunes through its site.

In the big picture, it's true, album sales are still dropping. The producer lifestyle, with its incessant travel and long club nights, is punishing. The studio session and concert backup jobs that used to help many musicians pay the rent are going away, Krukowski told me, as top stars realize that they can use computers to record and perform without bands. Concerts, merchandise sales and crowdfunding can bring in revenue, but they may never replace the losses from the recording industry's implosion.

As always, music is a precarious career. But what's encouraging is that digital technology is drawing in a new generation of music makers, who are using it to create their own brands of psychedelic feedback. The spirit of Hendrix lives. SA

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Illustration by Jay Bendt

ASTROPHYSICS

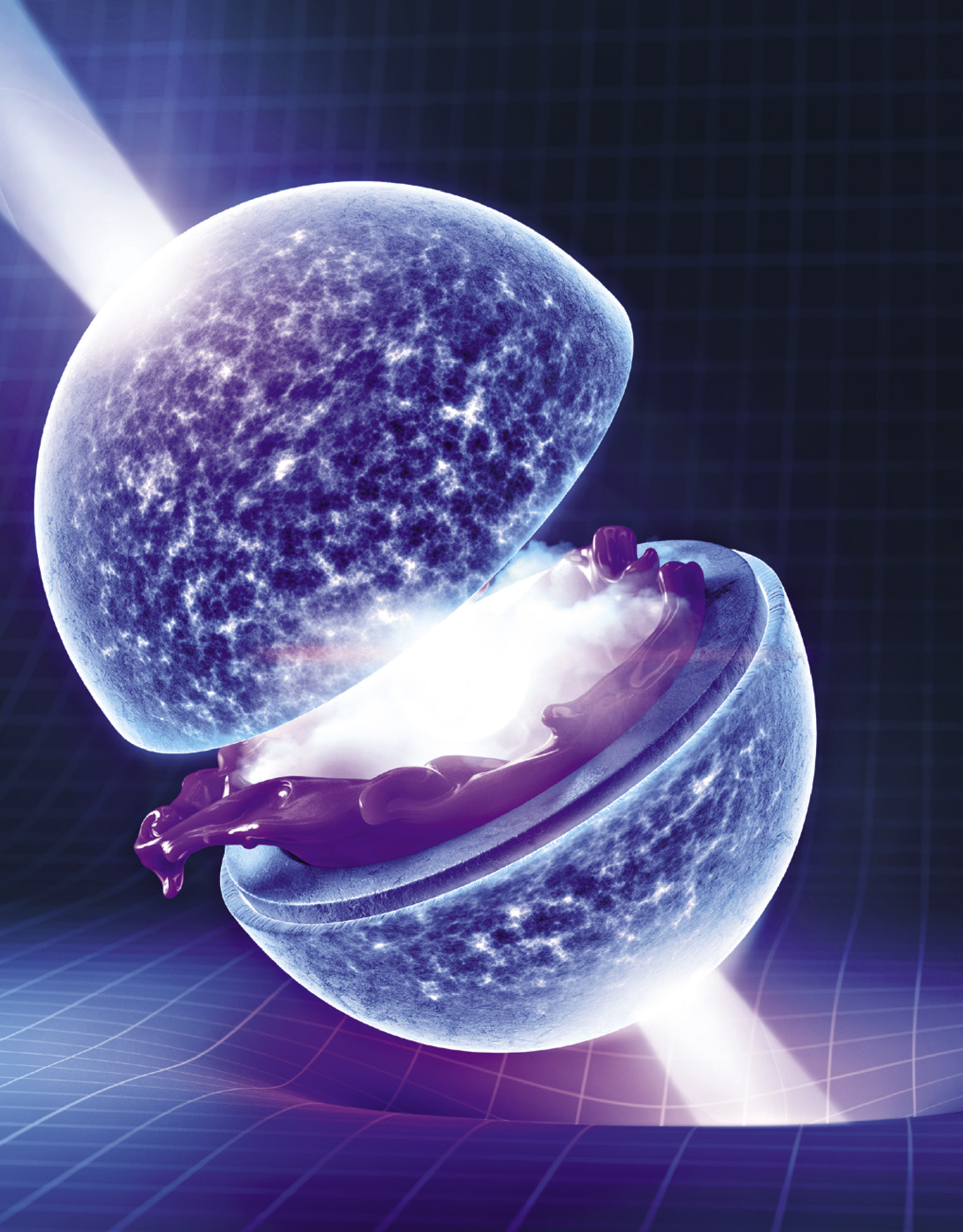
THE INNER LIVES OF NEUTRON STARS

The insides of neutron stars—the densest form of matter in the universe—have long been a mystery, but it is one that scientists are starting to crack

By Clara Moskowitz

Illustration by FOREAL

WHEN A STAR THE SIZE OF 20 SUNS DIES, IT BECOMES, IN THE WORDS OF ASTROPHYSICIST Zaven Arzoumanian, "the most outrageous object that most people have never heard of"—a city-size body of improbable density known as a neutron star. A chunk of neutron star the size of a Ping-Pong ball would weigh more than a billion metric tons. Below the star's surface, under the crush of gravity, protons and electrons melt into one another to form a bulk of mostly neutrons—hence the name. At least, that is what we think. The issue is far from settled. Astronomers have never seen a neutron star up close, and no laboratory on Earth can create anything even approaching the same density, so the inner structure of these objects is one of the greatest mysteries in space. "They are matter at the highest stable density that nature allows, in a configuration that we don't understand," says Arzoumanian, who works at NASA's Goddard Space Flight Center. They are also the most strongly gravitating form of matter known—add just a bit more mass, and they would be black holes, which are not matter at all but rather purely curved space. "What goes on at that threshold," Arzoumanian says, "is what we're trying to explore."



Clara Moskowitz is a senior editor at *Scientific American,* specializing in space and physics.

IN BRIEF

Neutron stars are born when stars within a certain mass range run out of fuel and collapse, leaving extremely compact remnants behind. They are the densest form of matter in the universe.

Scientists know that inside a neutron star, gravity crushes protons and electrons together to form neutrons, but they do not know what forms these neutrons take. Do they link up to create a viscosity-free "superfluid" or break down further into the quarks and gluons that constitute them?

Detectors capable of measuring gravitational waves from neutron star collisions and other new experiments promise to provide insight into these enigmatic objects.

There are several competing theories about what goes on at that threshold. Some ideas suggest that neutron stars really are just full of regular neutrons and maybe a few protons here and there. Others propose much stranger possibilities. Perhaps the neutrons inside neutron stars dissolve further into their constituent particles, called quarks and gluons, which swim untethered in a free-flowing sea. And it is possible that the interiors of these stars are made of even more exotic stuff, such as hyperons—weird particles composed not of regular "up" and "down" quarks (the kind found in atoms) but their heavier "strange quark" cousins.

Short of cutting open a neutron star and looking inside, there is no easy way to know which of these theories is right. But scientists are making progress. A big break came in August 2017, when terrestrial experiments detected gravitational waves—undulations in spacetime produced by the acceleration of massive objects—from what looked like a head-on collision of two neutron stars. These waves carried information about the masses and sizes of the stars right before the crash, which scientists have used to place new limits on the properties and possible compositions of all neutron stars.

Clues are also coming from the Neutron Star Interior Composition Explorer (NICER), an experiment that started at the International Space Station in June 2017. NICER watches pulsars, which are highly magnetic, furiously rotating neutron stars that emit sweeping beams of light. As these beams pass over Earth, we see pulsars blink on and off at more than 700 times a second. Through these experiments and others, the prospect of understanding what is inside a neutron star finally looks possible. If scientists can do that, they will have a handle not just on one class of cosmic oddity but on the fundamental limits of matter and gravity as well.

SUPERFLUID SEAS

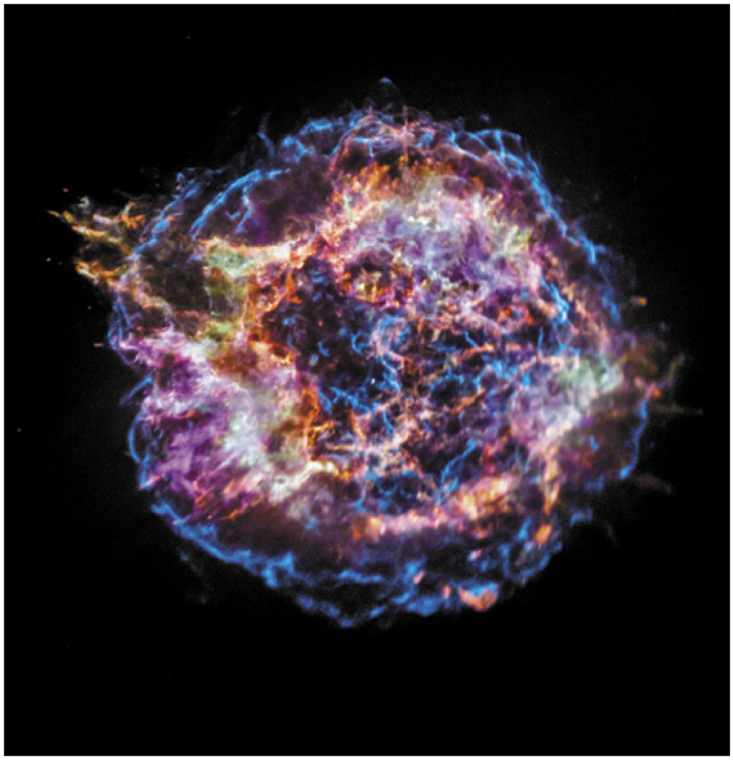
NEUTRON STARS ARE FORGED in the cataclysms known as supernovae, which occur when stars run out of fuel and cease generating energy in their cores. Suddenly gravity has no opposition, and it slams down on the star like a piston, blowing the outer layers away and smashing the core, which at this point in a star's life is mostly iron. The gravity is so strong it quite literally crushes the atoms, pushing the electrons inside the nucleus until they fuse with protons to create neutrons. "The iron is compressed by a factor of 100,000 in each direction," says Mark Alford, a physicist at Washington University in St. Louis. "The atom goes from being a tenth of a nanometer across to just a blob of neutrons a few femtometers wide." That is like shrinking Earth down to the size of a single city block. (A femtometer is a millionth of a nanometer, which is itself a billionth of a meter.) When the star has finished collapsing, it contains about 20 neutrons for every proton. It is much like a single giant atomic nucleus, says James Lattimer, an astronomer at Stony Brook University—with an important difference. "A nucleus is held together by nuclear interactions," Lattimer says. "A neutron star is held together by gravity."

Astronomers Walter Baade and Fritz Zwicky proposed neutron stars in 1934 as an answer to the question of what might be left over after a supernova—a term they coined at the same time for the extra-bright explosions being spotted across the sky. It had only been two years since British physicist James Chadwick discovered the neutron. Initially some scientists were skeptical that such extreme objects could exist, and it was not until Jocelyn Bell Burnell and her colleagues observed pulsars in 1967—and researchers over the next year determined they must be spinning neutron stars—that the idea was widely accepted.

Physicists think that neutron stars can range from roughly one to two and a half times the mass of the sun and that they probably consist of at least three layers. The outer layer is a gaseous "atmosphere" of hydrogen and helium a few centimeters to meters thick. It floats atop a kilometer-deep outer "crust" made of atomic nuclei arranged in a crystal structure, with electrons and neutrons between them. The third, interior layer, which makes up the bulk of the star, is a bit of a mystery. Here nuclei are crammed in as tight as the laws of nuclear physics will allow, with no separation between them. As you move inward toward the core, each nucleus holds ever larger numbers of neutrons. At some point, the nuclei cannot contain any more neutrons, so they spill over: now there are no nuclei anymore, just nucleons (that is, neutrons or protons). Eventually in the innermost core, these may break down as well. "We are in the hypothetical regime where we do not know what happens at these insane pressures and densities," Alford says. "What we think might happen is that the neutrons actually get crushed together, and they overlap so much you can't really talk about it as being a fluid of neutrons anymore but a fluid of quarks."

What form that fluid takes is an open question. One possibility is that the quarks form a "superfluid," which has no viscosity and, once set in motion, will theoretically never stop moving. This bizarre state of matter is possible because quarks feel an affinity for other quarks, and if they are pushed close enough together, they can form bound "Cooper pairs." By itself, a quark is a fermion—a particle whose spin has the quantum-mechanical value of half an integer. When two quarks pair up, together they act as a single boson—a particle with spin equal to zero or one or another integer. After this change, the particle follows new rules. Fermions are bound by the Pauli exclusion principle, which says that no two identical fermions can occupy the same state—but bosons have no such restrictions. When they were fermions, the quarks were forced to take on higher energies to stack on top of one another in the crowded neutron stars. As bosons, however, they can stay in the lowest-possible energy state—any particle's preferred position—and still cram in together. When they do this, the quark pairs form a superfluid.

Outside the densest part of the core, where neutrons are likely intact, neutrons can also pair up to make a superfluid. In fact, scientists are fairly sure neutrons in the crust of the star do this. The evidence comes from observations of pulsar "glitches," episodes in which a spinning neutron star rapidly speeds up. Theorists think that these glitches occur when the rotation speed of the star as a whole grows out of sync with the rotation of the superfluid inside its crust. Overall, the star's rotation naturally slows with time; the superfluid, flowing without friction, does not. When the difference between these rates gets too great, the superfluid transfers angular momentum to the crust. "It's like an earthquake," Lattimer says. "You get a hiccup and a burst of energy, and the spin frequency increases for a brief time and then settles back down again."



CASSIOPEIA A is the remnant of an ancient supernova. At its center is a neutron star whose core may contain "superfluid."

In 2011 Lattimer and his colleagues suggested they had also found evidence of a superfluid in a neutron star's core, but he admits that this is still open to debate. To find that evidence, Lattimer's team, led by Dany Page of the National Autonomous University of Mexico, studied 15 years of x-ray observations of Cassiopeia A, the remnant of a supernova that first became visible on Earth in the 17th century. The scientists found that the pulsar at the center of the nebula is cooling faster than traditional theory suggests it should. One explanation is that many of the neutrons inside the star are pairing up to become a superfluid. The pairs break and re-form, emitting neutrinos, which causes the neutron star to lose energy and cool off. "This is something we never thought we would see," Lattimer says. "But lo and behold, there is this one star with the right age for us to see this. The proof in the pudding is going to come in another 50 or so years, when it should start to cool more slowly because once the superfluid is made, there is no more extra energy to be lost."

WEIRD QUARKS

SUPERFLUIDS ARE ONLY ONE of the exotic possibilities waiting behind the mystery doors of neutron stars. It is also possible that they are home to rare "strange quarks."

Quarks come in six kinds, or flavors—up, down, charm, strange, top and bottom. Only the lightest two, up and down, are found in atoms. The rest of the flavors are so massive and unstable that they usually appear only as short-lived detritus from high-energy particle collisions inside atom smashers such as the Large Hadron Collider at CERN near Geneva. But in the extremely dense interior of neutron stars, the up and down quarks inside neutrons might sometimes transform into strange quarks. (The other unusual flavors—charm, top and bottom—are so massive that they likely would not form even there.) If strange quarks appear and remain bound to other quarks, they would make the mutant neutrons called hyperons. It is also possible that these quarks are not contained in particles at all—they might roam freely in a kind of quark soup.

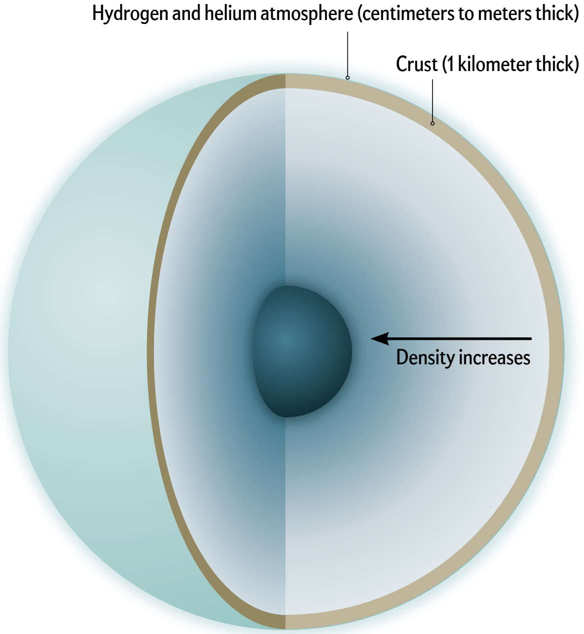
Each of these possibilities should change the size of neutron stars in a measurable way. Intact neutrons inside the core would, in Arzoumanian's words, act "like marbles and make a hard, solid core." The solid core would tend to push on the outer layers and increase the size of the entire star. On the other hand, if the neutrons dissolved into a stew of quarks and gluons, they would make a "softer, squishier" and smaller star, he says. Arzoumanian is a co-principal investigator and science lead for the NICER experiment, which aims to determine which of these alternatives is true: "One of NICER's key objectives is to make a measurement of [neutron stars'] mass and radius that will help us pick out or exclude certain theories of dense matter."

NICER is a washing-machine-size box mounted to the exterior of the International Space Station. It steadily monitors several dozen pulsars spread across the sky, detecting x-ray photons from them. By measuring the photons' timing and energy, as well as how the

NASA, CXC AND SAO

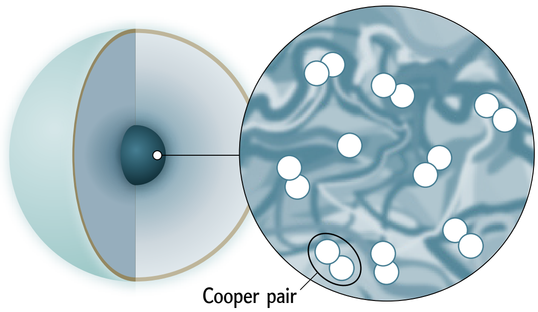
Inside a Neutron Star

Neutron stars are a puzzle. Scientists know they have a slight gaseous atmosphere above a thin crust layer made of heavy atomic nuclei and some floating electrons. But inside these outer layers lies the core—an unknown substance that is likely mostly neutrons. But what form these neutrons take and whether they break down into their ingredients, quarks and gluons, inside the densest inner core is an open question.



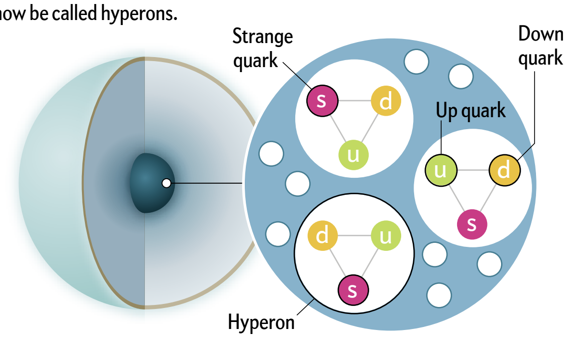
Core Hypothesis 1: Superfluid Seas

One possibility is that particles in the inner core are squeezed in so tight that some of them join to form new particles, called Cooper pairs. This can happen with protons, neutrons or, if these particles have dissolved, quarks. The new particles create a "superfluid" that flows without resistance.



Core Hypothesis 2: Weird Quarks

The incredible density could also prompt quarks in the inner core to transform from their usual type, "up" or "down," into exotic "strange quarks." If the quarks are still inside neutrons, these neutrons would now be called hyperons.



stars' gravitational fields bend their light, NICER allows scientists to calculate the masses and radii of a collection of pulsars and compare them. "If NICER finds stars with roughly the same mass but very different radii, that would mean there's something funny going on," Alford says, "some new form of matter that, when it appears, makes the stars shrink down." Such a transition could occur, for instance, when neutrons break apart into quarks and gluons.

Measuring the sizes of neutron stars is a useful way to narrow the range of possible forms that matter inside neutron stars can take. Scientists once thought half the neutrons in any given neutron star would turn into hyperons that contained strange quarks; theoretical calculations suggested that such a hyperon-rich star could not exceed 1.5 times the mass of the sun. In 2010, however, astronomers led by Paul Demorest of the National Radio Astronomy Observatory measured the mass of one neutron star at 1.97 solar masses, eliminating a number of theories about the interior of a neutron star. Now physicists estimate that hyperons cannot make up more than 10 percent of a neutron star.

CRASH SITE DETECTIVES

STUDYING INDIVIDUAL neutron stars can tell us a lot, but we can learn much more when two of them slam together. For years telescopes have detected blasts of light, called gamma-ray bursts, that researchers suspected came from a crash of two neutron stars. In the August 2017 detection of gravitational waves, astronomers saw the first confirmed neutron star merger.

Specifically, on August 17, 2017, two experiments—the Laser Interferometer Gravitational-wave Observatory, or LIGO (based in Washington State and Louisiana), and Virgo (a European project based near Pisa, Italy)—simultaneously detected gravitational ripples produced as two neutron stars spiraled toward each other and merged to form either a single neutron star or a black hole. This was not the first detection of gravitational waves, but all the previous sightings were created by the collisions of two black holes. Before this date, scientists had never observed waves coming from neutrons stars, and this was also the first time that telescopes had responded to a gravitational-wave detection and seen light coming from the same place in the sky at the same time. The light and waves together provided a bounty of

Illustration by Nigel Hawtin

information about where and how the crash happened that proved a boon for neutron star physics. "I was quite flabbergasted," Lattimer says of the lucky observation. "I thought this is just too good to be true."

Astrophysicists traced the waves back to a pair of neutron stars about 130 million light-years from Earth. The details of the waves—their frequency and strength and the pattern they followed over time—allowed researchers to estimate that each weighed roughly 1.4 solar masses and stretched between 11 and 12 kilometers in radius before the crash. This knowledge will help scientists to formulate an essential descriptor for understanding neutron stars—their equation of state. The equation describes the density matter will take under different pressures and temperatures and should apply to all neutron stars in the universe. Theorists have come up with several possible formulations of the equation of state that correspond to different configurations of matter inside neutron stars, and the new measurements offered a chance to rule some out. The discovery that the neutron stars' radii were relatively small, for instance, was a surprise. Some theories run into difficulty when they try to fit both these compact neutron stars and known heavy stars, such as the 1.97-solar-mass behemoth, into the same fundamental equation of state. "It's starting to make our equation of state thread a needle path through these different observations," says Jocelyn Read, an astrophysicist at California State University, Fullerton, and co-leader of LIGO's Extreme Matter team. "Trying to make compact stars, as well as supporting massive stars, is getting to be challenging to the theory. It's definitely interesting and might get more interesting."

So far LIGO and Virgo have seen only this one neutron star collision, but another such observation could come any day now. "I've been working in this field long enough," Read says, "that it's just so fantastic to move from an era of what-ifs: 'If we could see gravitational waves, then we might be able to do this.' Now we're actually getting a chance to do this, and it hasn't gotten old yet."

THE LIMITS OF MATTER

IN TIME, AS GRAVITATIONAL-WAVE DETECTORS improve in sensitivity, the payoffs could be huge. For instance, one test of what is inside a neutron star involves looking for gravitational waves emitted by any swirling liquid in its middle. If the liquid has very low or no viscosity—as a superfluid would—it might begin flowing in patterns, called r-modes, that release gravitational waves. "These gravitational waves would be much weaker than from a merger," Alford says. "It is matter quietly sloshing versus being ripped apart." Alford and his collaborators determined that the currently running Advanced LIGO detector would not be able to see these waves, but future upgrades to LIGO, as well as planned observatories such as the ground-based Einstein Telescope under consideration in Europe, might.

Cracking the case on neutron stars would give us a picture of matter at its barely comprehensible extremes—a form so removed from the atoms that make up our world that it stretches the bounds of what is possible. It might turn imagined curiosities such as sloshing quark matter, superfluid neutrons and outlandish hyperon stars into reality. And understanding neutron stars could do something more: physicists' deeper goal is to use these squashed stars to tackle larger open questions, such as the laws that govern nuclear interactions—the complicated dance among protons, neutrons, quarks and gluons—as well as the biggest mystery of all—the nature of gravity.

Neutron stars are just one way of investigating nuclear forces, and simultaneous work is going on at particle accelerators around the world, which act like microscopes to peer inside atomic nuclei. When more of the nuclear problem is nailed down, scientists can turn their focus to gravity. "Neutron stars are a mixture of gravitational physics and nuclear physics," says Or Hen, a physicist at the Massachusetts Institute of Technology. "Right now we are using neutron stars as a lab to understand nuclear physics. But because we have access to nuclei here on Earth, we should be able to constrain the nuclear aspect of the problem well enough eventually. Then we can use neutron stars to understand gravity, which is one of the biggest challenges in physics."

Cracking the case on neutron stars would give us a picture of matter at its barely comprehensible extremes.

Gravity as currently understood—through Einstein's general theory of relativity—does not get along with the theory of quantum mechanics. Ultimately one of the theories must budge, and physicists do not know which it will be. "We will get there," Hen says, "and that is a very exciting prospect." SA

MORE TO EXPLORE

Rapid Cooling of the Neutron Star in Cassiopeia A Triggered by Neutron Superfluidity in Dense Matter. Dany Page et al. in *Physical Review Letters*, Vol. 106, Article No. 081101; February 22, 2011.

GW170817: Measurements of Neutron Star Radii and Equation of State. B. P. Abbott et al. (The LIGO Scientific Collaboration and the Virgo Collaboration) in *Physical Review Letters*, Vol. 121, Article No. 161101; October 15, 2018.

FROM OUR ARCHIVES

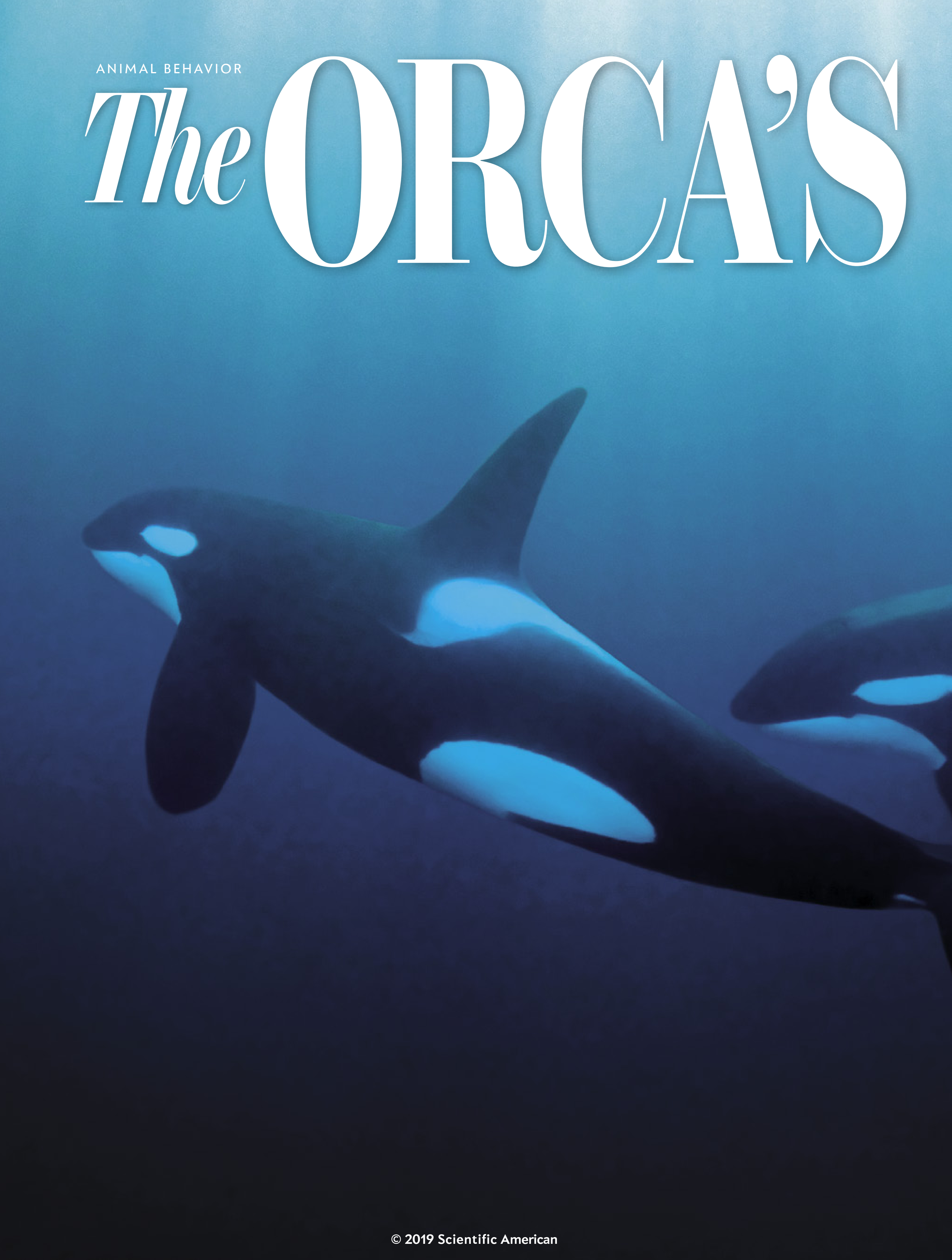
Magnetars. Chryssa Kouveliotou, Robert C. Duncan and Christopher Thompson; February 2003.

Messengers from the Sky. Ann Finkbeiner; May 2018.

scientificamerican.com/magazine/sa

ANIMAL BEHAVIOR

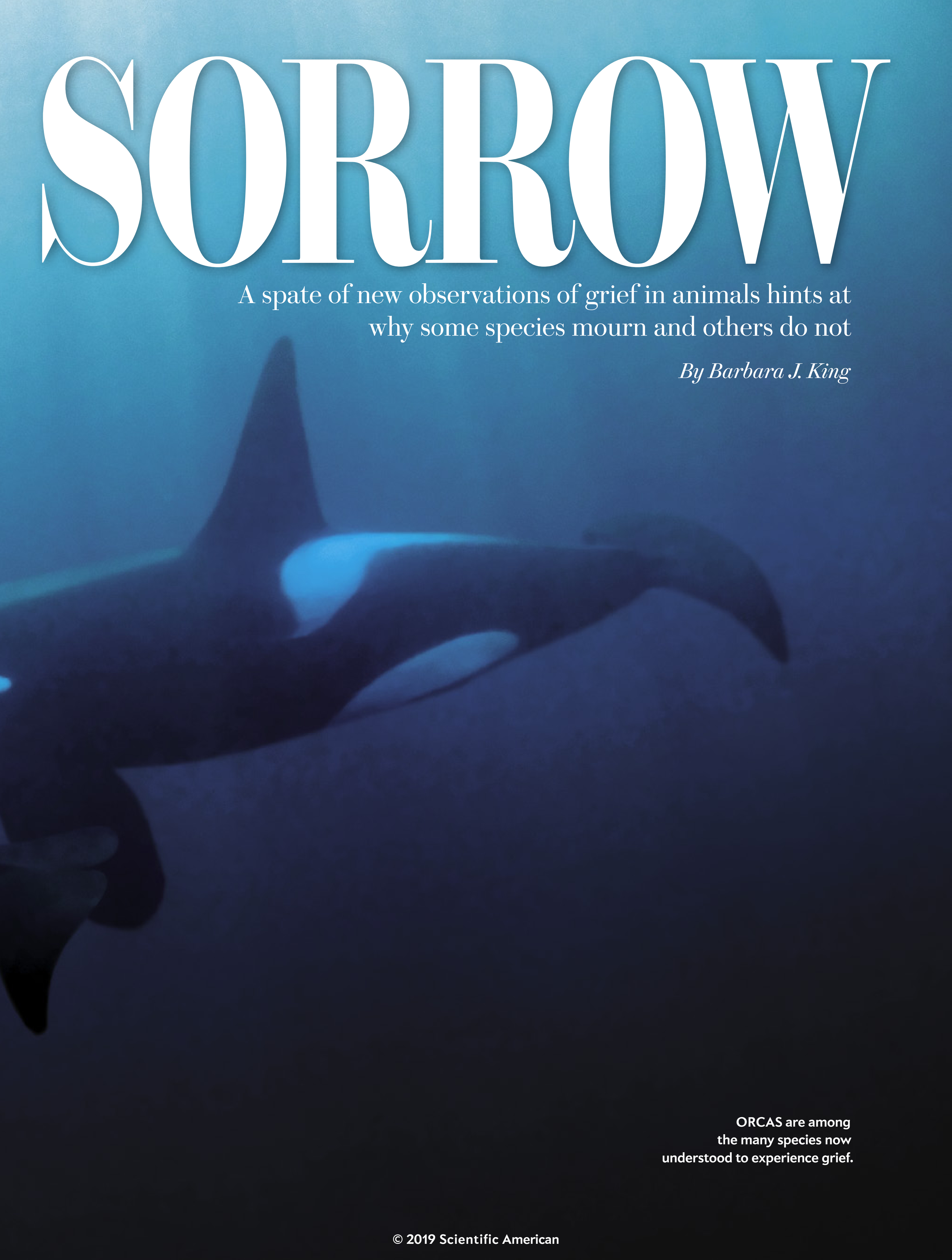
The ORCA'S



SORROW

A spate of new observations of grief in animals hints at why some species mourn and others do not

By Barbara J. King



ORCAS are among the many species now understood to experience grief.

Barbara J. King is a science writer and professor emerita of anthropology at the College of William & Mary.

LAST JULY A FEMALE ORCA named J35 captured worldwide attention for her unprecedented vigil. J35, also known as Tahlequah, is a member of the closely monitored Southern Resident population of orcas in the Salish Sea, off the coast of Washington State and British Columbia. She had just given birth, following a nearly year-and-a-half-long gestation period. It was her second offspring, a daughter, and the first live birth in the declining Southern Resident community in three years. But 30 minutes after birth, the calf died. J35 would not let her baby go. With great effort, she swam with the tiny body on her head and made deep dives to retrieve it when it slipped off. Other members of her pod registered her distress: at one point, a group of females gathered in a tight circle around J35, an act of apparent emotional attunement that lasted at least two hours. Seventeen days and 1,000 miles passed before J35 finally released her daughter's corpse for good.

J35's response to her calf's death was a powerful reminder that humans are not the only species that experiences grief. For decades animal behavior experts were wary of ascribing that emotion to other species. But our thinking has shifted as new evidence has come to light. Six years ago I wrote about the then nascent field of animal grief for *Scientific American*. Since then, the number of case studies has exploded. Some, such as the example of J35, capture fresh and poignant details from species already known to mourn; others document the phenomenon in new species.

Together these findings are yielding fascinating insights into the origins of grief. Previously it seemed that bereavement was associated with large-brained mammals—namely, primates, elephants and cetaceans. But the latest evidence indicates otherwise. Brainy mammals may grieve in more nuanced ways than some other animals because of their advanced abilities to reason and the complex social dynamics within their groups. It is now clear, however, that the expression of grief does not depend on relative brain size or cognitive power alone. The capacity to form intimate relationships is emerging as a significant, separate factor in determining which species mourn their losses.

DEFINING GRIEF

THE STUDY OF ANIMAL GRIEF is still sufficiently new that investigators continue to wrestle with how to recognize it. In 2017, within the small mountain city of Prescott, Ariz., an adult female collared peccary—one of a small herd of five of the piglike mammals, also known as javelinas—died. Over the next 10 days the herd mates of this individual visited, ate near, slept right up against her body and protected it from predators. This prolonged response to death was recorded by a motion-sensitive wildlife camera, a birthday present to then third grade student Dante de Kort, who set it up two days after he noticed the peccary corpse near his home. When de Kort shared images of the animals' behavior at his school's science fair the next month, he met biologist Mariana Altrichter of Prescott College. That serendipitous encounter between the boy and the researcher led to the publication of an article on the peccaries in the February 2018 issue of the journal *Ethology* (de Kort was the lead author) and to a renewed conversation among scientists about the definition and scope of grief in the animal kingdom.

De Kort had stationed his camera five meters from the body of the female peccary and set it to take 10-second-long films at intervals of 30 seconds. It captured 93 videos with peccaries in them. For roughly half of the recorded time, herd members walked or stood within five meters of the dead individual. And for more than a third of the time, they contacted the body directly. At various points, they nuzzled, smelled, stared at, bit and tried to lift up the dead body. They also slept in direct contact with it and defended it from coyotes. In nearly half of the recorded time, the same two peccaries (at least, probably the same two, according to best efforts to identify individuals) were present at the body.

In their paper, de Kort and his co-authors noted that the peccaries' responses expanded the behavioral complexity known for this group and showed that they resembled humans and chimpanzees in their reaction to death. But the scientists stopped short of calling the reaction grief. In fact, they stated that they "cannot determine if there is grieving."

Peccaries belong to the artiodactyl branch of the mammal family tree. Other members of this group include sheep and ante-

IN BRIEF

Scientists have traditionally been reluctant to attribute human emotions, including grief, to species other than our own.

In recent years, however, evidence for animal grief has accumulated. A wide variety of animals have been found to mourn the loss of close companions.

These findings suggest that multiple factors determine whether or not a species exhibits emotional responses to death.

PRECEDING PAGES: FRANCO BANFI *Getty Images*

FEMALE ORCA known as J35 held onto the body of her dead calf for 17 days before releasing it.

CENTER FOR WHALE RESEARCH *whaleresearch.com*

lopes. Little is known about grief in artiodactyls. But the peccaries' behavior closely matches the criteria for grief I set forth in my 2013 book *How Animals Grieve:* Survivors alter their behavior in the wake of a death in significant ways that indicate intense distress. Depending on the species, these changes may include atypical patterns of eating or sleeping; withdrawal from social activities; and expression of upset at or near the body through vocalizations, facial expressions or body language.

Can we state with absolute certainty that the peccaries, or some of the peccaries, were grieving, as opposed to exhibiting a generalized distress about a change in the dynamics of their herd? No. My definition of grief relies on interpretation of cues made visible to us by individual animals, and in this practice, there is inevitably room for error because we cannot read animals' minds or know their intentions. Yet given that we know peccaries form small, cohesive groups characterized mainly by cooperation and friendly interactions such as grooming, I find it just as risky to dismiss the strong likelihood of a grief response. In an e-mail to me, Altrichter explained that she and her colleagues did not want to interpret the emotional aspect of the peccaries' behavior in their paper, preferring to stick to reporting the observable facts. But she allowed that the creatures' response "meets a reasonable definition of grief for nonhuman animals."

In the field of animal behavior, or ethology, the reluctance to claim grief outright in the peer-reviewed scientific literature stems from the discipline's long history of bringing charges of anthropomorphism—the projection of human qualities or capacities onto other species—against scientists who venture into the realm of animal emotion. Those charges are sometimes still leveled within the scientific community today. Yet it turns out that it is the science of animal behavior itself that shows we humans have no monopoly on the expression of sorrow (or, for that matter, its opposite: joy) in the animal kingdom.

A clarification on terminology is key here. In the field of neuroscience, "emotion" is a body state triggered by external stimuli, whereas "feeling" is a mental state that accompanies the changes in body state. In this scheme, feelings are the conscious experiences. By using the term "emotion," I do not mean to imply that animals are unaware of their own grief, though. In the framework I am using, common in anthropology and developmental psychology, perception and processing of stimuli in brain circuits do prepare an individual to express an emotion, but that emotion emerges in the context of an unfolding event between social partners. It is expressed by animals who are conscious, aware beings. For this reason, I would be surprised if researchers were to observe grief in social insects, such as ants, termites and bees, that retrieve and even sometimes bury corpses of dead companions entirely through a system of chemical signaling, as opposed to conscious decision-making.

HEARTBREAK ALL AROUND

THE PECCARIES PROVIDE STRONG EVIDENCE that the capacity for grief is not limited to large-brained animals. But they are not the only species to do so.

Film taken at the Donkey Farm Foundation sanctuary in the Netherlands shows distressed donkeys milling around and emitting startlingly loud vocal calls at the body of an old male donkey laid out on the ground. A sorrowful donkey was also the subject of a report sent to me earlier in 2018 from the Farm Animal Rescue and Rehoming Movement (FARRM) animal sanctuary in Alberta, Canada. Founder Melissa Foley and volunteer Stephanie Belland were concerned that a resident donkey named Lena was having great trouble recovering from the death of the horse Jake, with whom she had been very close for three years. When at 32 years of age Jake fell gravely ill, a vet put him down. That first night Jake's body lay under a tarp until he could be buried, but Lena tore the coverings off. "Throughout the night, Lena circled and refused to leave," Foley and Belland recalled. "When we buried Jake the next day, she followed his body to the hole we had dug and remained standing over his grave for days, pawing at the dirt and braying throughout the night. She refused to leave even for food and water."

This description brought tears to my eyes. Over the next weeks Lena began to recover; she gradually resumed normal eating and drinking and sought out the company of other horses. Perhaps the opportunity she had been given to spend time with Jake's body helped her. Indeed, a growing trend in sanctuaries, zoos and veterinary practices is to allow a surviving companion to do so, an applied outcome of research on animal grief that I welcome.

Ferrets, too, express sorrow at death, according to Salise Shuttlesworth, founder and executive director of the Friends For Life no-kill animal shelter in Houston. In an unexpected and sad turn of events, all four of Shuttlesworth's female ferrets, between seven and eight years of age, died of unrelated illnesses within a six-week period. The two that lived the longest were Pinky and Effie. When Effie's adrenal disease reached an advanced stage, Shuttlesworth arranged for in-home euthanasia. Before this point, Pinky had searched the house intensively for her closest ferret friend, who had already died. When Effie's euthanasia procedure began, Pinky responded strongly again. "She pushed herself between the doctor's hands and Effie," Shuttlesworth told me. "When the doctor tried to listen to Effie's heart, Pinky pushed under the stethoscope. She groomed Effie's ear. Finally, she just laid against her, still." For more than two hours after Effie's death, Pinky didn't move from that position. She died of heart failure the next day.

Over the years I have also received credible reports of magpies and Canada geese exhibiting great distress at discovering the body of a companion or mate. Learning that cows mourn when their calves die or when, as on many meat or dairy farms, their calves are taken from them days after birth, never to be seen again, contributed to my recent decision to eat mostly plant-based foods.

Yet not every animal response to death qualifies as grief. At my own home, my husband and I photographed events following the death of our rescued cat, Hayley, whom we had put down because she had advanced, untreatable cancer. In the outdoor enclosure where six semiferal cats live, including Hayley's sister, Kayley, we placed Hayley's body on the ground on a cloth. Several cats approached, inspected and sniffed the body, but Kayley did not. She sat still and stared at her sister from a distance for many minutes after the others had gone back to their own routines. She did not wail, as cats and dogs sometimes do when faced with the death of a partner. Was Kayley grieving? Based on her close relationship with her sister, I might suspect so, but I cannot responsibly state grief was present when Kayley exhibited no visible signs of it.

Sometimes, too, more credible alternative explanations carry the day. In 2017 a video shot by Jonathan Davis of Randolph, Mass., showed a group of wild turkeys on a street circling the body of a dead cat. When the clip went viral, folk theories erupted: Was this some kind of emotional, cross-species death ritual? Far more likely, wildlife biologists say, the turkeys were instinctively curious about a dead body they noticed, with each one following another in a circle of close inspection.

TIES THAT BIND

BEYOND GREATLY EXPANDING the diversity of species found to mourn, these and other recently documented examples of animal grief are illuminating the social conditions that foster this emotion. Writing in a 2018 special issue of *Philosophical Transactions of the Royal Society B* devoted to animal and human responses to death, Claire F. I. Watson and Tetsuro Matsuzawa, both at Kyoto University's Primate Research Institute in Japan, observed that most reports about responses to death in mammals to date concern mothers and their dead offspring. This is true. But there are some interesting exceptions to this rule.

1

DONKEYS, PECCARIES AND MONKEYS have recently joined the ranks of animals known to exhibit emotional responses to death.

We now know that in primates, close social relationships beyond the maternal-infant one may yield intense responses to death. When Thomas, a nine-year-old male chimp, died from a rampant lung infection at the Chimfunshi Wildlife Orphanage in Zambia in 2011, other apes in his group of 43 spent time at his body, often with a physical stillness that is quite atypical for this excitable species of ape. Describing the behavior in a paper published in 2017 in *Scientific Reports,* Edwin J. C. van Leeuwen of the University of St. Andrews in Scotland noted that two close social partners of Thomas displayed marked reactions. Pan, the adult male with whom Thomas had forged a friendship, visited and inspected the body more often than the other two males did and displayed energetically around the body. Noel, an adult female who had adopted Thomas in the wake of his mother's death, did something never before observed in chimpanzees: she cleaned Thomas's teeth using a grass tool. Noel persisted in this

CRISTIAN BORTES *Getty Images* (1)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TIM ZUROWSKI *Getty Images* (2); CYRIL RUOSO *Getty Images* (3)

activity even when other chimps had been enticed away from the body by sanctuary workers offering fruit, a preferred food. We cannot know how long the animals' unusual behaviors—at a minimum, consistent with grief—would have continued had Thomas's body not been removed by sanctuary staff 20 minutes after its discovery.

Other examples of grief outside the bounds of the mother-infant bond come from our more distant primate cousins. Six years ago I noted a near absence of convincing evidence for emotional responses to death in monkeys. That situation has changed—we now have reports of these behaviors in common marmosets and Barbary macaques. And in 2016 Bin Yang of the Shaanxi Institute of Zoology in China and his colleagues announced that they had observed responses to death in Sichuan snub-nosed monkeys in central China. A female had fallen from a tree and struck her head on a stone. As she lay, gravely injured, her group mates surrounded her for close to an hour and "closely tended" her, "peering at and occasionally sniffing her face, grooming and embracing her, and gently pulling her hand," Yang and his co-authors reported. The single adult male of the group gave warning calls when an infant and a juvenile from another one-male group attempted to approach. When the female died, this male touched her repeatedly and pulled on her hand. He left after about five minutes, then returned the next day with his group to the spot where she had died (the body had been buried by a research assistant). The male had had a strong bond with the female over a three-year period after her immigration into the male's group.

As far as animal grief research has come, so much more remains to be discovered. For one thing, our hypotheses about the factors that determine whether or not a species experiences grief need testing. A 2018 paper in *Zoology* by Giovanni Bearzi, president of the Italian nonprofit organization Dolphin Biology and Conservation, suggests a way forward. Bearzi and his colleagues combed through all records published between 1970 and 2016 that describe so-called postmortem attentive behavior (PAB) by individual cetaceans. Both wild and captive cetaceans were included, but events that occurred in captivity under conditions that would not occur in the wild were excluded. Behaviors observed included a whale or dolphin attending a body, keeping a body afloat and carrying a body. Whereas in some cases of PAB, the survivor animal may be attempting to revive a social partner, in other cases, it clearly meets the criteria for grief: altered behavior lasting for days that indicates distress. The study found that nearly a quarter of the 88 species of dolphins and whales showed some kind of PAB. An overwhelming majority (92.3 percent) of these cases occurred in Delphinidae, a family of relatively small-bodied cetaceans that include dolphins, orcas and pilot whales. In contrast, the large-bodied mysticetes, or baleen whales, were, with a single exception, not observed to show any PAB. Intriguingly, Delphinidae are larger-brained and more social than baleen whales. Here lies the future of animal grief research: comparative analyses of responses to death across closely related species.

More than any other topic in animal behavior I have written about over the course of 30 years, animal grief strikes a chord. Why? A cross-species perspective on grief tells us that intense emotion expressed around death is not exclusive to humans but is found in other animals whose social relationships go beyond adaptive "bonding" for survival and reproduction. Recognizing this fact gives us an important pathway to connect with the natural world. But beyond suffering emotionally as the result of separation from a friend or loved one, do individuals of any species other than our own grasp the permanence of death? Do they anticipate their own death? I wonder whether any scientific evidence could satisfactorily answer questions of this nature. As ethological observations proceed, however, they are likely to reveal an ever sharper picture of who grieves and under what circumstances. SA

MORE TO EXPLORE

How Animals Grieve. Barbara J. King. University of Chicago Press, 2013.

Personalities on the Plate: The Lives and Minds of Animals We Eat. Barbara J. King. University of Chicago Press, 2017.

Evolutionary Thanatology: Impacts of the Dead on the Living in Humans and Other Animals. Edited by James R. Anderson, Paul Pettitt and Dora Biro. Special issue of *Philosophical Transactions of the Royal Society B,* Vol. 373; September 5, 2018.

FROM OUR ARCHIVES

When Animals Mourn. Barbara J. King; July 2013.

scientificamerican.com/magazine/sa

THE UNDISCOVERED ILLNESS

PSYCHIATRY

HUNDREDS OF THOUSANDS OF PEOPLE EXPERIENCE MANIA WITHOUT EVER GETTING DEPRESSED. WHY DOES PSYCHIATRY INSIST ON CALLING THEM BIPOLAR?

By Simon Makin

Photography by The Voorhes

IN OCTOBER 1997, at the age of 58, David Ho had an unusual experience while listening to a recording of Bach. "I began to dance and pretended to conduct," he says. "And as I practiced, instead of following the music, I felt as if I were creating it. I entered into a state of selfless oblivion, like a trance. My mind exploded. Flashes of insight rained down, and I saw beauty everywhere, in faces, living things and the cosmos. I became disinhibited, spontaneous, liberated."

Simon Makin is a freelance science writer based in London.

Ho was in the grips of his first episode of mania. His description sounds like an enviable burst of creative energy, but the symptoms of mania can also include inflated self-esteem, grandiosity, racing thoughts, extreme talkativeness, decreased need for sleep, increased activity or agitation, reckless behavior, delusions and other psychotic events. Severe episodes can impair day-to-day functions, sometimes enough to require hospitalization.

Perhaps the most surprising thing about such cases is that in the eyes of the psychiatric profession, mania does not exist as a distinct and unalloyed condition. Mania is usually known as the upside of bipolar disorder. For most people, it occurs alongside periods of depression, the downside. But Ho, who has had 20 manic episodes since 1997, has never suffered from depression. Thousands of people in the U.S. share that experience. Unlike those who experience only depression, however, patients with mania alone are lumped with those who have bipolar disorder. This puts psychiatry in the strange position of claiming that depression by itself is different from depression accompanied by mania but that mania by itself is not.

Most psychiatrists agree unipolar mania exists, but there is debate about whether it differs sufficiently from bipolar disorder in important enough ways to warrant a distinct diagnosis. Central to that debate is the tension in psychiatry between fewer, broader categories and more numerous, tightly defined ones. But the missing diagnosis may have consequences for patients: some studies suggest that people with unipolar mania may respond differently to certain treatments. If, as some researchers believe, unipolar mania and bipolar disorder differ in their underlying biology, classifying mania separately could speed development of new treatments that are more personalized and effective. But because unipolar mania is far less common than bipolar disorder, research into the condition has been both scant and equivocal.

As both a patient and a clinical psychologist, Ho is well placed to advance this debate. In 2016 he published a self-study in the journal *Psychosis* cataloguing his symptoms, which include enhanced recall, increased empathy and spiritual experiences. He has suffered some ill effects, including severe fatigue, confusion and behavior that caused concern among friends and colleagues: he once burst into tears while delivering a lecture. But his professional training has helped him control his impulses and avoid delusional thinking. On balance, he believes that his madness, as he calls it, has enriched rather than damaged his life. "I'm aware my case may be atypical," Ho says. "Precisely for this reason, it challenges prevailing psychiatric beliefs that fail to acknowledge the positive value of mental disorders."

A MODERN ILLNESS

CREDIT FOR THE MODERN CONCEPT of bipolar disorder usually goes to 19th-century French psychiatrist Jean-Pierre Falret, who called it *folie circulaire,* or "circular insanity," for its periods of pathologically elevated and depressed moods, usually separated by symptom-free periods of varying length. This idea became gospel in the early 20th century, when a father of modern psychiatry, Emil Kraepelin, proposed a historically significant hypothesis.

At the time, psychiatry drew a distinction between so-called reactive psychoses, which were seen as a response to outside events, and endogenous psychoses, which were innate. Kraepelin divided all endogenous psychoses into two broad classes: dementia praecox—now known as schizophrenia—and manic-depressive insanity, now known as bipolar disorder. Endogenous depression was therefore classed as a form of manic-depressive insanity. All mania also fell under the same rubric because mania was thought never to be a reaction to outside events. There were dissenters, notably the renowned German neurologist Carl Wernicke, who held that mania was related to hyperactivity of neural firing and depression to decreased neural activity. But Kraepelin's idea dominated and persists in today's diagnostic system.

The question of what to include under the umbrella of bipolar disorder reignited in 1966. In separate investigations, psychiatrists Carlo Perris of Umeå University in Sweden and Jules Angst of the University of Zurich in Switzerland each studied some 300 patients with either true bipolar disorder or depression alone and more than 2,000 of their close relatives.

IN BRIEF

Mania usually occurs with depressive episodes as part of bipolar disorder. Yet some bipolar patients experience only mania, raising the question of whether another diagnosis is needed.

Evidence to justify separate diagnoses for unipolar mania and bipolar disorder has been elusive, but studies hinting at measurable differences are starting to emerge.

Some researchers recommend defining unipolar mania as an official subtype of bipolar disorder to raise awareness and facilitate further research into what distinguishes it.

Both researchers found that relatives of the bipolar patients had more mood disorders than those of patients with depression alone. They also discovered that although bipolar illness was common in the relatives of bipolar patients, it was no more common in relatives of depressed patients than in the general population. These findings, Perris and Angst argued, suggested that bipolar disorder and depression were genetically different conditions.

As a consequence, when the third edition of the *Diagnostic and Statistical Manual of Mental Disorders,* or *DSM,* appeared in 1980, it included major depressive disorder as a condition distinct from bipolar disorder. Perris and Angst's studies focused only on depression and did not address mania. "There weren't enough cases of pure mania to do anything reasonable," Angst says.

Whether unipolar mania should have its own diagnosis is complicated by bipolar disorder's clinical diversity. The manic and depressive phases vary in severity and the extent that one or the other dominates. The pattern of episodes varies unpredictably and from patient to patient. Mixed states, involving aspects of opposite mood extremes simultaneously, sometimes occur, too. Indeed, many psychiatrists argue that mood disorders are best thought of as lying on a spectrum, ranging from major depression through various bipolar presentations to pure mania.

IN SEARCH OF A SUBTYPE

THE VARIABILITY OF SYMPTOMS, along with findings from large psychiatric genetics studies that implicate numerous biological factors, suggests that bipolar disorder includes a range of subtly different conditions. "One reason we still have limited understanding of bipolar disorder after 50 years of intense research is that it's treated as one entity, and it's clearly not," says psychiatrist Paul Grof of the University of Toronto.

The resistance to subtyping may be the result in part of changes in research funding over the past few decades, as the pharmaceutical industry has taken over progressively more psychiatric research from universities, Grof says. Drug companies generally just want to know if a new drug is better than a placebo, and the larger the patient group, the greater the likelihood of finding a significant difference. Subdividing bipolar disorder into smaller populations would complicate these efforts. The industry also prefers to study diagnoses recognized by the Food and Drug Administration—and unipolar mania is not on its list.

Institutional inertia can also come into play. Every rewrite of the *Diagnostic and Statistical Manual of Mental Disorders* is a laborious process. Each edition is based on the previous one, and any change must be backed by fresh evidence, with papers submitted to committees justifying the decision. The last edition, *DSM-5,* was published in 2013, and in the view of the committee tasked with reviewing mood disorders, unipolar mania was covered by the bipolar diagnosis known as BP-I, which is mania with or without associated depression. "There was very limited discussion as to whether mania should be separate because the onset and course of illness weren't seen as that different from BP-I," says psychiatrist Trisha Suppes of Stanford University, who was a member of the *DSM-5* work group for mood disorders.

The lack of a separate diagnosis may be making evidence harder to gather. The standardized clinical interview used under the *DSM* to make diagnoses for research studies has no category for unipolar mania, meaning investigating the condition would have to rely on ad hoc techniques that might not align with those used in other studies. Unipolar mania is thus at the hub of a catch-22: the absence of a diagnosis is an impediment to research, and the paucity of research makes creation of a diagnosis less likely.

In studies that do occur, the lack of a formal designation for unipolar mania makes it difficult to compare results. "A major problem is definitions," says Allan Young, a psychiatrist at King's College London. One source of disagreement is the severity of symptoms necessary for a case to qualify as mania. Another is the frequency of episodes. Some studies include anybody who has had at least one episode of mania with no history of depression, whereas others require three or four. Still others stipulate a minimum number of years of illness. These differences have led to widely disparate prevalence estimates for unipolar mania, ranging from 1.1 to 65.3 percent of bipolar patients.

Most of the studies completed so far also have methodological problems. The bulk are retrospective, in which researchers simply ask participants to recount past experiences—a process known to underestimate depression, perhaps inflating estimates of pure mania. Prospective studies that follow patients for years and include periodic assessments are better. "What you really want is someone who's lived their whole life, had multiple episodes of mania, and never had depression," Young says. "The first lady I saw like this died in her late 60s and had her first episode at 21, which is getting on for 50 years, so that's very convincing."

One of the longest prospective studies, led by David Solomon, now at the Warren Alpert Medical School of Brown University, began in 1978 and was published in 2003. It began as a study of 229 bipolar patients, 27 of whom had mania with no history of depression. The investigators followed those 27 patients for up to 20 years; seven of them remained free of depression throughout the period. The results suggest that of the original 229 patients, 3 percent had unipolar mania. Solomon does not advocate the creation of a separate diagnosis for unipolar mania unless future research establishes differences in genesis, prognosis or treatment response. But if the rate reported in the study held for the general population, the number of people with unipolar mania in the U.S. would be around 100,000—and hundreds of thousands more worldwide.

The stories of people with unipolar mania help to explain why some researchers are convinced that the disorder is a separate entity. Lindsey, a ski coach from Portland, Me., is one such case. She was 18 when she had her first experience of mania. At 36, she has never been depressed, yet she still has a diagnosis of bipolar disorder. "I'm the happiest person I know," she says. "I never accepted my diagnosis." As a result, she rejected treatment and continued to have episodes. She has been hospitalized five times and has landed in jail more than once.

Lindsey's episodes start with euphoria but can spiral into delusions and difficulty speaking. While manic, she feels no fatigue, hunger or pain. One such episode, in her late 20s, began on a hike in New Mexico when she was overcome by a vision that the world was coming to an end. Lindsey called her father, who flew out to meet her and drive her home to Maine. "She had medication," her father says. "She just wasn't taking it." Early in the morning on an overnight stop in Nashville, Lindsey started playing the piano in the hotel lobby. An employee called the police, and Lindsey fled in the car.

In the adventure that followed, she deliberately got lost, buried her possessions near a railroad track and abandoned the car. She then hopped a freight train, got off in the middle of rural Tennessee, climbed out of a rock-walled valley and wandered into a chapel, where the pastor was able to glean enough information to contact her family. Shortly after resuming the drive home, Lindsey ran away from her father at a highway rest stop and started picking daisies in a fenced-off electrical area. The police were called again, and although the officer urged her to leave with her father, she insisted on being arrested.

In her cell, a guard pepper-sprayed her, and she ended up in the office of the jail's counselor. Lindsey was barely able to speak at this point, but she wrote "unipolar" repeatedly on a blackboard. The counselor then read Lindsey a description of mania. She credits this encounter as the moment she accepted the need to take medication. The counselor gave her Zyprexa (olanzapine), an antipsychotic. She recovered and takes it to this day, though not without reservations. "My medication is like a dose of sadness, hunger, fatigue and pain," she says. Lindsey was euphoric throughout her ordeal, even while being pepper-sprayed. Only the people around her suffer. "I feel like I've been blessed with this illness that makes me so happy," she says, "but I feel selfish because of how it affects my family."

Lindsey married Andy, a journalist, in 2015, not long after he witnessed her last hospitalization. "It made the relationship stronger in the end," he says. "I got to see her as she clawed her way back to sanity. It was impressive." The most important factor in her treatment is whether a physician accepts that she is not bipolar. "When that's ignored, she no longer trusts that person," Andy says.

Psychic Fuel for the Creative Brain

The mad genius may be more than a cliché

Of all the tropes of artists and mental afflictions, the most enduring is the one of a genius in the throes of mania. Iconic figures ranging from William Blake to Ernest Hemingway to Kurt Cobain were known or believed to be bipolar. The association has intuitive appeal: the euphoria, abundant energy and racing thoughts of mania are credible fuel for creativity.

Scientific evidence for the association has mostly been inconclusive. Much of the data comes from historical sources, and most accounts are anecdotal. Modern investigative techniques have revealed surprisingly little about what happens in the brain during mania, partly because brain imaging requires minimal head movement, so scanning someone in a floridly manic state is a challenge. As a dynamic process involving the interplay of multiple brain networks, creativity is also difficult to research.

But comparing findings from research into bipolar disorder with certain studies of creativity reveals hints of a link: cognitive "disinhibition" seems to be a feature of both the creative state described as being in the "flow" and altered brain circuits in bipolar disorder.

Brain-imaging studies have found reduced activity in a part of the prefrontal cortex that helps to regulate emotion, which may be linked to impaired impulse control and extremes of mood in bipolar patients. (The prefrontal cortex is the brain's "orchestra conductor" responsible for directing various mental processes.) Some of these studies have also found diminished activity in an area involved in suppressing the kind of spontaneous thought that appears to well up from the unconscious, seemingly out of nowhere.

These results are reminiscent of a 2008 study of improvising jazz musicians and a 2012 study of freestyling rappers, conducted by the team of speech neuroscientist Allen Braun, then at the National Institutes of Health, which found reduced activity in the part of the prefrontal cortex that inhibits spontaneous cognition. They also found an increase in activity in a section of the prefrontal cortex that is part of the so-called default mode network, which revs up when a

IT ALL GETS REAL

A CURIOUS QUIRK in the tale of this neglected disorder is that prevalence estimates vary worldwide and are consistently higher in non-Western countries. After qualifying in South Africa in 1997, psychiatrist Christoffel Grobler worked in an inpatient unit in Ireland, where his bipolar patients were mostly in depressed states. When Grobler returned to South Africa in 2009, he noticed the opposite pattern: his patients were mostly in manic states. To investigate, in 2010 he and his colleagues interviewed 103 bipolar patients in three hospitals, using a standard diagnostic questionnaire. They found that 32 percent of patients qualified as unipolar, defined as having at least five manic episodes over four or more years. "When I present this at conferences, people come up and say, 'We see this all the time,'" Grobler says.

Regional variations are tricky to interpret because cultural differences come into play: depression is more likely to be considered part of normal life in Africa, for example. The quality and procedures of health care systems differ, and other causes, including infection or intoxication, may be a factor. But Grobler is convinced the geographical differences are genetic in origin and that unipolar mania therefore represents a distinct condition.

Getting to the bottom of this question will require large, multicultural international studies. In the meantime, scientists are trying to compensate for a shortage of data. One reason most early studies failed to find differences between mania and bipolar disorder may be that they are so slight that they can be reliably detected only in large samples. Although he is now in his 90s, Angst has recently tried to address this problem by consolidating data from nine epidemiological studies conducted in the U.S., Germany, Switzerland, Brazil and Holland. That study, published online last November in *Bipolar Disorders,* found that people with unipolar mania were more likely to be male but less likely to have attempted suicide or to suffer from anxiety, drug use and eating disorders. Angst and his colleagues claim these findings suggest unipolar mania "should be established as a separate diagnosis."

Some of these findings align with three reviews of research on unipolar mania published in the past five years. All three found that unipolar mania is less likely to co-occur with anxiety (which often accompanies depression) but more likely to come with psychotic symptoms. Unipolar mania also seems to confer less social impairment and involve fewer recurrences and better remission rates than bipolar disorder.

Perhaps most important, people with unipolar mania show subtle differences in their response to drugs administered as part person is not focusing on a task but is rather imagining things or ruminating on the past. The researchers believe what they observed reflects relaxation of focused attention and control, making way for a creative thought process in which inspiration bubbles up from the unconscious. Other studies have found reduced thickness of certain cortical regions in both creative and bipolar brains, which may be linked to altered brain activity and disinhibited cognition.

Another element in the thinking patterns of creative and manic people is the ability to make mental connections that elude others. Neuroscientist Nancy Andreasen of the University of Iowa has found that creative people show greater activity in the so-called association cortices, which are regions tasked with linking related elements of cognition. These brain areas are not devoted to processing specific sensory or motor functions but instead with tasks such as tying together a written word with its sound and meaning. Andreasen believes creative ideas probably occur when these types of associations occur freely in the brain during unconscious mental states, when thoughts become momentarily disorganized—not unlike psychotic states of mania.

This observation resonates with clinical psychologist David Ho, who has experienced racing thoughts and extraordinarily enhanced recall during manic episodes, letting him write without inhibition or self-doubt. “With repression vanished, my mind functioned with holistic oneness,” he says. “Creative ideas rained down faster than I could cope.” Researchers do not know if the association cortices are more active in mania, but all these findings suggest that at key moments of the creative process, our thought processes flow more freely, with novel combinations of sights, sounds, memories, meanings and feelings producing insight and originality in creative work akin perhaps to what happens during mania.

Of course, mental illness is neither necessary nor sufficient for creative talent, and severe manic episodes most likely are too debilitating for any kind of sustained activity. But researchers have found that family members of people with bipolar disorder also tend to be more creative than average, supporting the idea that mild manifestations of the disorder may furnish cognitive benefits.

It is important not to romanticize conditions that mainly cause suffering, but evidence that mania can enhance creativity in some people may help reduce the stigma of a diagnosis. “It is possible to retain a measure of madness in dignified living,” Ho says, “and of dignity even in a state of madness.” *—S.M.*

of preventive treatment. Three studies have found that unipolar mania patients respond less well to lithium (a mood stabilizer and first option for bipolar) than true bipolar disorder patients do.

The most recent of these studies, published in 2012 by Olcay Yazici and Sibel Cakir, both at Istanbul University, also examined the question of whether unipolar mania is merely bipolar disorder weighted to the manic end of the spectrum—so-called dominant manic polarity. They divided 121 patients into two groups, 34 with unipolar mania and 87 with classic bipolar disorder. As the earlier studies found, the unipolar group had a lower response rate to lithium, and their response to another frontline bipolar treatment, the anticonvulsant Depakote (divalproex sodium), was no different.

The researchers next grouped all 121 patients according to whether the majority of their episodes were manic or depressive and then created a further division of patients whose manic episodes accounted for at least 80 percent of the total. A smaller percentage of patients who had at least a majority of manic episodes responded to lithium than patients who had more depressive episodes did, and this difference was greater for patients whose mania put them in the 80 percent group. Most tellingly, when those with unipolar mania were excluded from this analysis, these differences disappeared, suggesting the treatment difference relates to unipolar mania, not to dominant manic polarity, implying that unipolar mania is its own entity.

THE WAY AHEAD

THOSE WHO OPPOSE a separate diagnosis sometimes point out that the mania in unipolar mania is indistinguishable from that in bipolar disorder. But the same is true of depression, and many studies have found differences in the brains of people with major depression and those with bipolar disorder. Future work that compares brains of people with unipolar mania and bipolar disorder might be just as revealing.

Biological and brain-imaging studies of unipolar mania are rare. But one from a quarter of a century ago gives clues to differences in physiology. A 1992 CT scan study led by Sukdeb Mukherjee of the Medical College of Georgia at Augusta University found that unipolar mania patients had smaller third ventricles (one of four interconnected cavities in the brain that let cerebrospinal fluid flow) than bipolar patients did. This result is intriguing because subsequent studies found that bipolar patients who experienced multiple episodes have larger ventricles than people experiencing their first episode or healthy control subjects, a hint that enlarged ventricles may be linked to pathology. The implication that unipolar mania may not cause as much damage in the brain tallies with the better outcomes associated with the condition.

Creating a separate diagnosis for unipolar mania remains controversial. An interim step would be to recognize it as an official subtype of bipolar disorder. Such a move might encourage research and raise awareness among clinicians. “There’s a mystery here we don’t understand: Why do some people get mania and then depression, whereas others stay unipolar manic?” Suppes asks. “It’s deserving of more research than it’s gotten so far.” Further investigation might also benefit patients who do not identify with other labels. Lindsey pleads, “The most important thing my doctor could do for me is say, ‘I’m sorry, we were wrong—you’re not bipolar, you’re unipolar.’” SA

MORE TO EXPLORE

Unipolar Mania: A Distinct Entity? Olcay Yazıcı in *Journal of Affective Disorders,* Vols. 152–154, pages 52–56; January 2014.

Madness May Enrich Your Life: A Self-Study of Unipolar Mood Elevation. David Y. F. Ho in *Psychosis,* Vol. 8, No. 2, pages 180–185; 2016.

Differences between Unipolar Mania and Bipolar-I Disorder: Evidence from Nine Epidemiological Studies. Jules Angst et al. in *Bipolar Disorders*. Published online November 2018.

FROM OUR ARCHIVES

Mental Illness Overlap. Mark Fischetti and Martin Krzywinski; Graphic Science, July 2018.

scientificamerican.com/magazine/sa

CLIMATE

THE WEATHER AMPLIFIER

Strange waves in the jet stream foretell a future full of heat waves and floods

By Michael E. Mann

WILDFIRE RAGES near Delta, Calif., in September 2018, stoked by relentless heat and drought.

CONSIDER THE FOLLOWING SUMMER EXTREMES: In 2003 Europe's worst heat wave in history killed more than 30,000 citizens. In 2010 wildfires in Russia and floods in Pakistan caused unprecedented damage and death. The 2011 U.S. heat wave and drought caused ranchers in Oklahoma to lose a quarter of their cattle. The 2016 Alberta wildfires constituted the costliest disaster in Canadian history. And the summer of 2018 that the U.S. experienced was notorious: temperatures flared above 100 degrees Fahrenheit for days on end across the desert Southwest, heavy rains and floods inundated the mid-Atlantic states, and California had a shocking wildfire season. Extreme heat waves, floods and wildfires raged across Europe and Asia, too.

Michael E. Mann is a professor of atmospheric science and director of the Earth System Science Center at Pennsylvania State University. He has written or co-written four books, including *Dire Predictions, The Hockey Stick and the Climate Wars, The Madhouse Effect* and *The Tantrum That Saved the World.*

Is it coincidence that the most devastating summer weather has occurred in recent decades? My colleagues and I do not think so. All these events had a striking feature in common: a very unusual pattern in the jet stream. The jet stream is a narrow band of strong wind that blows west to east around the Northern Hemisphere, generally along the U.S.-Canada border, continuing across the Atlantic Ocean, Europe and Asia. The band is sometimes fairly straight, but it can take on big bends—shaped like an S lying on its side. It typically curls northward from the Pacific Ocean into western Canada, then turns southward across the U.S. Midwest, then back up toward Nova Scotia. This shape usually proceeds west to east across the U.S. in a few days, bringing warm air north or cool air south and creating areas of rain or snow, especially near the bends. The jet stream controls our daily weather.

During the extreme events I noted, the jet stream acted strangely. The bends went exceptionally far north and south, and they stalled—they did not progress eastward. The larger these bends, the more punishing the weather gets near the northern peak and southern trough. And when they stall—as they did over the U.S. in the summer of 2018—those regions can receive heavy rain day after day or get baked by the sun day after day. Record floods, droughts, heat waves and wildfires occur.

My collaborators and I have recently shown that these highly curved, stalled wave patterns have become more common because of global warming, boosting extreme weather. But we predict that the rising severity may level off for the next several decades. That may sound strangely "good"—the bad spells will continue, but at least they will not get worse. We also predict that the extreme events will start becoming much more severe, beginning around 2050 or so—particularly in summer. Threats to people's health and safety will increase, storm damage will get more extensive and crops needed to feed a rising population will be ruined.

How do we know? Wave mathematics and quantum mechanics tell us. Yes—the mathematics that characterize the behavior of electrons at the smallest scale help us describe the behavior of our atmosphere at global scales. They indicate that the rise in dangerous weather, the coming plateau and the subsequent surge are driven by a curious trade-off between greenhouse gas concentrations from fossil-fuel burning and sulfur pollution from industrial smokestacks. And that trade-off raises the question of whether cutting emissions will prevent the jet stream from wreaking havoc.

ROSSBY BRINGS BAD WEATHER

THE JET STREAM FORMS where warm surface air from the subtropics around the globe moves northward and meets cold surface air from the polar region—roughly where the U.S. meets Canada. The jet blows at around 35,000 feet up, along the boundary between the troposphere (the lowest level of the atmosphere, where weather happens) and the stratosphere (the next level, where airliners fly).

The greater the temperature difference when the subtropical and polar air meet, the stronger the jet stream wind. During summer the temperature difference is less than during winter, so the jet stream is weaker. When it weakens, it is more likely to exhibit broad north-south bends.

But why do the bends form where they do? The jet stream is affected by a set of large waves that waft through the atmosphere, created naturally as the earth rotates through a fluid—in this case, air. They are Rossby waves, named after Swedish-American meteorologist Carl-Gustaf Rossby, who first explained in the 1930s the physics of large-scale atmospheric motions. They occur throughout the oceans, too.

Rossby waves in the atmosphere extend for hundreds of miles and move west to east in the Northern Hemisphere. When the temperature difference between the air masses decreases in summer, the Rossby waves tend to bend more and proceed more slowly from west to east over North America. The jet stream follows the shape and path of those waves.

Other waves also course through the atmosphere and the ocean. For example, gravity waves arise from a temporary disturbance between gravity pulling the atmosphere down and

IN BRIEF

When the jet stream's shape becomes highly bent, it can bring heavy summer rain or heat. And if the jet stalls, the bad weather can continue for days.

Mathematics from quantum mechanics explains how resonance in the atmosphere can amplify the bends, making harsh weather even worse.

Through about 2050, aerosols in the air from coal plants will slow the increasing severity, but as the plants install scrubbers, the intensity will rise again.

PRECEDING PAGES: JOSH EDELSON *Getty Images*

DEEP FLOODS caused by an atmospheric effect called quasi-resonant amplification submerged Khairpur Nathan Shah, Pakistan, in 2010.

GIDEON MENDEL *Getty Images*

buoyancy forces pushing it up, such as an air current passing over a mountain range. Kelvin waves occur in the Pacific in a tight corridor straddling the equator. There they travel predictably, west to east, periodically warming and cooling the surface waters, a key ingredient of the El Niño/Southern Oscillation climate phenomenon.

The bends in the jet stream create local surface weather systems that move eastward as the bends proceed that way. We see them on weather maps as the big H's and L's—high- and low-pressure systems. A high-pressure system tucked inside the northern bend, or ridge, rotates clockwise and in summer brings dry, hot weather. A low-pressure system tucked inside the southern bend, or trough, rotates counterclockwise, leading to wet, cool weather. If the jet stream is weak enough, the S-shaped Rossby wave it is tracking can stall in place, without proceeding eastward—a "standing wave" pattern. The high and low weather systems spin in place, persistently baking the earth below or barraging it with relentless rainstorms and flooding—what happened with Hurricane Harvey over Texas and Hurricane Florence over the eastern-central U.S.

RESONANCE MAKES IT WORSE

TRULY EXTREME WEATHER tends to occur when the bends in the Rossby waves, and therefore the jet stream, are greatly amplified. The higher the ridges and lower the troughs, the deeper the high- and low-pressure systems. In this standing-wave pattern, the high-pressure system stagnates (sometimes called a blocking pattern). That is exactly what caused the July 2018 heat wave in the U.S. Southwest and simultaneous floods in the mid-Atlantic. Another classic example was the ridge over Russia in July 2010 associated with record heat, dryness and wildfires and, downstream of it, a deep trough over Pakistan associated with record flooding.

The amplitude that routine Rossby waves can attain is limited by the energy they radiate away as they bend north and south and as they proceed eastward. Under certain conditions, however, the atmosphere can act as a kind of waveguide. Imagine a west-east line across central Canada and another one across the southern U.S. A bent Rossby wave stays put, within these "walls," losing little energy. This confinement locks in the curved jet stream and the strong high- and low-pressure systems.

The coaxial cable leading from your cable company to your television is an example of a waveguide. The electromagnetic waves that transmit the TV signal from it to you are largely confined within the cylindrical wall of the cable, and little of the signal's energy is lost. Thank the physics of waveguides for the crisp images you enjoy.

When waves are stuck in place as standing waves, under certain circumstances the bends can grow readily in amplitude—what is known in physics as resonance. When this happens to Rossby waves, more common in summer, it is called quasi-resonant amplification, or QRA. Several years ago Vladimir Petoukhov and his collaborators at the Potsdam Institute for Climate Impact Research in Germany showed that the conditions supporting QRA depend on the shape of the jet stream. Climate change, it turns out, can impact the shape of the jet stream and thus QRA and the frequency of extreme summer weather events.

To understand how this confluence happens, we need to consult the same mathematics that was developed in the early 20th century to solve certain problems in quantum mechanics. That connection is particularly satisfying to me. I began my career in theoretical physics before moving into atmospheric science, so it is reassuring that those decades-old quantum mechanics textbooks I held onto are still useful in my work.

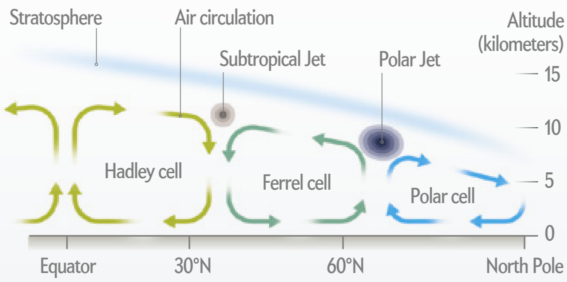
THE QUANTUM CONNECTION

UNDERSTANDING HOW the behavior of an atmospheric wave is mathematically similar to the behavior of an electron will help reveal a key reason why droughts and floods are getting worse.

In classical physics, an electron can become trapped when it is

Extreme Weather Locked in Place

The jet stream drives weather across the Northern Hemisphere. When it bends, it can create strong pressure centers that deliver high heat or heavy rain (*globes*). Very large bends can get stuck in place, prolonging the extreme conditions for many days, especially during summer. Curiously, the planetary-scale physics resembles that of quantum mechanics at the atomic scale (*box*).



Waveguide in the Sky

The atmospheric waveguide that traps Rossby waves in place is mathematically similar to a quantum waveguide that traps an electron. In classical physics, an electron inside a box with infinitely high walls (which represent a high-energy barrier) acts like a particle, bouncing back and forth **A**. If the walls have modest energy, an electron can escape. But in quantum physics, an electron acts like a wave trapped inside a waveguide; if the waveguide is weak (modest energy), the probability that the electron can be found outside the walls of the waveguide is sizable **B**. But if the waveguide has high energy, the likelihood of the electron "tunneling" through the walls is much smaller—similar to Rossby waves associated with an extremely bent jet stream that get stuck inside an atmospheric waveguide, punishing the earth below with persistent heat or rain.

Jet Stream Circles the Earth

Jet streams arise at roughly 30 and 60 degrees latitude, between the atmosphere's major air circulation cells (*above*). The Northern Hemisphere's polar jet blows west to east around the globe, sometimes in a nearly straight line, sometimes with slight bends (*below*). Weather systems tend to follow the path.

Pressure Centers Grow

In summer, pronounced bends in the jet stream create low-pressure systems (*L*) that bring cool, wet weather and high-pressure systems (*H*) that produce hot, dry conditions. Sometimes the jet stream takes on a repeating, undulating pattern (*shown*), following the shape of Rossby waves created in the atmosphere as the earth rotates through it. The pattern, and weather, proceeds west to east.

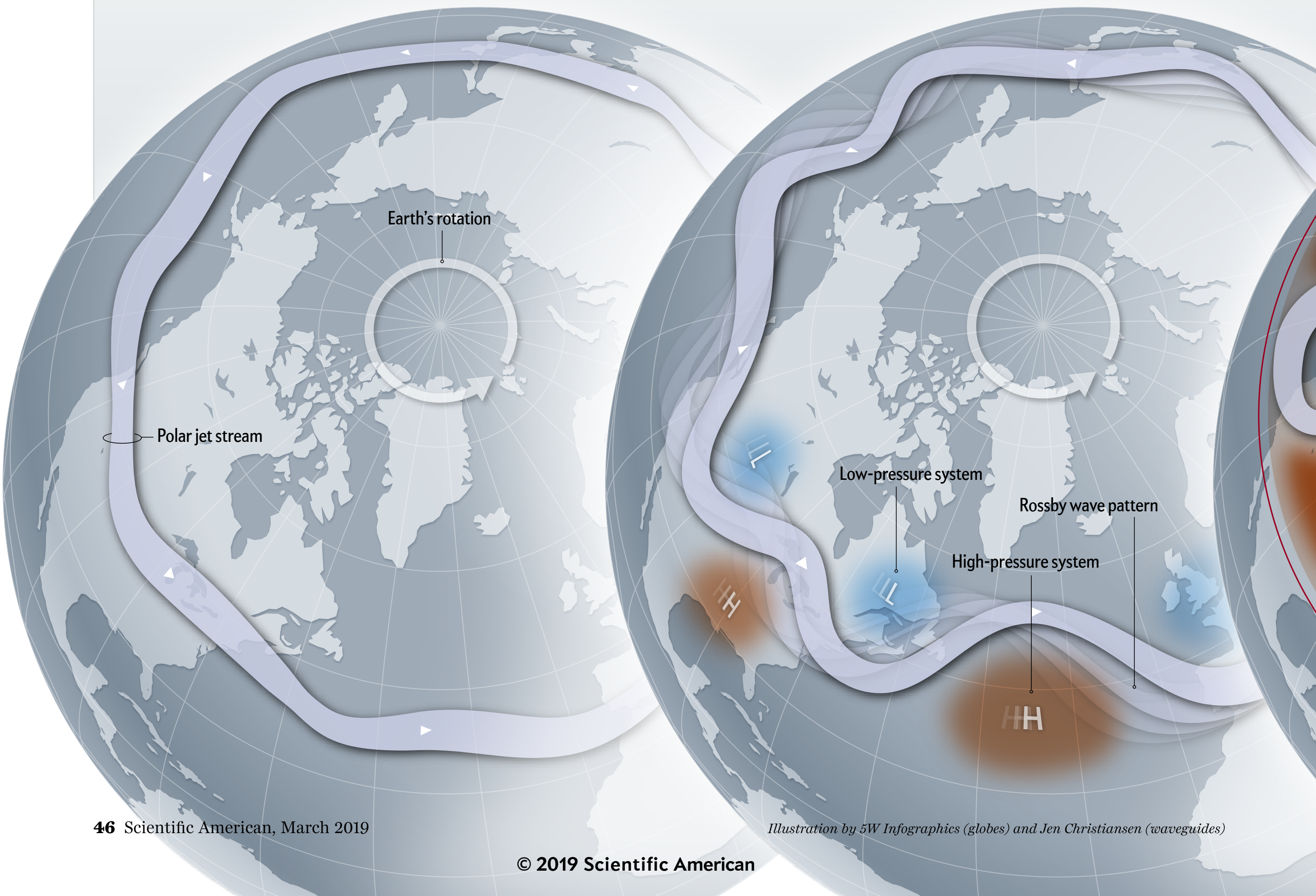
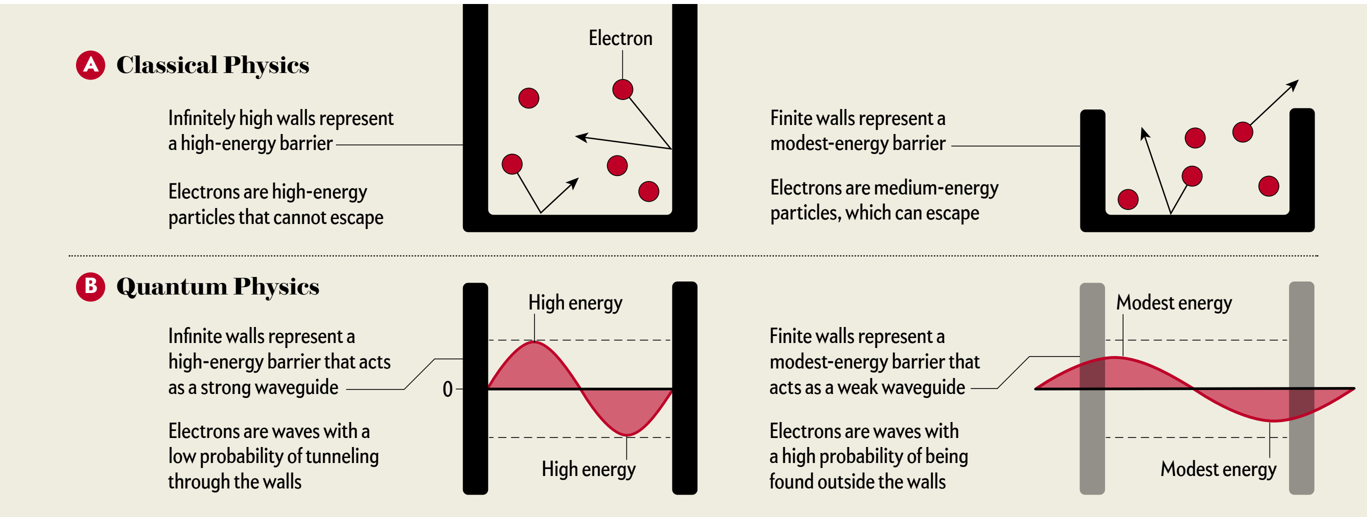


Illustration by 5W Infographics (globes) and Jen Christiansen (waveguides)

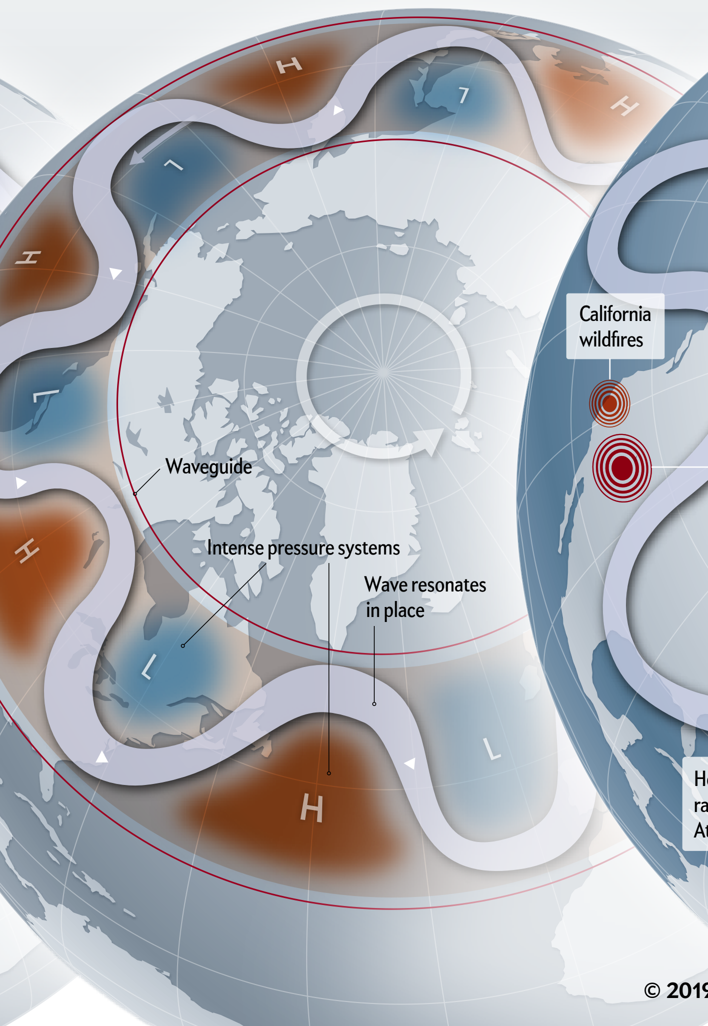


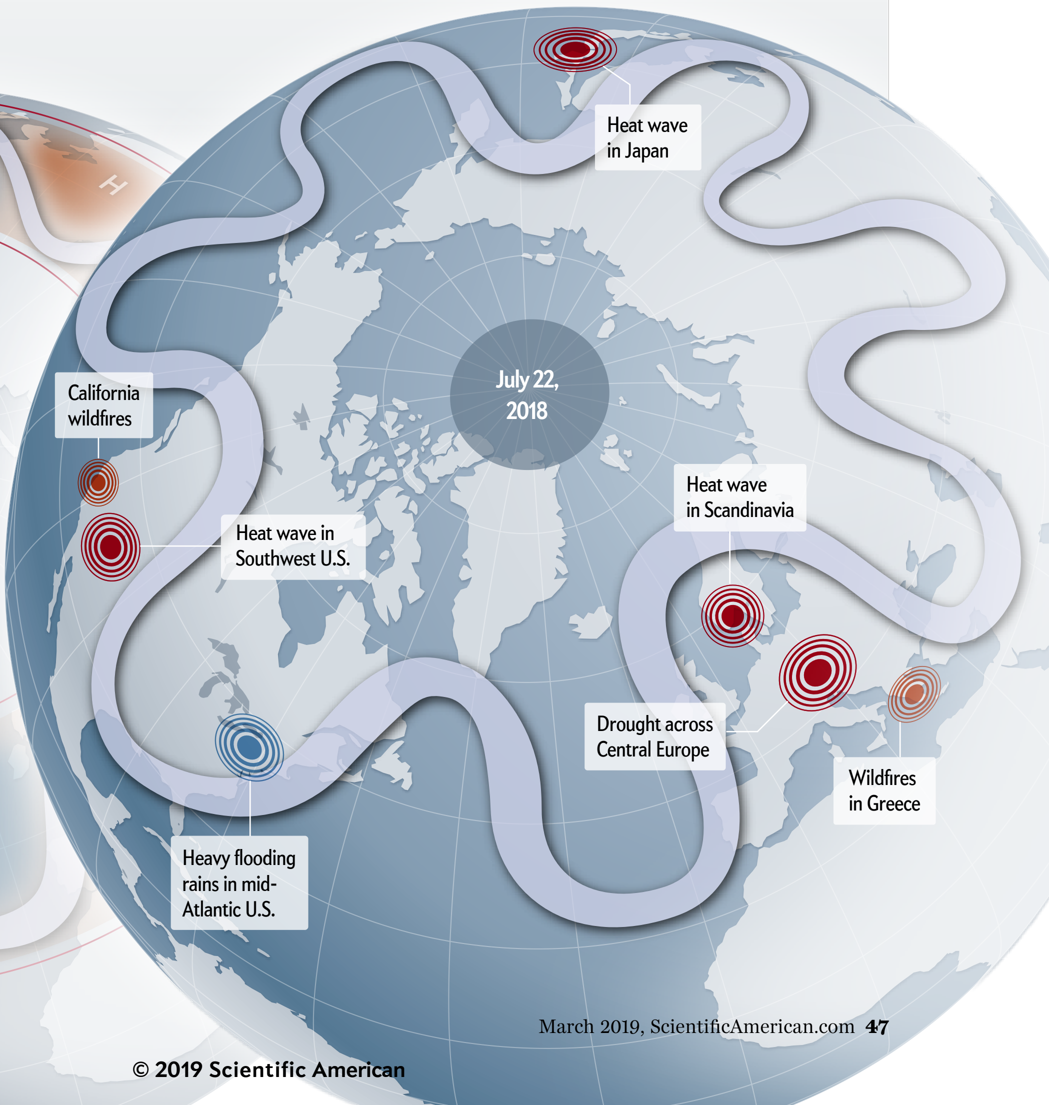
Storms Resonate

Large Rossby waves, and the jet stream bends that track them, can get stuck in place, forming a standing wave. The atmosphere can then act as a waveguide (*red lines*), which encourages the bends to resonate and amplify, reaching even farther north and south (*shown*). The weather systems become intense and get locked in place for days. The situation arises more commonly in summer than winter.

Destructive Day

A resonating jet stream, stalled during late July and early August 2018, touched off or magnified extreme weather around the planet. On July 22, heat waves and droughts gripped several regions and aggravated wildfires, while heavy flooding occurred in other areas.





PARCHED SUNFLOWERS (*1*) and stunted seeds (*2*) near Golssen, Germany, were wrought by a prolonged heat wave in 2018.

surrounded by high potential energy. Imagine looking though a box from the side, with walls that are infinitely high. The electron cannot pass through the walls, because they have infinitely high energy that cannot be overcome. The electron bounces back and forth, left to right, in a straight line.

In the quantum mechanics picture, things are different. The electron no longer has a definite position. Instead the probability of finding the electron is determined by the famous Schrödinger equation, a wave equation. The motion of the electron—or more precisely, the probability of where the electron is most likely to be found—is described by a sinusoidal curve: an S laying down on its side. Sound familiar? The electron acts in part like a particle and in part like a wave.

Something interesting happens when the potential energy "walls" are not infinite in height but instead are finite. In that case, the electron has a small probability of actually penetrating the wall, and it can pass all the way through it if the wall is thin enough. It is as if you hit a tennis ball against a concrete wall, and it "tunneled" through the wall and out the other side. The same probability pertains to the opposite wall. The electron is largely confined to the box but with just a bit of "leakage" across the boundaries. Welcome to the peculiar world of quantum mechanics.

Looking through this finite box is the same as looking down the inside of a slightly leaky three-dimensional waveguide—like a coaxial cable. The mathematical nugget that allows us to solve the equations that describe these objects was put forward in 1926, known as the WKB approximation, after the three scientists who introduced it: Gregor Wentzel, Hendrik Kramers and Léon Brillouin. The WKB approximation is used in quantum mechanics for lots of wave equations and to aid the design of products such as the tunnel diode in your smartphone.

In the early 1980s David Karoly, now at Australia's Commonwealth Scientific and Industrial Research Organization, and Brian Hoskins of the University of Reading in England demonstrated that the atmosphere can behave like a waveguide for stalled, or standing, Rossby waves that have certain short wavelengths (roughly the width of the continental U.S., or six to eight full wavelengths all the way around the Northern Hemisphere).

The standing Rossby wave becomes trapped inside the waveguide, with only minimal leakage of energy through the northern and southern boundaries—just like the electron. In this situation, the waves can grow in amplitude because of QRA. Stuck in place, the now huge standing wave creates extreme weather systems inside the ridges and troughs that persist for days. The WKB approximation, which leads to solutions to waveguide problems in quantum mechanics, also helps to solve the Rossby waveguide problem.

A CHANGING WAVE CLIMATE

WITH THIS UNDERSTANDING, we can now see how climate change is affecting the standing waves that give us persistent weather extremes. Several years ago Petoukhov and his Potsdam collaborators built on Karoly and Hoskins's work, showing that waveguide conditions for standing Rossby waves arise primarily in summer. Often in summer, the jet stream is not a single, strong west-to-east wind. It alternates between two corridors, one to the north and one to the south of the typical location along the U.S.-Canada border.

Using the WKB approximation, Petoukhov's group showed that it is precisely under these "double-peak" jet conditions that the atmosphere can behave as a waveguide for Rossby waves with a short wavelength. The amplitude of these waves is generally small: the bends do not extend very far north or south. But if an initial bend is generated when an air mass moving west to east hits the Rocky Mountains or the Alps or when it encounters a strong surface temperature contrast at the boundary between land and ocean, the Rossby waves can readily grow much larger bends through the QRA mechanism.

Whether conditions are favorable for QRA varies from year to year. They depend in large part on the north-south pattern of temperature variations in the lower atmosphere—something that climate models resolve well. In 2017 my colleagues and I showed that there has been a greater tendency in recent decades for conditions that favor QRA. Climate simulations show that the trend is driven by increases in greenhouse gas concentrations over time. Natural factors such as fluctuations in solar output and volcanic eruptions, as well as other human factors such as atmospheric sulfur dioxide pollution in particular, have also played a role. The simulations, called CMIP5, are the result of modeling by more than 50 groups worldwide done for the most recent report of the Intergovernmental Panel on Climate Change (IPCC).

Temperature data recorded at weather stations and the models show that climate change is causing the Arctic to warm faster

SEAN GALLUP *Getty Images*

than the rest of the Northern Hemisphere, a situation known as Arctic amplification. A smaller difference in temperature between midlatitudes and polar latitudes creates a slower jet stream overall, which favors more persistent weather patterns and is associated with the double-peak jet and QRA.

This mounting trend helps to explain the spate of long-lasting, extreme summer weather events seen around the Northern Hemisphere over the past two decades. Scientists have recently shown that QRA conditions are linked to the 2003 European heat wave, the 2010 wildfires in Russia and associated Pakistan floods, the drought that gripped Oklahoma and other parts of the U.S. in 2011, as well as wildfires in California in 2015 and the 2016 Alberta wildfires. Now we can add to that list the unprecedented California wildfires of 2018. Human-caused climate change has increased the likelihood of these excessive weather events by roughly 50 percent over the past few decades.

THE STALL

IT SOUNDS LIKE EXTREME WEATHER should just keep getting worse. And some basic factors suggest it will. For example, a warmer atmosphere holds more moisture, leading to more heavy rainfalls and flooding. And a warmer planet means more frequent, prolonged and intense heat waves. But what about the standing-wave jet stream and QRA?

As the great physicist Niels Bohr and subsequently baseball legend Yogi Berra are said to have remarked, predictions are hard—"especially about the future." In a paper my colleagues and I published in October 2018 in *Science Advances,* we analyzed how QRA events are likely to change as a result of projected future climate change. We did indeed expect that the upward trend would continue unabated, but that is not what we found.

The IPCC and the CMIP5 experiments assess future conditions under different scenarios, everything from deep, immediate cuts in carbon dioxide emissions to a world that just keeps emitting more and more CO_2 along the trajectory it has been taking. Under that so-called business-as-usual scenario, we found that the trend toward conditions favoring QRA flattens out until around 2050. Then it accelerates in the second half of this century.

The reason, we found, involves another important but sometimes overlooked human driver of climate change: atmospheric pollutants such as sulfur dioxide, which are produced by coal burning and other industrial activities. These pollutants form particulates known as aerosols that drift in the atmosphere and reflect sunlight back to space, cooling the earth below.

Aerosol pollution was responsible for acid rain from the 1950s to 1970s in the northeastern U.S. The Clean Air Act required industrial plants to install "scrubbers" in smokestacks to remove the sulfur dioxide from the emissions. That helped to save forests, lakes and streams, but it also left fewer aerosols in the atmosphere to reflect sunlight and counteract warming from rising CO_2, one reason global warming has accelerated since the 1970s.

Much of the rest of the world—most important, China, which accounts for nearly half of all current coal burning—still employs old-style industrial practices. The IPCC business-as-usual scenario assumes that countries such as China will continue to burn coal, contributing to greater CO_2 emissions that would more than triple the preindustrial level by the end of the 21st century. The scenario also assumes, however, that these industries will install scrubbers over the next several decades.

That will lead to a dramatic reduction in aerosols between now and midcentury—and much more warming. The effect is especially large in the midlatitudes during summer, when there is maximal sunlight; much of it will no longer be reflected. In some model simulations, the resulting midlatitude summer warming is so great that it exceeds the Arctic warming. Arctic amplification lessens or even stops. That would mean no increase or even a decrease in QRA—and no further worsening of the jet stream pattern behind the rise in extreme summer weather.

DESTINY IN OUR HANDS

SUCH A FUTURE seems like a good deal. But it is actually a Faustian bargain. The short-term mitigating effect comes at great long-term expense. By midcentury the aerosols are mostly gone, so from that point on, rising greenhouse gases continue to drive all temperatures up. Once again the rise becomes faster in the polar region. Arctic amplification resumes, and the QRA events—the stalled, intense, hot, dry and wet weather patterns—start increasing again. By the end of the century they rise by roughly 50 percent relative to now. The change will be most prominent in summer, in midlatitudes, which is especially troubling because that is where most people live and because that is where and when large quantities of crops grow—many of which do not hold up well in high heat.

Is there a way out? If the world acts now to quickly get off the business-as-usual treadmill and significantly lower carbon emissions, we can avoid a catastrophic two degrees Celsius (3.6 degrees F) warming of the planet, and we will most likely avert any additional increases in QRA events. The safest (and most cost-effective) path forward is to immediately curtail fossil-fuel burning and other human activities that elevate greenhouse gas concentrations.

It is worth noting that the world has to make decisions under uncertainty. Some simulations indicate much bigger (more than threefold) increases in QRA events, whereas others actually show decreases. The spread arises in large part from the different ways the climate models treat aerosols. Will the predictions converge? We do not yet know. Arguably, the wisest path forward, given the uncertainty and the huge potential risk if the worst-case scenario bears out, is to strongly reduce emissions.

Of course, it would be useful to reduce the uncertainties. Doing so comes down, at least in part, to the honing of physics. In this case, it is the physics of aerosols and their scattering of sunlight—the electromagnetic waves emanating from the sun. Once again this calls on understanding the physics of wave behavior. We have come full circle. SA

MORE TO EXPLORE

Influence of Anthropogenic Climate Change on Planetary Wave Resonance and Extreme Weather Events. Michael E. Mann et al. in *Scientific Reports,* Vol. 7, Article No. 45242; March 27, 2017.

The Influence of Arctic Amplification on Mid-latitude Summer Circulation. D. Coumou et al. in *Nature Communications,* Vol. 9, Article No. 2959; August 20, 2018.

Projected Changes in Persistent Extreme Summer Weather Events: The Role of Quasi-Resonant Amplification. Michael E. Mann et al. in *Science Advances,* Vol. 4, No. 10, Article No. eaat3272; October 2018.

FROM OUR ARCHIVES

The Jet Stream Is Getting Weird. Jeff Masters; December 2014.

scientificamerican.com/magazine/sa

BIOLOGY

UNTANGLING THE GENOME

New discoveries on ancient loops in DNA offer clues into gene regulation

By Erez Lieberman Aiden

Illustration by Traci Daberko

BECAUSE I FIND IT HARD TO RELATE TO SOMETHING AS SMALL as the structure of the human genome, I like to imagine it scaled up a millionfold. At this size, each DNA molecule—a chromosome—is as wide as a ramen noodle. Laid end to end, all 46 of the scaled-up chromosomes that compose a cell's genome would stretch from New York to Kansas City, although they instead fold up to fit inside a structure the size of a house—the cell nucleus. Collectively, the 46 chromosomes contain two sets of roughly 20,000 genes. Each gene spells out a coded message telling the cell how to make a particular protein; at the millionfold scale, a gene is as long as a car.

IN BRIEF

The author and his colleagues have shown that the human genome's DNA forms some 10,000 loops in our cells. The cells of mice and other creatures have many of the same loops.

More recently, the team figured out how the loops form. They are produced by biological machinery that operates something like the sliding buckles on backpack straps that are used to adjust their length.

These loops seem to play a role in regulating the activity of genes, although new findings raise the possibility they may have another, as yet undiscovered purpose.

Peering into the nucleus, you would see the DNA doing a lot of wiggling. Back when I was a Ph.D. student about a decade ago, I was stirring the ramen noodles in my dinner and wondering how the genome, unlike my noodles, avoided tangling into a mess that would prevent its crucial genetic messages from being sent.

In 2014 my colleagues and I contributed one piece of the answer to this question, adding to a growing realization that the structure of the genome inside the nucleus is far from random. Our team at the Baylor College of Medicine, led by my students Suhas Rao, Miriam Huntley and Adrian Sanborn, found that the human genome folds in a way that forms about 10,000 loops. These loops obey a simple code, hidden in the sequence of the genome itself. They turn out to be ancient structures; many of the same loops occur in mice, a shared legacy from an ancestral species that lived more than 60 million years ago. This persistence through time suggests that the loops are important to survival.

The loops seem to help control gene activity. All cells have the same genes, but if the patterns of activity did not differ, the body could not exist: a heart muscle cell would be no different from a brain cell. Just how these distinctive patterns are orchestrated has been a puzzle. Loops now appear to be one of the pattern controllers, a conductor of the genetic orchestra, influencing when particular genes become active enough to affect cell function.

As we continue to explore the loops, we expect to better understand gene regulation and to find clues about how many diseases arise. More recently, we and others have figured out how these loops form, dancing an elegant tango that keeps the genome tangle-free.

FACEBOOK FOR THE GENOME

MY MUSINGS ABOUT entangled DNA related to a larger question: How does the 3-D arrangement of DNA in the cell nucleus influence gene activity? Since the late 1970s evidence had been piling up, indicating that small segments of DNA, known as enhancers, were needed to activate genes. Biologists had also learned that enhancers could lie very far from their target genes in a string of DNA. To trigger a gene's "on" switch—a stretch of DNA adjacent to the gene known as a promoter—the string would presumably have to loop back onto itself, bringing the enhancer close to the promoter. But was the presumption correct? I became captivated by this problem and could think of only one way to settle it: find all the loops.

Conceptually the plan to do so was simple. If two people hang out especially often, it is logical to assume that they are friends. Similarly, we reasoned, if two stretches of DNA ("loci") that are far apart along the chromosome tend to hang out especially often, the DNA has probably folded into a loop. What we needed was a way to measure how frequently bits of the genome interact with one another: to build something like Facebook but for the human genome.

To turn our idea into reality, we adapted a method described in 1993 by Katherine Cullen, then at Vanderbilt University, and her colleagues. At that time, the genome had confounded all known forms of imaging: like a bad portrait subject, the wiggling chromosomal noodles refused to sit still. But Cullen made the jittery chromosomes work to her advantage. As chromosomes jiggled, she knew, different bits of the genome would bump into one another. Bits that were in pretty close proximity in 3-D would bump into one another a lot; bits that were far apart would touch only rarely. So if you could measure the bump frequencies, you could figure out which parts of the genome were close in 3-D space.

To measure this bump frequency, Cullen and her colleagues developed what they called the nuclear ligation assay (NLA). In essence, you take cells and, without destroying their nuclei, stabilize their genomes. Then you send in an enzyme to cut the DNA into tiny pieces and deploy a protein that fuses the ends of two nearby fragments, forming a single strand. Finally, you examine the sequence of DNA base pairs (the paired letters of the DNA code that form the "rungs" of DNA's familiar "ladder") in the collection of fused fragments. If, in cell after cell, you see fusions of a particular pair of DNA bits that did not originally sit next to each other on a chromosome (known as ligation junctions), you can conclude that the two DNA bits often come near to each other in the 3-D space of the cells' nuclei.

Cullen's insight, published in the journal *Science,* allowed her to demonstrate that two bits of DNA bookending a specific long stretch of DNA bumped into each other far more often than chance would predict. In other words, the DNA formed a loop.

Back in 1993, experiments using the nuclear ligation assay were hard to perform. Fortunately, by the time I saw Cullen's paper as a graduate student in the mid-2000s, there was a serviceable human genome reference, and DNA sequencing was becoming extremely cheap. I and three others at the Broad Institute of the Massachusetts Institute of Technology and Harvard University—Chad Nusbaum, Andreas Gnirke and Eric Lander—sketched out an approach that would analyze the contact frequency not of a single pair of DNA positions but of every pair of positions in the entire genome at the same time. It would also allow us to pinpoint exactly where each half of each ligation junction came from.

We decided to base our new method on a variant of Cullen's procedure that had been developed by Job Dekker of the University of Massachusetts Medical School. Rather than using intact cell nuclei, as Cullen had, Dekker blew the nucleus apart and performed the crucial ligation steps in an extremely dilute solution. This modification, which Dekker had popularized and dubbed "chromosome conformation capture," or "3C," was believed to yield a more reliable estimate of bump frequency.

Next, we added a few steps to 3C. Before gluing fragments together, we would attach easily detectable labels to the ends of the shattered DNA—to mark the spot where two nearby bits became joined. After this step, we would cut the glued fragments into smaller pieces and pull out only the stretches bearing the labels; these bits would contain pure ligation junctions. Working with Dekker, his then postdoctoral fellow Nynke van Berkum and Louise Williams of the Broad Institute, we found that we could identify millions of contacts all at once. I called the method "Hi-C," a play on "3C" and the name of one of my favorite drinks as a child. We published the method in 2009.

Our very first Hi-C maps of whole genomes showed that chromosomes, despite all their wiggling, were not folding up into a random jumble inside the nucleus. Instead each chromosome was partitioned into domains: stretches of DNA containing segments that made frequent contact with one another. Loci in one domain interacted with loci in other domains less frequently. What is more, our Hi-C data revealed that each of the domains sat within one of two larger spatial neighborhoods in cell nuclei. We called these neighborhoods "compartments" and labeled them A and B.

We found that the A compartment was rich in markers of genetic activity, such as messenger RNAs, which are molecules that genes send off to tell the rest of the cell what to do. The B compartment was more densely packed and was largely inactive. When the domains turned on or off, they moved from one compartment to the other. (Today we know that cell nuclei contain multiple A and B subcompartments.)

The discovery of this dynamic compartmentalization excited us because it confirmed that the genome's large-scale 3-D structure was not random but instead intimately associated with gene activity. But I was disappointed that one folding feature never seemed to appear in the Hi-C data: loops!

Hi-C data are often represented as a heat map: a plot showing how frequently two loci in a chromosome form contacts with each other. In such plots, the contact frequency between two loci is indicated by the brightness of the spot on the x and y axes, representing the intersection of the loci. A loop should manifest as an unusually bright spot corresponding to the loop's two anchor points. But we did not see any such peaks in brightness. If we could not show that loops were forming, we could not explore whether enhancers activated genes by physically coming into close proximity with promoters.

Erez Lieberman Aiden is director of the Center for Genome Architecture at the Baylor College of Medicine and Rice University.

To measure how frequently bits of the genome interact, we needed to build something like Facebook but for the human genome.

MAKING A LOOP MAP

THIS PROBLEM STUMPED us for the next three years. Then, in 2012, Rao and Huntley figured out what had gone wrong. They realized that one aspect of Hi-C—destroying cell nuclei before ligation—disrupted fine structures such as loops. So they set out to develop an updated Hi-C method that kept nuclei intact during ligation.

The new approach, called in situ Hi-C, made a huge difference. In studies of white blood cells, Rao and Huntley found that bright peaks now appeared all over our heat maps, each representing a putative loop. But it had now been six years since I had started working to map the loops; I no longer believed my own eyes. My team and I worried that we might be seeing things in the data that were not really there.

To make sure I was not dealing with confirmation bias, I brought the maps home to my son, Gabriel, who was then three. "Do you see a red dot?" "Yes," he said. "Can you point at it?" He could.

We had it: a map showing 10,000 loops, spread out across the human genome. We checked to see whether the loops linked gene promoters and enhancers. They often did.

In a further test, we compared our blood cell maps with new ones for a different kind of cell—from the lung. We saw many of the same loops, but we also saw new connections that we presumed involved different enhancers and different target genes. These changes in the looping pattern suggested that loops might be involved in regulating the genes that give a cell its distinctive identity.

We wondered if looping was unique to humans or if the same loops were present in other organisms. So we made a map of the loops in mouse cells and found that half the loops were present at the corresponding position in the human genome. These shared loops had been conserved over at least 60 million years of evolution, from ancestral creatures that roamed the earth long before the Colorado River began to carve out the Grand Canyon.

LOOPY LOGIC

ONE INTERESTING implication of our data was that loops are not static: they seemed to constantly arise, come apart and form again. Naturally we wanted to know how this worked.

We suspected that hundreds of proteins were involved. The data, however, told a different story. In loop after loop, two protein factors stood out. One, named CTCF, had been discovered by Victor Lobanenkov and his colleagues in 1990. It contains 11 components called zinc fingers that allow CTCF to bind very tightly to certain spots on DNA. The second factor, cohesin, discovered in 1997 by Kim Nasmyth, now at the University of Oxford, is a ring-shaped complex made up of multiple proteins. It was thought that two cohesin rings might link up and function together, with each ring in the pair encircling DNA and sliding on it freely, like a ring on a necklace.

Seeing these proteins was not a total surprise: many earlier studies had suggested their possible involvement in genome folding, although such a ubiquitous role at loop anchors—especially at loops linking promoters and enhancers—was unexpected.

Then we stumbled onto something truly weird. Rao, Huntley and I had asked Ido Machol, a new computational scientist in the laboratory, to study the distribution of histone proteins (which help to package DNA inside the nucleus) near CTCF molecules. Machol noticed that there were more histone proteins immediately outside of loops than immediately inside, as though the histones somehow knew where a loop was positioned relative to the CTCF molecules. I suspected that the finding just reflected a bug in Machol's code. But as the weeks passed, Machol did not find any bugs.

We began to look for a biological explanation. In the original paper describing the discovery of CTCF, Lobanenkov had shown that CTCF does not attach at arbitrary positions on DNA. Instead it always binds to a particular DNA word—a specific sequence of roughly 20 bases, called a motif. Because DNA is a double helix, it has two strands. Motifs can appear on either strand, pointing toward either terminus of the vast DNA noodle. The relative orientation of DNA motifs is often random, like a

The Loopy Genome

Under a microscope, a cell's genome—its collection of chromosomes—resembles a chaotic jumble of noodles. Yet the arrangement is far from random. For instance, finer resolution than is shown below would reveal that the genome folds into about 10,000 loops that do not become entangled with one another. Recent work has revealed a key loop-forming process, called extrusion (*top right*). The looping helps to determine which genes get expressed, or activated, in different cells (*bottom right*)—thereby influencing the functions the cells perform.

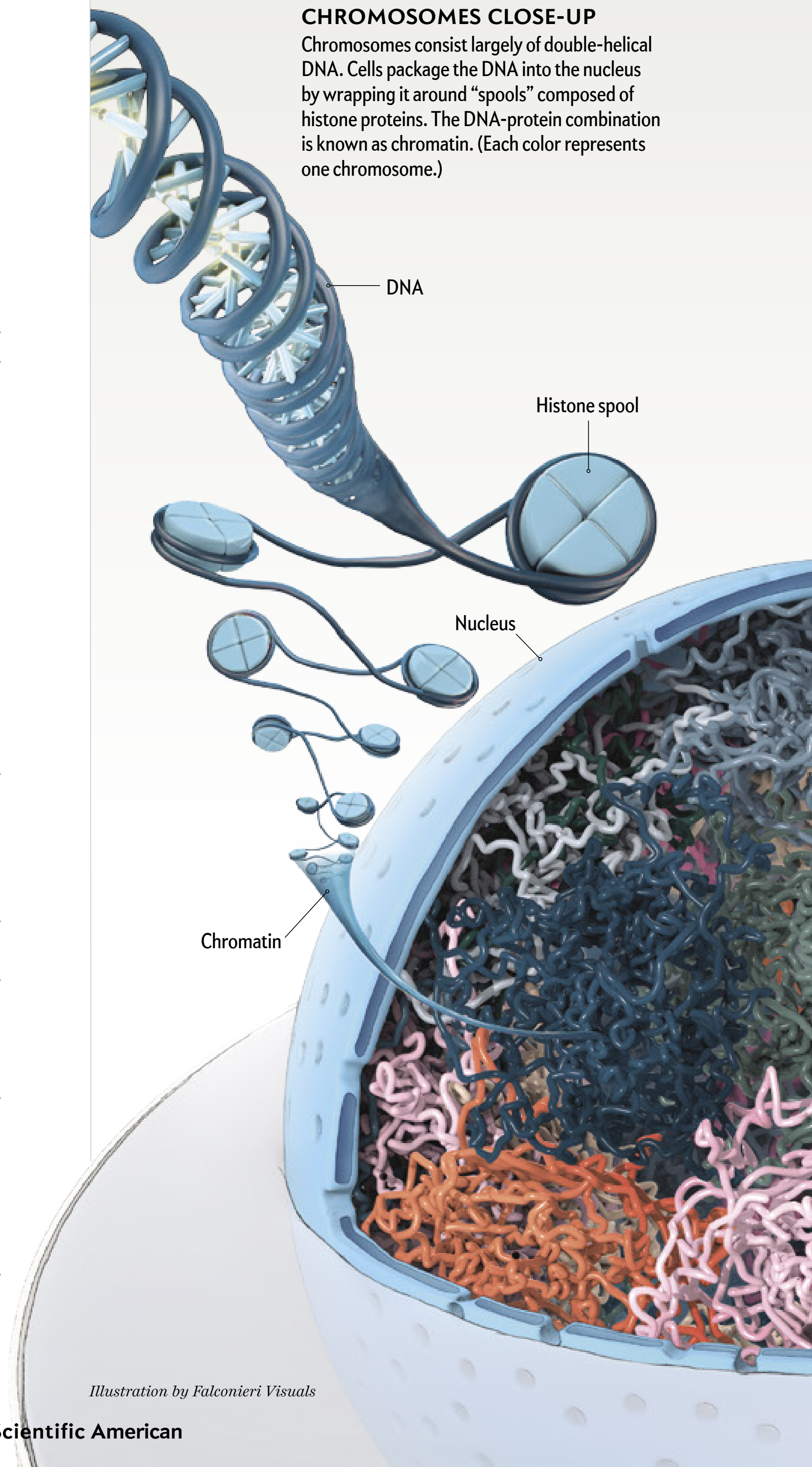
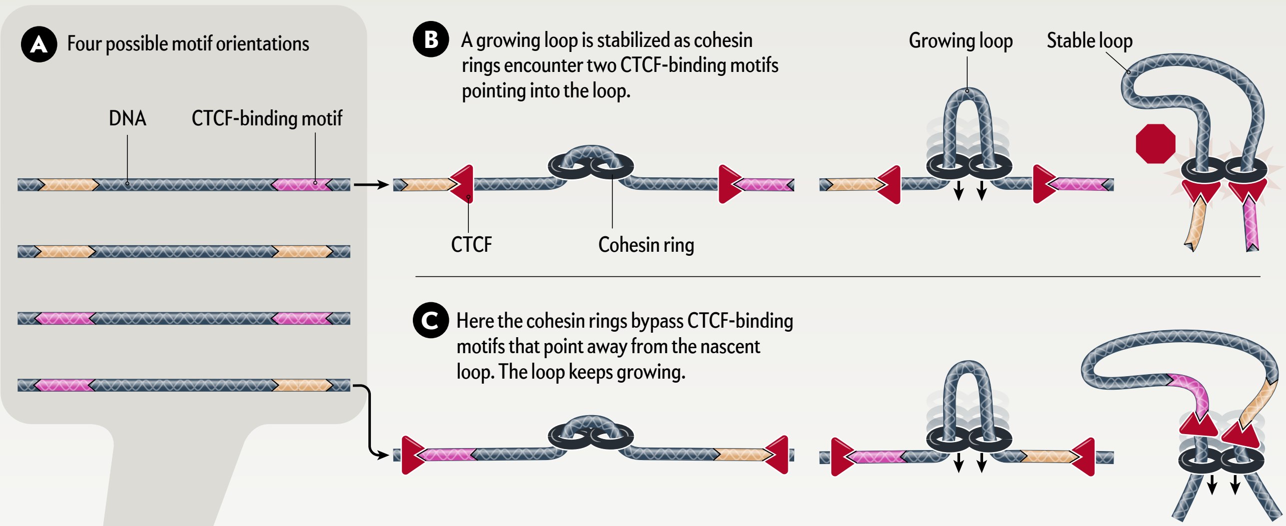


Illustration by Falconieri Visuals

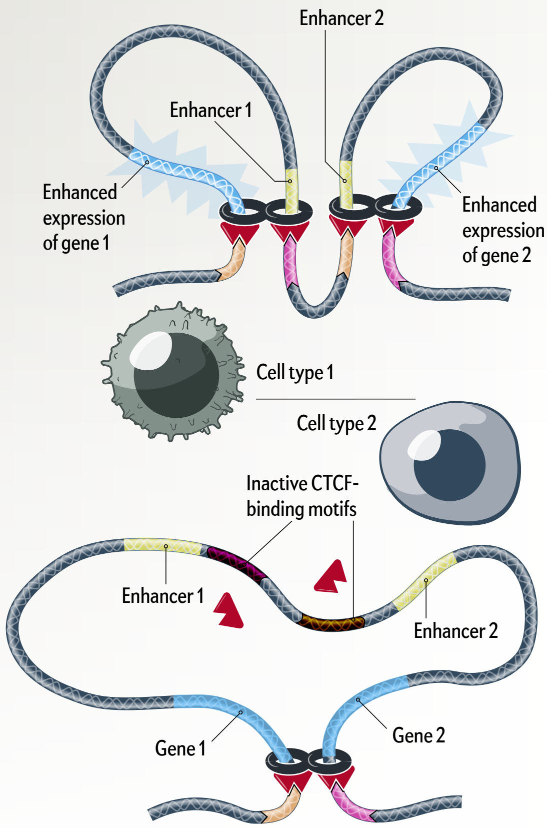
HOW LOOPS FORM

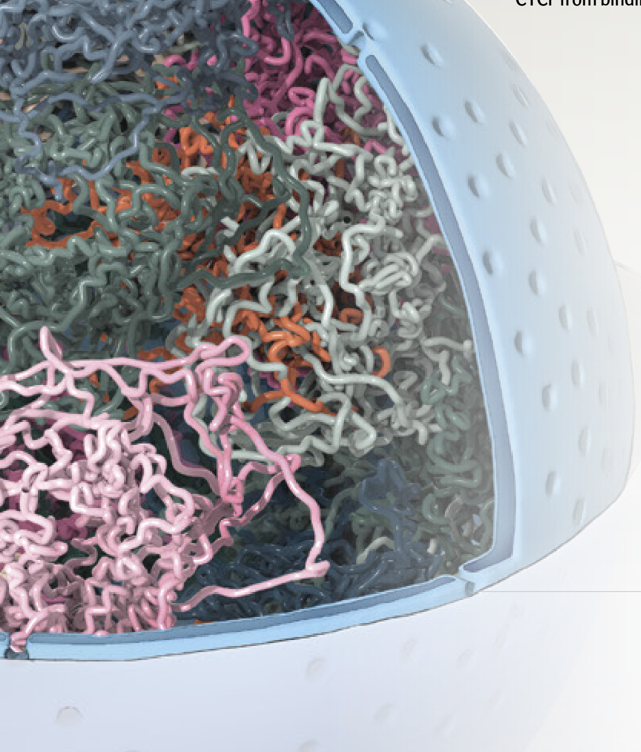
Loop extrusion begins when an “extrusion complex” lands on DNA. As two tethered subunits of the complex, which include a ring-shaped structure called cohesin, slide in opposite directions, the loop grows. A protein called CTCF can arrest the loop’s growth—under a specific condition. CTCF binds to a particular sequence in the DNA that points in one of two directions **A**. When a cohesin ring encounters a CTCF bound to a motif that points into the loop, the subunit will stop in its tracks. If it meets a CTCF pointing the other way, it keeps going. If both rings meet inward-pointing CTCF proteins, they will both stop, anchoring the loop in place **B**. In any other orientation, the loop will continue to grow **C**.



WHY LOOPING MATTERS

To function properly, certain genes need to come into contact with a DNA segment called an enhancer. But enhancers often sit far from their corresponding genes. Looping can solve that problem by bringing enhancers and their genes close together (*top*). All cells have the same genes and the same CTCF-binding motifs, but cells that do not need particular genes can suppress those genes by removing loops (*bottom*), such as by deactivating CTCF-binding motifs. This prevents CTCF from binding to them.





coin flip: there is a 50 percent chance that a typical motif points toward one terminus and a 50 percent chance that it points towards the other. So we expected, at first, to see random orientations of CTCF-binding motifs at loop anchors.

We wondered if the CTCF-binding motifs at loop anchors were giving histones a clue to where they should connect to the DNA near the motifs. We checked, and, to our astonishment, the two tiny CTCF-binding motifs—even if they were separated by millions of DNA letters in unfolded DNA—always pointed toward each other and into the loop, in what we named the convergent orientation. This convergent rule explained how the histones could know where to position themselves—they just had to determine which way the CTCF-binding motif was pointing.

But in resolving one puzzle, the convergent rule had created a second, far greater mystery. The nonrandom orientation of the motifs defied expectations.

Gene regulation may be a side gig for loops; perhaps their main function in cells is something else entirely.

For perspective, let us again scale up the genome by a factor of one million. Now the motifs are each five millimeters long and separated by as much as a kilometer of genomic noodle. And yet, somehow, as if guided by a magical compass, the motifs at opposite ends of a stretch of loop-forming DNA always point at each other. Like any good magic trick, the convergent rule seemed physically impossible. It also contradicted the accepted view of how loops probably formed.

At the time, nearly everyone—ourselves included—believed that genome loops formed by diffusion. In that scheme, a protein needed for forming a loop binds at one end of a stretch of DNA. Next, another loop-enabling protein binds at the other end. Then, as usual, the DNA wiggles. Finally, if the wiggling brings the two proteins together, they form a physical link, thereby creating a loop. The trouble is, the entire DNA chain has so much room to wiggle that, if the diffusion model were correct, the relative orientation of the CTCF-binding motifs could not matter. And yet we were seeing convergence. Within the year two teams, one led by Suzana Hadjur of University College London and one led by Yijun Ruan of the Jackson Laboratory, confirmed the convergent rule in their own data sets. The rule was here to stay, and the loops we saw could not be forming by diffusion.

DRIVE-BY LOOPING

IF LOOPS DID not form by diffusion, then how did they arise? And what were the roles of CTCF and cohesin? We did what we always do in case of a genome-folding emergency: we started playing with our headphone cables.

I am pretty sure that most people who work on genome folding keep a long, noodlelike object handy: a piece of yarn, a plastic tube. When you get stuck on a hard problem, you pull this object out and futz around. One day Rao and I were passing the headphones back and forth as we explored possible models of loop formation. Suddenly it occurred to us that the answer was not in our headphones; it was on our backpacks.

Imagine the apparatus that adjusts the length of backpack straps. This object, called a tri-glide, consists, more or less, of two rings that are physically attached to each other. The strap comes in the first ring and goes out the second. If you want to adjust the strap length, you pull some of the strap through one of the rings and start making a loop. And you can keep making the loop bigger until you reach a bit of folded-over material that stops you.

Perhaps pairs of cohesin rings worked like tri-glides? At first, they attach anywhere on the genome, with the DNA going in one ring and out the other. But then, the two rings slide in opposite directions (one to the left along the linear molecule and one to the right), extruding a growing loop as they go. They do not slide forever, though. Eventually one approaches a site where a CTCF molecule is bound. If the underlying CTCF-binding motif is pointing toward the approaching ring, then the sliding ring stops on contact. But if the motif is facing the other way, the cohesin ignores it and keeps going. (In this way, a CTCF-binding motif is like a stop sign for cohesin traffic: if the sign is facing you, you stop; if the sign is facing the other way, you do not.) The second ring keeps going until it, too, arrives at an inward-pointing CTCF-bound motif. The loop is now complete.

If cohesin rings actually worked that way, then loops would form only between pairs of CTCF-binding motifs that obeyed the convergent rule. We quickly realized that this extrusion process would provide a crucial benefit to cells. If loops formed by diffusion, then pairs of loops in a chromosome could easily become entwined, leading chromosomes to form knots and get entangled with one another. This would make it hard for genes to operate properly and could prevent chromosomes from separating when cells need to divide. In contrast, loops produced by extrusion do not form knots or entanglements—which is why your backpack straps do not get knotted no matter how much you adjust their length with a tri-glide.

The model was wild speculation. It made many basic assumptions for which we had no shred of direct evidence, such as the notion that cohesin could slide along DNA. We worried we were crazy. But as we read through the literature on cohesin, we realized Nasmyth himself had proposed back in 2001 that cohesin might extrude DNA. Sanborn ran detailed simulations that closely recapitulated the data in our maps. And when Rao experimented on real DNA, the looping changed exactly in the ways that Sanborn's model predicted.

Deleting a CTCF-binding motif at a loop anchor eliminated the loop. Flipping a motif's orientation made the original loop disappear but caused another loop to form on the other side. Adding a CTCF-binding motif—so long as it pointed the right way—also led to the formation of a new loop. We then found that we could add and remove loops to a genome at will.

We quickly wrote and submitted a paper on our extrusion model and the loop-engineering experiments that we had performed to test it. The field was heating up, and within a few weeks of one another in late 2015, our lab and two other teams published papers demonstrating that this kind of 3-D genome surgery worked. Similarly, three teams—ours, one at Emory University and one at M.I.T.—reported that the convergent rule favored a model in which loops form by extrusion. At last, the scientific community was starting to untangle the logic of loops.

Progress continued, now at a breakneck pace. At the Gladstone Institutes, Benoit Bruneau and his colleagues showed that interfering with CTCF greatly weakened loops. At the European Molecular Biology Laboratory, Francois Spitz and his co-workers got a similar result by eliminating a protein thought to load cohesin onto DNA. At the Netherlands Cancer Institute, Benjamin Rowland's team showed that eliminating a factor that removes cohesin from DNA led to bigger loops, presumably because cohesin could now slide for longer. And in our lab, Rao showed that by degrading cohesin itself, we could eliminate all the cohesin loops within minutes.

But we all longed for direct confirmation: seeing extrusion in action. Finally, in April 2018, Cees Dekker of the Delft University of Technology in the Netherlands and his colleagues did just that. By using yeast's condensin—a complex of proteins that is closely related to cohesin—they made a microscopic movie that many of us in the field of nuclear architecture will never forget. First you see a ribbon of DNA. Then condensin lands, forming a little nodule of DNA. The nodule grows and grows until the viewer realizes what it really is: an extruded loop.

TURNING TOWARD HEALTH

AS THE MECHANISMS and rules for loop formation emerge, the importance of looping for health and disease is becoming clearer. For instance, Frederick Alt of Harvard University and his colleagues have begun to articulate the role that looping plays in antibody production. Your body makes antibodies to pathogens it has never encountered before by cutting and pasting segments of antibody genes. Alt's team found that this process is accomplished by forming multiple CTCF-anchored loops and then cutting them out.

The lab of Stefan Mundlos of the Max Planck Institute for Molecular Genetics in Berlin has shown that modifying a single CTCF-binding motif in mice causes the animals to develop an abnormal number of digits in their paws. Humans with the corresponding change did not have five fingers. And Rafael Casellas of the National Institutes of Health has shown that disrupting CTCF-binding motifs in a mouse plasmacytoma—a kind of cancer—could slow the tumor's growth by 40 percent.

Yet as the notion of loop extrusion has gained credence, deeper theories about the role that loops play in gene regulation have been coming apart. For decades scientists thought that loops worked like switches: when the loop between an enhancer and a promoter was present, the corresponding gene turned on. Therefore, we expected that when we removed cohesin from cells, gene expression would go haywire, with thousands of genes changing their activity level. As predicted, many genes did change. But the changes were fairly small. Loops—at least those formed by extrusion—are not binary switches after all. Instead they seem to function more like knobs, turning gene activity up a little or down a little, fine-tuning a cell's supply of different proteins.

In other words, nature has thrown us for a loop. We thought that we understood the rules of the game, that loops turn genes on. But now that we have seen loops in action, we must concede that our vision was too simplistic. It is even possible that gene regulation may be a side gig for loops; perhaps their main function in cells is something else entirely.

Like any explorers in uncharted territory, we need better maps. My colleague Ruan and I at the NIH's Encyclopedia of DNA Elements (ENCODE) Project are currently working with our colleagues to create the first atlas of looping in the human genome, mapping the loops in tissues across the human body. Our groups, and many others, have also joined together in the 4D Nucleome consortium that is developing new methods for tackling these problems. And Olga Dudchenko, a postdoc in my lab, has created the DNA Zoo—a consortium of academic labs, zoos and aquariums around the world that is trying to assemble the genomes of hundreds of species, chronicling the evolution of loops across the tree of life.

For researchers the ending of one scientific story is always the beginning of another. Two billion years ago, before the emergence of the cell nucleus, the process of DNA extrusion arose. Why? Once more, into the loop. SA

MORE TO EXPLORE

Interaction between Transcription Regulatory Regions of Prolactin Chromatin. K. E. Cullen, M. P. Kladde and M. A. Seyfred in *Science,* Vol. 261, pages 2003–2006; July 9, 1993.

A 3D Map of the Human Genome at Kilobase Resolution Reveals Principles of Chromatin Looping. Suhas S. P. Rao et al. in *Cell,* Vol. 159, No. 7, pages 1665–1680; December 18, 2014.

Chromatin Extrusion Explains Key Features of Loop and Domain Formation in Wild-Type and Engineered Genomes. Adrian L. Sanborn et al. in *Proceedings of the National Academy of Sciences USA,* Vol. 112, No. 47, pages E6456–E6465; November 24, 2015.

Real-Time Imaging of DNA Loop Extrusion by Condensin. Mahipal Ganji et al. in *Science,* Vol. 360, pages 102–105; April 6, 2018.

FROM OUR ARCHIVES

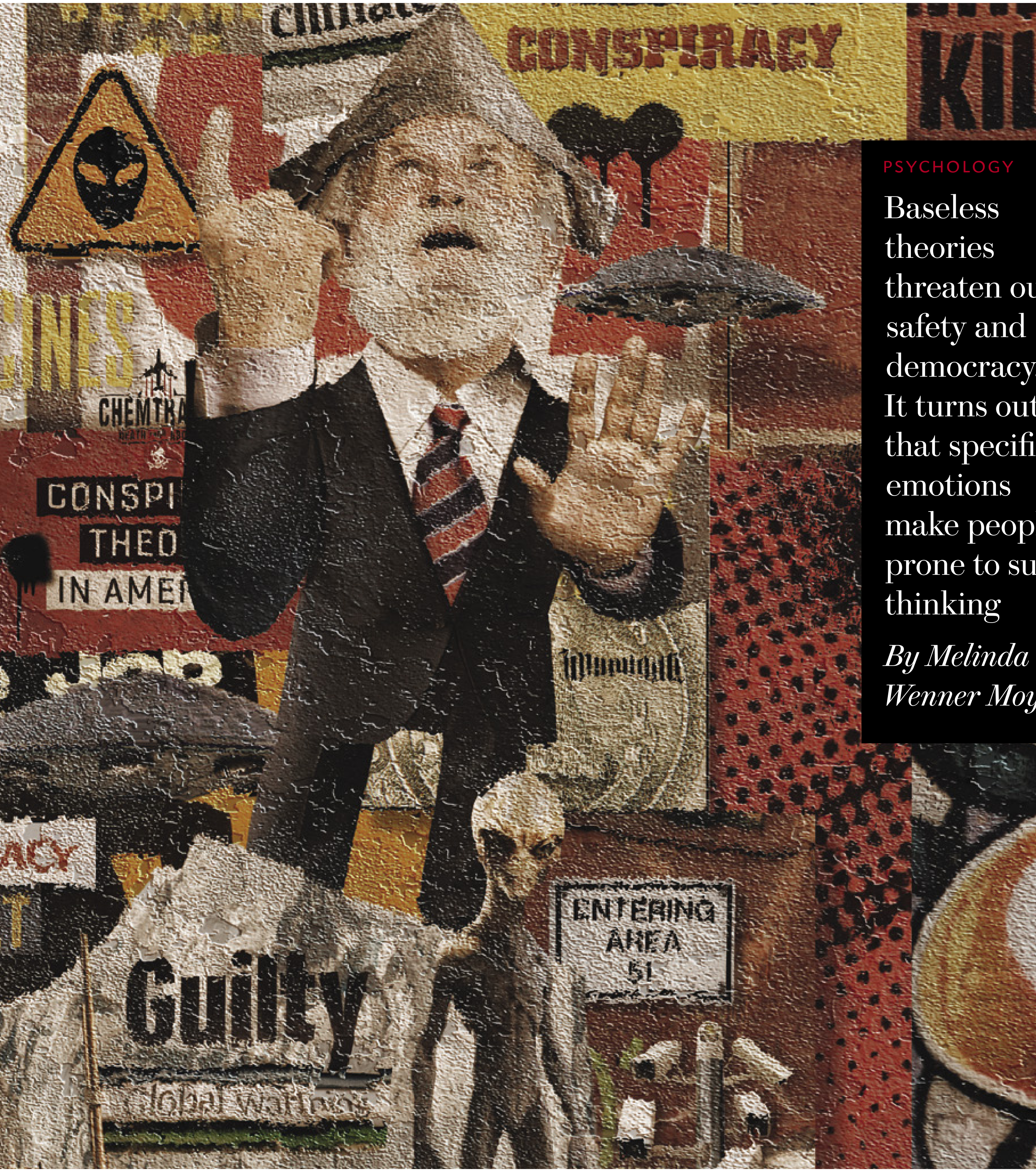
The Inner Life of the Genome. Tom Misteli; February 2011.

scientificamerican.com/magazine/sa

WHY WE BELIEVE CONSPIRACY

Illustration by Eddie Guy

THEORIES



PSYCHOLOGY

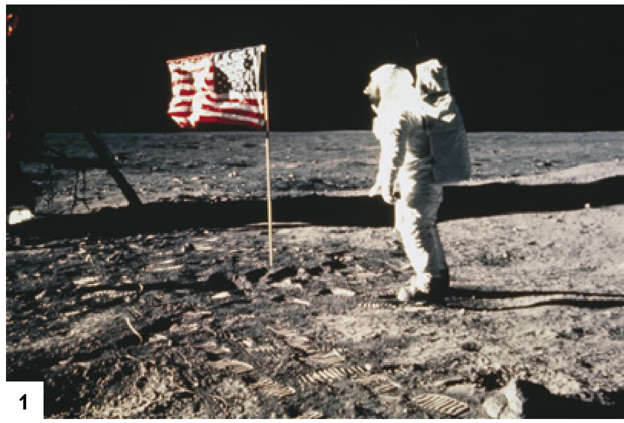
Baseless theories threaten our safety and democracy. It turns out that specific emotions make people prone to such thinking

By Melinda Wenner Moyer

STEPHAN LEWANDOWSKY WAS DEEP IN DENIAL. ABOUT SIX YEARS ago the cognitive scientist had thrown himself into a study of why some people refuse to accept the overwhelming evidence that the planet is warming and humans are responsible. As he delved into this climate change denialism, Lewandowsky, then at the University of Western Australia, discovered that many of the naysayers also believed in outlandish plots, such as the idea that the *Apollo* moon landing was a hoax created by the American government. "A lot of the discourse these people were engaging in on the Internet was totally conspiratorial," he recalls.

Melinda Wenner Moyer is a contributing editor at *Scientific American*. She wrote about resurgent epidemics in the U.S. in the May 2018 issue.

Lewandowsky's findings, published in 2013 in *Psychological Science,* brought these conspiracy theorists out of the woodwork. Offended by his claims, they criticized his integrity online and demanded that he be fired. (He was not, although he has since moved to the University of Bristol in England.) But as Lewandowsky waded through one irate post after another, he discovered that his critics—in response to his assertions about their conspiratorial tendencies—were actually spreading new conspiracy theories *about him.* These people accused him and his colleagues of faking survey responses and of conducting the research without ethical approval. When his personal Web site crashed, one blogger accused him of intentionally blocking critics from seeing it. None of it was true.



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The irony was amusing at first, but the ranting even included a death threat, and calls and e-mails to his university became so vicious that the administrative staff who fielded them asked their managers for help. That was when Lewandowsky changed his assessment. "I quickly realized that there was nothing funny about these guys at all," he says.

The dangerous consequences of the conspiratorial perspective—the idea that people or groups are colluding in hidden ways to produce a particular outcome—have become painfully clear. The gunman who shot and killed 11 people and injured six others in a Pittsburgh synagogue in October 2018 justified his attack by claiming that Jewish people were stealthily supporting illegal immigrants. In 2016 a conspiracy theory positing that high-ranking Democratic Party officials were involved in a child sex ring involving several Washington, D.C., area restaurants incited one believer to fire an assault weapon inside a pizzeria. Luckily no one was hurt.

The mindset is surprisingly common, although thankfully it does not often lead to gunfire. More than a quarter of the American population believes there are conspiracies "behind many things in the world," according to a 2017 analysis of government survey data by University of Oxford and University of Liverpool researchers. The prevalence of conspiracy mongering may not be new, but today the theories are becoming more visible, says Viren Swami, a social psychologist at Anglia Ruskin University in England, who studies the phenomenon. For instance, when more than a dozen bombs were sent to prominent Democrats and Trump critics, as well as CNN,

IN BRIEF

False conspiracy theories can drive people to violence, as they did for the Pittsburgh synagogue shooter, and affect political activity.

Anxious people are especially drawn to conspiratorial thinking, experiments show, and the mindset is also triggered by a loss of control.

You can spot hallmarks of fake theories, such as internal contradictions in the "evidence" and contentions based on shaky assumptions, psychologists say.

PRECEDING PAGES: GETTY IMAGES (*illustration reference*); THIS PAGE: GETTY IMAGES (1) in October 2018, a number of high-profile conservatives quickly suggested that the explosives were really a "false flag," a fake attack orchestrated by Democrats to mobilize their supporters during the U.S. midterm elections.

One obvious reason for the current raised profile of this kind of thinking is that the U.S. president is a vocal conspiracy theorist. Donald Trump has suggested, among other things, that the father of Senator Ted Cruz of Texas helped to assassinate President John F. Kennedy and that Democrats funded the same migrant caravan traveling from Honduras to the U.S. that worried the Pittsburgh synagogue shooter.

But there are other factors at play, too. New research suggests that events happening worldwide are nurturing underlying emotions that make people more willing to believe in conspiracies. Experiments have revealed that feelings of anxiety make people think more conspiratorially. Such feelings, along with a sense of disenfranchisement, currently grip many Americans, according to surveys. In such situations, a conspiracy theory can provide comfort by identifying a convenient scapegoat and thereby making the world seem more straightforward and controllable. "People can assume that if these bad guys weren't there, then everything would be fine," Lewandowsky says. "Whereas if you don't believe in a conspiracy theory, then you just have to say terrible things happen randomly."

Discerning fact from fiction can be difficult, however, and some seemingly wild conspiracy ideas turn out to be true. The once scoffed at notion that Russian nationals meddled in the 2016 presidential election is now supported by a slew of guilty pleas, evidence-based indictments and U.S. intelligence agency conclusions. So how is one to know what to believe? There, too, psychologists have been at work and have uncovered strategies that can help people distinguish plausible theories from those that are almost certainly fake—strategies that seem to become more important by the day.

2 3 4

CONSPIRACY THEORISTS believe plots are behind many situations. Some hold that the *Apollo* moon landing was faked (*1*), others that the White House forced Supreme Court Justice Anthony Kennedy to retire (*2*), and others that Trump slogans on a mail bomber's van were put there to frame Republicans (*3*). The gunman who killed 11 synagogue members in 2018 claimed a Jewish group was undermining America (*4*).

BRENDAN SMIALOWSKI *Getty Images* (2); ALAMY (3); JEFF SWENSEN *Getty Images* (4)

THE ANXIETY CONNECTION

In May 2018 the American Psychiatric Association released the results of a national survey suggesting that 39 percent of Americans feel more anxious than they did a year ago, primarily about health, safety, finances, politics and relationships. Another 2017 report found that 63 percent of Americans are extremely worried about the future of the nation and that 59 percent consider this the lowest point in U.S. history that they can remember. These feelings span the political spectrum. A 2018 Pew Research Center survey found that the majority of both Democrats and Republicans feel that "their side" in politics has been losing in recent years on issues they find important.

Such existential crises can promote conspiratorial thinking. In a 2015 study in the Netherlands, researchers split college students into three groups. People in one group were primed to feel powerless. The scientists asked them to recall and write about a time in their lives when they felt they were not in control of the situation they were in. Those in a second group were cued in the opposite direction. They were asked to write about a time when they felt totally in control. And still others, in a third group, were asked something neutral: to describe what they had for dinner last night. Then the researchers asked all the groups how they felt about the construction of a new subway line in Amsterdam that had been plagued by problems.

Students who had been primed to feel in control were less likely than students in the other two groups to support conspiracy theories regarding the subway line, such as the belief that the city council was stealing from the subway's budget and that it was intentionally jeopardizing residents' safety. Other studies have uncovered similar effects. Swami and his colleagues, for instance, reported in 2016 that individuals who feel stressed are more likely than others to believe in conspiracy theories, and a 2017 study found that promoting anxiety in people also makes them more conspiracy-minded.

Feeling alienated or unwanted also seems to make conspiratorial thinking more attractive. In 2017 Princeton University psychologists set up an experiment with trios of people. The researchers asked all participants to write two paragraphs describing themselves and then told them that their descriptions would be shared with the other two in their group, who would use that information to decide if they would work with the person in the future. After telling some subjects that they had been accepted by their group and others that they had been rejected, the researchers evaluated the subjects' thoughts on various conspiracy-related scenarios. The "rejected" participants, feeling alienated, were more likely than the others to think the scenarios involved a coordinated conspiracy.

It is not just personal crises that encourage individuals to form conspiratorial suspicions. Collective social setbacks do so as well. In a 2018 study, researchers at the University of Minnesota and Lehigh University surveyed more than 3,000 Americans. They found that participants who felt that American values are eroding were more likely than others to agree with conspiratorial statements, such as that "many major events have behind them the actions of a small group of influential people." Joseph Uscinski, a political scientist at the University of Miami, and his colleagues have shown that people who dislike the current political party in power think more conspiratorially than those who support the controlling party. Recently in the U.S., a number of unproved conjectures have come from political liberals as conservatives have ascended to control the government. These include the charge that the White House coerced Anthony Kennedy to retire from the U.S. Supreme Court and the allegation that Russian president Vladimir Putin is blackmailing Trump with a video of him watching prostitutes urinate on a Moscow hotel bed.

When feelings of personal alienation or anxiety are combined with a sense that society is in jeopardy, people experience a kind of conspiratorial double whammy. In a study conducted in 2009, near the start of the U.S.'s Great Recession, Daniel Sullivan, a psychologist now at the University of Arizona, and his colleagues told one group that parts of their lives were largely out of their control because they could be exposed to a natural disaster or some other catastrophe and told another group that things were under their control. Then participants were asked to read essays that argued that the government was handling the economic crisis either well or poorly. Those cued about uncontrolled life situations and told their government was doing a bad job were the most likely to think that negative events in their lives would be instigated by enemies rather than random chance, which is a conspiratorial hallmark.

When feelings of personal alienation or anxiety are combined with a sense that society is in jeopardy, people experience a kind of conspiratorial double whammy, according to a study conducted near the start of the U.S.'s Great Recession.

While humans seek solace in conspiracy theories, however, they rarely find it. "They're appealing but not necessarily satisfying," says Daniel Jolley, a psychologist at Staffordshire University in England. For one thing, conspiratorial thinking can incite individuals to behave in a way that increases their sense of powerlessness, making them feel even worse. A 2014 study co-authored by Jolley found that people who are presented with conspiracy theories about climate change—scientists are just chasing grant money, for instance—are less likely to plan to vote, whereas a 2017 study reported that believing in work-related conspiracies—such as the idea that managers make decisions to protect their own interests—causes individuals to feel less committed to their job. "It can snowball and become a pretty vicious, nasty cycle of inaction and negative behavior," says Karen Douglas, a psychologist at the University of Kent in England and a co-author of the paper on work-related conspiracies.

The negative and alienated beliefs can also promote dangerous behaviors in some, as with the Pittsburgh shootings and the pizzeria attack. But the theories need not involve weapons to inflict harm. People who believe vaccine conspiracy theories, for example, say they are less inclined to vaccinate their kids, which creates pockets of infectious disease that put entire communities at risk.

TELLING FACT FROM FICTION

IT MAY BE POSSIBLE to quell conspiracy ideation, at least to some degree. One long-standing question has been whether or not it is a good idea to counter conspiracy theories with logic and evidence. Some older research has pointed to a "backfire effect"—the idea that refuting misinformation can just make individuals dig their heels in deeper. "If you think there are powerful forces trying to conspire and cover [things] up, when you're given what you see as a cover story, it only shows you how right you are," Uscinski says.

But more recent research suggests that this putative effect is, in fact, rare. A 2016 study reported that when researchers refuted a conspiracy theory by pointing out its logical inconsistencies, it became less enchanting to people. And in a paper published online in 2018 in *Political Behavior,* researchers recruited more than 10,000 people and presented them with corrections to various claims made by political figures. The authors concluded that "evidence of factual backfire is far more tenuous than prior research suggests." In a recent review, the researchers who first described the backfire effect said that it may arise most often when people are being challenged over ideas that define their worldview or sense of self. Finding ways to counter conspiracy theories without challenging a person's identity may therefore be an effective strategy.

Encouraging analytic thinking may also help. In a 2014 study published in *Cognition*, Swami and his colleagues recruited 112 people for an experiment. First, they had everyone fill out a questionnaire that evaluated how strongly they believed in various conspiracy theories. A few weeks later the subjects came back in, and the researchers split them into two groups. One group completed a task that included unscrambling words in sentences containing words such as "analyze" and "rational," which primed them to think more analytically. The second group completed a neutral task.

Then the researchers readministered the conspiracy theory test to the two groups. Although the groups had been no different in terms of conspiratorial thinking at the beginning of the experiment, the subjects who had been incited to think analytically became less conspiratorial. Thus, by giving people "the tools and the skills to analyze data and to look at data critically and objectively," we might be able to suppress conspiratorial thinking, Swami says.

Analytic thinking can also help discern implausible theories from ones that, crazy as they sound, are supported by evidence. Karen Murphy, an educational psychologist at Pennsylvania State University, suggests that individuals who want to improve their analytic thinking skills should ask three key questions when interpreting conspiracy claims. One: What is your evidence? Two: What is your source for that evidence? Three: What is the reasoning that links your evidence back to the claim? Sources of evidence need to be accurate, credible and relevant. For instance, "you shouldn't take advice from your mom about whether the yellow color under your fingernails is a bad sign," Murphy says—that kind of information should come from someone who has expertise on the topic, such as a physician.

In addition, false conspiracy theories have several hallmarks, Lewandowsky says. Three of them are particularly noticeable. First, the theories include contradictions. For example, some deniers of climate change argue that there is no scientific consensus on the issue while framing themselves as heroes pushing back against established consensus. Both cannot be true. A second telltale sign is when a contention is based on shaky assumptions. Trump, for instance, claimed that millions of illegal immigrants cast ballots in the 2016 presidential election and were the reason he lost the popular vote. Beyond the complete lack of evidence for such voting, his assumption was that multitudes of such votes—if they existed—would have been for his Democratic opponent. Yet past polls of unauthorized Hispanic immigrants suggest that many of them would have voted for a Republican candidate over a Democratic one.

A third sign that a claim is a far-fetched theory, rather than an actual conspiracy, is that those who support it interpret evidence against their theory as evidence *for* it. When the van of the alleged mail bomber Cesar Sayoc was found in Florida plastered with Trump stickers, for instance, some individuals said this helped to prove that Democrats were really behind the bombs. "If anyone thinks this is what a real conservative's van looks like, you are being willfully ignorant. Cesar Sayoc is clearly just a fall guy for this obvious false flag," one person posted on Twitter.

Conspiracy theories are a human reaction to confusing times. "We're all just trying to understand the world and what's happening in it," says Rob Brotherton, a psychologist at Barnard College and author of *Suspicious Minds: Why We Believe in Conspiracy Theories* (Bloomsbury Sigma, 2015). But real harm can come from such thinking, especially when believers engage in violence as a show of support. By looking out for suspicious signatures and asking thoughtful questions about the stories we encounter, it is still possible to separate truth from lies. It may not always be an easy task, but it is a crucial one for all of us. SA

MORE TO EXPLORE

NASA Faked the Moon Landing—Therefore, (Climate) Science Is a Hoax: An Anatomy of the Motivated Rejection of Science. Stephan Lewandowsky et al. in *Psychological Science,* Vol. 24, No. 5, pages 622–633; May 2013.

The Influence of Control on Belief in Conspiracy Theories: Conceptual and Applied Extensions. Jan-Willem van Prooijen and Michele Acker in *Applied Cognitive Psychology,* Vol. 29, No. 5, pages 753–761; September/October 2015.

Putting the Stress on Conspiracy Theories: Examining Associations between Psychological Stress, Anxiety, and Belief in Conspiracy Theories. Viren Swami et al. in *Personality and Individual Differences,* Vol. 99, pages 72–76; September 2016.

Suspicion in the Workplace: Organizational Conspiracy Theories and Work-Related Outcomes. Karen M. Douglas and Ana C. Leite in *British Journal of Psychology,* Vol. 108, No. 3; pages 486–506; August 2017.

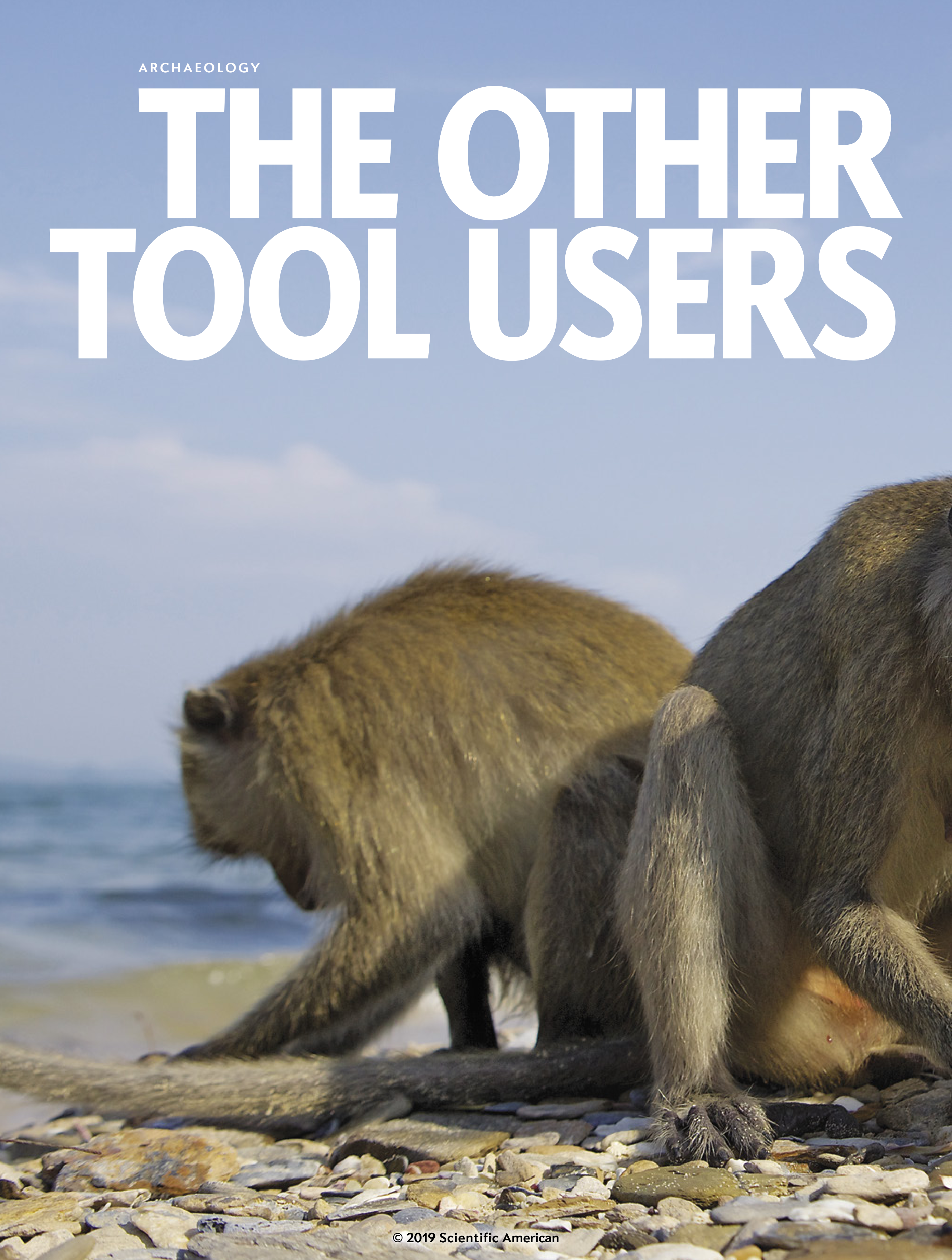
FROM OUR ARCHIVES

What a Hoax. Sander van der Linden; *Scientific American Mind,* September/October 2013.

scientificamerican.com/magazine/sa

ARCHAEOLOGY

THE OTHER TOOL USERS



Excavations of stone tools left behind by nonhuman primates are illuminating the origins of technological innovation

By Michael Haslam

WILD BURMESE long-tailed macaques use stone tools to open shellfish on a beach in Thailand.

THE TIDE IS RISING FAST, BUT THE MONKEYS don't seem to mind. They bicker and loll on the rocks and mangroves farther up the shore, munching quietly on an oyster or enjoying a gentle grooming. The younger ones make a game of jumping from a tree branch into the warm, clear sea below. Like everyone along this coastal stretch of rural Thailand, they live in tune with the daily tidal rhythms.

Michael Haslam is an independent researcher based in London. His work focuses on the evolution of technology in humans and other species.

IN BRIEF

Archaeologists have traditionally focused solely on the recovery of material culture belonging to members of the human family.

But some nonhuman primates, as well as other species, use tools.

In recent years researchers have begun to unearth the archaeological records of these other creatures.

Such investigations stand to elucidate the factors that governed the rise of human and nonhuman technology.

I, however, am quite concerned about the incoming water. It's a balmy December day in 2013, and I'm crouched on the beach beside a neat square hole, reaching as far down as I can to scrape out another trowel-full of damp sand. The hole is only half a meter on each side, but it has taken hours to dig, ever since the overnight high tide receded. Careless movement will collapse the entire thing in on itself, which means that rushing is not an option.

This is an archaeological dig, and it looks much like you might imagine, with buckets, sieves, strings, levels, collecting bags and measuring tapes strewn about. Yet the ancient objects that drew me here to the small island of Piak Nam Yai in Laem Son National Park are not typical archaeological finds. I am not looking for coins, or pottery, or the remains of an old settlement, or long-lost human culture. Instead I am after bygone traces of the monkey culture that is on full display up the beach.

I am, at least itinerantly, a primate archaeologist: I use traditional archaeological methods to understand the past behavior of a variety of primate species. To be honest, the image that I get when I use this phrase is of Dr. Cornelius, the chimpanzee in the original 1968 film *Planet of the Apes* who controversially unearths evidence that humans were not always mute beasts. He is charged with heresy for his discovery, and although it is not discussed in the film, I strongly suspect that he also loses his funding. Cornelius resonates with me because my colleagues and I have recently been building a new scientific field that directly mirrors his work. For more than 150 years the term "archaeology" has described the scientific study of physical remains of a strictly human past. In that time, there have emerged a multitude of subfields focused on specific times, places or methods, but they have all had one central theme: understanding people. Nonhuman animals were a part of archaeological study but only as food, transport, pets or parasites. They orbited our world.

Certainly this focus has produced extraordinary achievements. For instance, in 2015 Sonia Harmand of Stony Brook University and her team stretched the known record of human behavior back to more than three million years ago when they found stone tools left by a distant ancestor at the site of Lomekwi in Kenya. (The fact that these objects are made of stone is not a coincidence, by the way. For the vast majority of that multimillion-year record, stone tools have been the only cultural artifacts that have survived to guide our interpretations of our origins—objects made from more perishable materials have been lost to time.)

By turning the spotlight on our closest evolutionary relatives—monkeys and apes—primate archaeology aims to build a richer framework for understanding this long history of human technological development. Humans and our direct ancestors are primates, too, of course, and illuminating our own evolutionary journey is still a central goal of this research. Placing the surprisingly complex rise of human technology into its wider biological context will give us a better grip on those features that derive from our shared primate heritage and those that are truly unique to us.

ABSENCE OF EVIDENCE

A BIG PART OF WHY archaeologists have traditionally focused exclusively on the recovery of human material culture is that for a long time, researchers thought that humans alone use and produce tools. Primatologist Jane Goodall was the first to show otherwise through her studies of chimpanzees in the 1960s. Anthropologist Louis Leakey had been discovering a variety of fossil humans and stone tools in ancient lakeshore environments in eastern Africa, and he wanted to know what kinds of activities the human ancestors there might have engaged in. So Leakey recruited Goodall and sent her to what is now Gombe Stream National Park, on the eastern shore of Lake Tanganyika in Tanzania, to see how the chimpanzees there behaved. Although her eventual discoveries had little to do with the actual lake, her observations of chimpanzees making and using tools to obtain food forever changed our perception of primate abilities. But the Gombe chimps (*Pan troglodytes schweinfurthii*) use tools only made from plants, which last a matter of weeks in the tropical climate. The mismatch in survival between the million-year-old stone tools found in abundance by Leakey and the sticks and grass tools found by Goodall was stark.

Fortunately, chimpanzees are an inventive lot, and in the 1970s researchers discovered several groups of the western subspecies (*Pan troglodytes verus*) using stone tools to crack open forest nuts. Genetic evidence suggests that this subspecies split from the main, central chimpanzee population perhaps half a million years ago. Given the lack of stone tool use among central or eastern chimpanzees (as seen at Gombe)—or among their sister species, bonobos (*Pan paniscus*)—it seems likely that the western population independently invented stone use since that time.

That discovery raised key questions about the origins of stone tools. Our common ancestor probably used plant tools, just as wild chimpanzees and bonobos, as well as orangutans and gorillas, do. But why did only a very few branches of the family tree look to stone as a

PRECEDING PAGES: MARK MacEWEN *Nature Picture Library* raw material? Furthermore, wild chimps have a very limited range of uses for stones, based chiefly on the mechanical advantage gained by employing a hard rock to crack open a stubborn nutshell. Humans, on the other hand, used stones to develop everything from cutting tools to projectile tips, from jewelry to the pyramids of Egypt and Central America. Why do the technological trajectories of chimps and humans look so different?

With just two examples of stone tool technology, developed independently by humans and chimpanzees, the steps leading to its emergence are difficult to resolve. We cannot simply take what one subset of chimps do and map it onto our early ancestors, arguing that human technology arose from stone-tool-mediated nut cracking. It would make just as little sense to take what a subset of modern humans do and map it onto chimpanzee ancestors.

One of the main issues is that we have virtually no record of the evolution of chimpanzees. Mounting DNA evidence indicates that humans and chimps diverged from their common ancestor around seven million years ago. Yet the only known chimpanzee fossils are three teeth dating to around half a million years ago. And the oldest known chimpanzee tools are little more than 4,000 years old. As a result, knowledge of our ape siblings is stuck in something of an eternal present, with our view of them almost entirely derived from the past few decades. If we evaluated humans over the same short time frame, we would gain very sparse understanding of how our technologies emerged and changed throughout our evolution. If we had to guess, would we consider chopsticks or cutlery to best represent ancestral human eating tools? Is the PlayStation or Xbox the more primitive form of a human plaything? These questions may seem slightly absurd, yet scientists often fail to consider whether past chimps behaved anything like those we see now. Were they less technologically proficient? Or more so?

We have reached the end of anthropocentric archaeology; going forward, archaeology has all past behavior in its sights.

Another central concern is that a two-way comparison offers few clues as to why certain features developed in one lineage and not the other. For example, as early as the 1860s, English naturalist John Lubbock (who coined the terms "Paleolithic" and "Neolithic" for chapters of the Stone Age) suggested that primate nut cracking could be a simple precursor of the human tendency to break stones against each other to create sharp-edged flakes for cutting. If so, why do living chimpanzees not flake stones? Does the absence of this behavior stem from a lack of imagination, time or opportunity? Ideally we would have a much broader selection of case studies to test our hypotheses about the development of technology. This is where the monkeys I have been studying clamber to our rescue.

GAME OF STONES

BACK ON THE BEACH in Thailand, the bottom of the hole is now filling with water. It seeps in from the sides, threatening to undercut and destabilize the walls even further. I have rigged a boat pump to a car battery to keep the level down, but I am losing the battle. Finally, with the waves lapping at my toes, I carefully bring up a series of small volcanic rocks, each one bearing distinct scars and pits on their rough surface.

Thanks to work over the past decade by primatologists Suchinda Malaivijitnond of Chulalongkorn University in Thailand and Michael Gumert of Nanyang Technological University in Singapore, we now know that wild Burmese long-tailed macaques (*Macaca fascicularis aurea*) on Piak Nam Yai and other islands along the coast of the Andaman Sea regularly use stone tools. The behavior extends north from Thailand into Myanmar, where it was first described in the 1880s by Alfred Carpenter, a British sea captain. That report seems to have gone largely unnoticed, though, and it was only in early 2005, during surveys to assess the effects of the devastating Indian Ocean tsunami of 2004, that macaque tool use was rediscovered.

The macaques' use of stones seems to be entrenched, given the similarity of observations from the 19th and 21st centuries. Once the tide goes out, the monkeys come down from the interior forests of their island. They select roughly hand-sized stones from those lying on the shore and use them to strike and remove the upper shell of oysters attached to the now exposed rocks. They typically need only five or six strikes to open each oyster, and they carry around the same tool to use over and over again. In extreme cases, my team has seen them use one stone hammer to crack and consume more than 60 oysters in a row.

Oysters are not the only food for which the macaques need a utensil. Intertidal zones such as this one are rich with animal life. Although the macaques prefer oysters, they are also on the lookout for marine snails and crabs. Unlike oysters, these prey can and do run away, so the monkeys gather them up and take them to a nearby flat rock. They then find a much larger stone than the ones used for oyster pounding—the largest weigh several kilograms—and use it to crush their food against the flat rock, which serves as an anvil. When the group is midfeast, the constant cracking and rapping sounds of stone on shell fill the air.

The end result of these low-tide grab-and-smash raids is a shoreline strewn with broken shells and battered stones. The monkeys select their tools with skill and persistence, using the pointed ends of small rocks to precisely hit the oysters and the large central areas of the bigger rocks to pound open snails. These two main patterns of behavior damage the tools in predictable ways, and my colleagues and I have shown that how a macaque tool was used (and therefore its potential target prey) can be determined from wear, which is readily distinguished from scars seen on naturally modified stones. It is this characteristic damage that I search for as I dig into the soft beach sands. The small volcanic rocks that I have rescued from the tides bear the oyster-processing marks. Although these artifacts do not push back the known antiquity of macaque tool use—the oldest ones date to just 65 years ago—they are the first monkey tools ever found through archaeological excavation.

CAPUCHINS AND CASHEWS

THESE MACAQUES are not the only monkeys that have left behind an archaeological record. Fast-forward to late 2014, and I am back beside a square hole, but this time there is no sea breeze to alleviate the heat. Surrounding me are the scrub forests and towering sandstone plateaus of the semiarid Serra da Capivara National Park in northeastern Brazil. A team of undergraduate students from a university in nearby São Raimundo Nonato is digging, while Tiago Falótico and Lydia Luncz—my primatologist postdoctoral researchers at the time—record the finds. Thankfully, there is no encroaching tide, just the occasional scorpion or spider objecting to us moving its leaf litter around.

We are here because the wild bearded capuchins (*Sapajus libidinosus*) that live in the park have proved themselves to be master technologists. In 2004 capuchin experts Dorothy Fragaszy of the University of Georgia and Elisabetta Visalberghi of the Institute of Cognitive Sciences and Technologies in Italy reported that they had observed wild capuchins in a similar habitat some 200 miles away using stone tools. Now we know that capuchins at a wide range of sites in Brazil's interior select and use heavy stones to break open the tough shells of the local nuts and fruits in a manner that superficially resembles the behavior of western chimpanzees. The capuchins in Serra da Capivara National Park are especially creative with their tools, however. In addition to cracking open nuts and fruits, they also use rocks to penetrate the soil and dig down in search of burrowing spiders and plant roots. In another parallel with their ape cousins, these capuchins also select and break off twigs and then bite them to size and strip the leaves to make probes that they use to hunt hard-to-reach prey, such as lizards hidden in crevices.

One food in particular has our eye during the excavation. Cashew trees are indigenous to this area of Brazil, although they are now grown commercially worldwide. Their nut is nutritious and tasty, but fresh cashews have a caustic liquid in their shell that painfully burns the skin. So the capuchins use heavy stone hammers to break into the nuts. Their tactic is effective and, lucky for us, leaves telltale impact marks and dark cashew liquid all over the tools. By surveying and mapping capuchin stones that have accumulated over several years of use, we were able to find the pockets of the forest most intensively exploited by the monkeys. Because the soil, moisture and shade conditions that suit cashew tree growth have not changed significantly over the past few thousand years, we reasoned that the sites that are heavily trafficked today probably also saw a lot of capuchin activity in the past. Our excavations at a selection of these sites bore this notion out. We found at least four distinct phases of former monkey tool use, reflected in groups of buried stone hammers and anvils with clear damage from use. Bolstering our conclusion that these were capuchin tools, we found no signs of human activity, whether fire or pottery, or any of the kinds of stone tools people are known to make.

The oldest layer with capuchin tools dates back to between 2,400 and 3,000 years ago. These implements are therefore the oldest known nonhuman artifacts outside Africa, and they record the behavior of monkeys living well before the European invasion of the Americas. We did not find any evidence of ancient plant tool use from our excavations, but as is true for humans and other apes, this absence probably reflects the usual bias toward the survival of rocks over sticks.

Finding tools of another monkey species through archaeological excavation would have been reward enough for our efforts. But the Serra da Capivara National Park capuchins had a surprise in store for us. During the same field season, I filmed the monkeys breaking hammer stones against other rocks that were embedded into a large conglomerate block. They seemed to be aiming to create quartz dust, which they then licked or sniffed. Other researchers had observed this behavior before, but when I collected the broken pieces of rock and later excavated around the conglomerate block, I noticed something that had not been reported previously: the capuchins' rock shards bore an unmistakable resemblance to the stone flakes seen at some early human ancestor sites. Detailed analysis of the stones by another of my then postdocs at the University of Oxford, Tomos Proffitt, proved that we had found the first example of a nonhuman primate deliberately breaking stones and leaving behind sharp-edged flakes.

To be clear, the capuchins have not yet been observed using the sharp flakes that they create. In the wild, that behavior remains exclusively human, for now. But if repeated flaking of stone hammers can be an unintended by-product of an until now unimagined activity—creating dust for ingestion—then this finding raises substantial questions about parts of the early human archaeological record. Archaeologists have tended to assume that early humans deliberately smashed rocks to create sharp flakes for a specific purpose—cutting meat, for example. Given what we see in the capuchins, however, we must ask ourselves whether our ancestors three million years ago might have been similarly uninterested in those sharp rocks they were making. Did they, too, produce accidental flakes for a considerable time before latching onto the idea of picking them up and cutting things? Honestly, we do not know. But now we must at least consider the possibility. It would certainly smooth the pathway for the uptake of cutting as an innovation if there was already a known and reliable way to make the tools, with sharp edges moving conceptually from hazardous waste to valuable resource.

BEYOND PRIMATES

WHATEVER THE LESSONS for our own technological evolution, the finds from Brazil and Thailand mean that we now have archaeological records for three nonhuman primate lineages. It is worth pausing for a second to consider that fact. A mere decade ago we were learning of the existence of stone-tool-wielding wild monkeys. Now we have taken the first steps to trace that behavior back into deep time. The human line today forms only a quarter of the known primate archaeological records, albeit the best investigated portion by far.

In a recent paper, my colleagues and I suggested that we have reached the end of anthropocentric archaeology; going forward, archaeology has all past behavior in its sights. Some scholars may disagree with my contention that archaeology is just a method, applicable to any animal that leaves an enduring material record of its behavior, rather than something reserved for our own lineage. But the work of a small group of primate archaeologists has shown that it can open up new ways of viewing both our own evolutionary pathway and that of other species. Clearly, technology—the skilled and learned integration of material culture into our lives—is not a human-specific oddity. To evolve, it does not require language, or human-style teaching and cooperation, or even a large brain: the capuchins and macaques each have adult brains around 5 percent of the size of an adult human brain.

Moreover, stone tool use has emerged independently at least four times in relatively recent primate evolution: in coastal (macaque), lakeside (human), forested (chimpanzee) and semiarid (capuchin) environments. This diversity means we can reasonably expect that the same behavior has emerged repeatedly in the past, cycle between the prize cashew trees and the bearded capuchins.

Uomini and I have also conducted fieldwork on the archaeology of New Caledonian crows, which are famous for their sophisticated tool use and cognitive skills. New Caledonian crows regularly exploit specific locations on the landscape; once durable tool materials are added into the mix, we have all the necessary ingredients for the formation and survival of archaeological sites that allow us to reconstruct past animal behavior. Archaeology is an intrinsically interdisciplinary science, and adding ancient animal tool use to its research targets has been a satisfying—and even intuitive—step.

By chance, the recent rise of primate archaeology has coincided with the release of a new series of *Planet of the Apes* films. In them, our great ape relatives develop crude technologies that nonetheless rapidly surpass those known from wild animals in the real world. Even a simple composite spear, joining a sharp head to a separate shaft, requires a cognitive leap that appears absent in modern wild ape tools. Controlled use of fire and the wearing of jewelry are similarly extraordinary attributes of apes in these films, with no real-life examples of these behaviors known outside the human lineage.

But the technological apes we see on screen do not seem completely outlandish. They are even plausible. Western chimpanzees fashion simple, one-piece spears to attack smaller primates, just as capuchins do for lizards. William McGrew of the University of St. Andrews in Scotland, the most knowledgeable observer of chimp tool use and an early advocate for primate archaeology, once reported on an eastern chimp wearing a "necklace" made of knotted monkey skin. What else may take place when humans and their notebooks are not following these animals?

Human archaeology has emerged as a reliable source of insights into our development and diversity, a result of the efforts of thousands of scientists and billions of dollars over more than a century. As a reward for this effort, we now have millions of years of material culture that can act as a scaffold for our evolutionary speculations and scenarios. We are only at the starting line for the work to build a similar structure for nonhuman animals. But with an open mind, who knows what we might find? It is time to get digging that next square hole. SA

1

2

WILD BEARDED CAPUCHIN in Brazil uses a stone tool to open a cashew nut (*1*). Stones bearing the same distinctive scars and stains found on modern-day capuchin tools have been excavated at archaeological sites dating back as far as 2,400 to 3,000 years ago (*2*).

MICHAEL HASLAM (1, 2)

among many primate taxa, even if they no longer exhibit it or have gone extinct. Excitingly, if this scenario is true, the stone tools used by those taxa are still out there, waiting to be discovered.

There is no reason that we should stop at primates. In the past few years I have begun archaeological work with stone-tool-using wild sea otters on the West Coast of the U.S. in conjunction with ethologist Natalie Uomini of the Max Planck Institute for the Science of Human History in Jena, Germany, and other colleagues based at the Monterey Bay Aquarium and the University of California, Santa Cruz. We have learned, for instance, that the sea otters repeatedly return to favored places along the shoreline to break open shellfish, leaving behind damaged stones and large piles of discarded shells that could easily be mistaken for prehistoric human shell middens, or rubbish heaps. The feedback cycle between these durable landscape markers and their attraction for young animals learning to use tools may be a critical component of technological traditions among sea otters, much like the

MORE TO EXPLORE

Archaeological Excavation of Wild Macaque Stone Tools. Michael Haslam et al. in *Journal of Human Evolution,* Vol. 96, pages 134–138; July 2016.

Pre-Columbian Monkey Tools. Michael Haslam et al. in *Current Biology,* Vol. 26, No. 13, pages R521–R522; July 2016.

Wild Monkeys Flake Stone Tools. Tomos Proffitt et al. in *Nature,* Vol. 539, pages 85–88; November 2016.

FROM OUR ARCHIVES

The New Origins of Technology. Kate Wong; May 2017.

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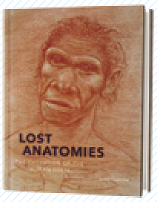
By Andrea Gawrylewski

Lost Anatomies:
The Evolution of the Human Form
by John Gurche. Abrams, 2019 ($40)

Fossil discoveries provide a thrilling, though only partial, picture of creatures that lived long ago. In this captivating collection of drawings and paintings, artist Gurche extrapolates the soft-tissue anatomy of various hominin specimens from their fossils, based on years of examining the relations of bone and tissue in modern apes and humans. Gurche aims for realism and never alters anatomy but lets art into his drawings in other ways—for example, an image of a *Homo neanderthalensis* skeleton that faithfully captures the bones' arrangement exactly as they were discovered is overlaid with whimsical blue and magenta orbs representing the sediment in which the fossil was found. He infuses character into the faces of early hominins, making it easy to imagine all they share with modern humans.

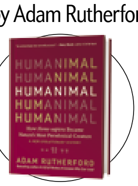


FEET of male bonobo (*Pan paniscus*), done with pen-and-ink and graphite on a board.

Einstein's Wife:
The Real Story of Mileva Einstein-Marić
by Allen Esterson and David C. Cassidy. Contribution by Ruth Lewin Sime. MIT Press, 2019 ($29.95)

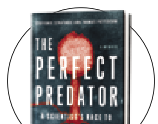
Throughout history Albert Einstein's first wife, Mileva Marić, was practically written out of the great physicist's story. Later she was credited as a secret collaborator on his most famous theories. Scholar Esterson and science historian Cassidy aim to set the record straight in this compelling biography. They pore over school transcripts, letters and contemporary accounts to assemble a cohesive picture of Marić's life. She overcame bias against women in science to pursue a Ph.D. in physics—but ultimately gave up her career when she married Einstein. As his confidant and study partner during his university days, Marić undoubtedly did contribute to Einstein's development as a scientist. But the authors find no evidence that she was a co-inventor of relativity, as some have claimed. "Tragically," they write, "she did not achieve her full potential as a scientist ... nor did she realize her hopes and dreams in marriage and in life." —*Clara Moskowitz*

Humanimal: How *Homo sapiens* Became Nature's Most Paradoxical Creature—A New Evolutionary History
by Adam Rutherford. The Experiment, 2019 ($25.95)



What makes humans exceptional is a question to which thinkers and scientists have devoted decades of obsession and research. And yet, observes geneticist and science writer Rutherford, "many of the things once thought to be uniquely human are not." Like us, many animals use tools, have sex for fun and communicate in complex ways. Indeed, we are not the only species with homosexuality (giraffes, for one) nor the only ones who exhibit viciously violent behaviors (bottlenose dolphins, for instance) or who grieve dead companions (observed in elephants and other animals). Looking at the latest evidence from behavioral science, genetics and paleoanthropology, Rutherford explores the ways that humans *do* differ from other animals and whether we are indeed as special as we once believed. "Paradoxically," he writes, the answer is "both no and yes." —*Emiliano Rodríguez Mega*

The Perfect Predator:
A Scientist's Race to Save Her Husband from a Deadly Superbug
by Steffanie Strathdee and Thomas Patterson. Hachette Books, 2019 ($28)



Epidemiologist Strathdee never suspected the turn her vacation to Egypt would take. One night in Luxor, her husband, psychologist Patterson, fell ill to an ailment that caused nonstop vomiting and agonizing pain. After Patterson was medevaced to Germany, a doctor confirmed he had been infected with *Acinetobacter baumannii,* a deadly and drug-resistant superbug that led to the closure of several intensive care units across Europe. "My husband was about to become some nameless statistic," Strathdee writes. In a desperate attempt to save his life, the couple agreed to experiment with a forgotten and mostly unregulated therapy: the use of viruses to kill off the resistant bacterium. Their account offers a fascinating and terrifying peek into the devastating outcomes of antibiotic misuse—and what happens when standard health care falls short. —*E.R.M.*

FROM *LOST ANATOMIES*, © 2019 JOHN GURCHE

Zeynep Tufekci is an associate professor at the University of North Carolina, whose research revolves around how technology, science and society interact.

Big Data and Small Decisions

For individuals a deluge of facts can be a problem

By Zeynep Tufekci

Last year, as back-to-back Hurricanes Florence and Michael threatened Chapel Hill, N.C., where I live and work, I faced a simple, binary decision like millions of others: Stay or go?

Nowadays data science is the hottest thing around. Companies cannot hire enough practitioners. There are books and online courses, and many universities are launching some flavor of a data science degree or center. Classes can barely accommodate the demand. One would hope that this golden age would mean we can make better decisions. But the deluge of data can, paradoxically, make decision-making harder: it doesn't easily translate into useful information. The democratization of access and the proliferation of expert commentary can make things even thornier. Finally, measurement itself is not a neutral process.

The days leading up to the landfall of both hurricanes, for example, were dominated by their number on the familiar Saffir-Simpson categories of 1 to 5, corresponding to sustained wind speeds, along with the "cone" of the storms' probable trajectories. Outside mandatory evacuation zones, it was up to everyone to decide for themselves what to do. As management consultant Peter Drucker is credited with saying: "If you can't measure it, you can't improve it." I'd add: "If you *do* measure it, you'll be trapped by the number." That's the problem with wind intensities: wind damage is obviously relevant, but the worst impact can come from flooding. Florence came ashore as a mere category 1, then dumped *three feet* of rain in some places—including away from the cone.

Seeking clarity, I checked in on the local TV meteorologists, who could pinpoint local impacts beyond one number. But arguably they had a bias toward emphasizing the dangers, which is better both for ratings and for self-preservation: it's much dicier if people don't evacuate when they should than if they flee unnecessarily. So I geared up to find more data. I sought out weather experts on social media and found well-curated lists. It seemed like a great idea at first. These were genuine experts. The commentary was respectful and intelligent. There were links to sources, and the discussion was rich.

But I quickly remembered why I never want to watch sausage being made. I learned a lot about European versus North American weather models—fascinating but fairly useless when you're trying to decide whether to pack up a few sentimental photographs and leave. One model predicted devastation, the other just some heavy rain. A storm could turn north, for a direct hit, or south—a miss. Worse, each model updated periodically, each run generating more expert discussion.

Now I knew too much but had even less clarity for decision-making. This is sometimes referred to as the "paradox of choice"—too many options can paralyze people trying to make a decision. It's that feeling you get standing in front of the ketchup shelves in the supermarket, overwhelmed. Organic or not? Low sugar? Sweetened with honey? With artificial sweeteners—and if so, sucralose or aspartame? Low sodium? I have resorted to blindly grabbing one—I just want a bottle of ketchup. (Well, glass or plastic?)

So if more data, better science and mightier computation can give us a hurricane's trajectory so many days in advance, why can't anyone make better predictions of impacts at the hyperlocal level? Unfortunately, broad predictions don't easily trickle down, because individual outcomes retain big error ranges—too many false positives and false negatives to be easily actionable.

So should we give up on data-driven decision-making in our own lives? Like many things in the age of big data, the way forward requires paying attention to things beyond the data—from how and what to measure to how to communicate about it. We need more frank talk about the shortcomings, so we can refine our understanding of the difference between a lot of data and useful information. And we especially need to build independent intermediaries to help guide us. Data science by itself can't do all that.

As for the hurricanes, I had just moved to my street so I did the simplest thing I could think of: I asked my neighbors who'd been there for a long time. They advised me to stock up on batteries. They stayed put, and so did I. SA

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Illustration by Sam Island

ANTI GRAVITY
THE ONGOING SEARCH FOR FUNDAMENTAL FARCES

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.

Oh, Chute

Someone finally did a study on the efficacy of parachutes

By Steve Mirsky

The randomized controlled trial (RCT) is often called the "gold standard of evidence" in medical research involving humans. In such an experiment, a random sorting leads to only some subjects getting the real intervention being tested.

The first known RCT took place in 1747, when Dr. James Lind, surgeon on the HMS *Salisbury,* staked out his place in history by giving some scurvy patients citrus fruits. At first, anyway. Then all the sailors got citrus, as it became obvious that scurvy was preventable through the inclusion in the diet of vitamin C via consumption of oranges, lemons and—of key importance to etymologists—limes, which led to all British sailors, and then all Brits in general, to become known as Limeys.

Skip ahead a quarter of a millennium to 2003, when the *BMJ,* formerly known by its spelled-out name of the *British Medical Journal* (and informally to some as the Limey Medical Journal), published an article entitled, "Parachute Use to Prevent Death and Major Trauma Related to Gravitational Challenge: Systematic Review of Randomised Controlled Trials."

The write-up was a response to a long-held criticism of RCTs, namely, that you don't need them to make reasonable conclusions about certain effects of certain actions—such as jumping out of a plane without a parachute. Indeed, the 2003 *BMJ* paper's objective, "To determine whether parachutes are effective in preventing major trauma related to gravitational challenge," met with a hard landing. "We were unable to identify any randomised controlled trials of parachute intervention," the authors admitted.

They explained further: "As with many interventions intended to prevent ill health, the effectiveness of parachutes has not been subjected to rigorous evaluation by using randomised controlled trials. Advocates of evidence based medicine have criticised the adoption of interventions evaluated by using only observational data. We think that everyone might benefit if the most radical protagonists of evidence based medicine organised and participated in a double blind, randomised, placebo controlled, crossover trial of the parachute."

Which brings us to the Christmas issue of the *BMJ,* always stocked with unconventional scholarship. The 2018 edition took up the gauntlet thrown back in 2003—researchers from Harvard University, the University of Michigan and U.C.L.A. joined with skydivers to publish "Parachute Use to Prevent Death and Major Trauma When Jumping from Aircraft: Randomized Controlled Trial."

The team enlisted and randomized 23 volunteers. Twelve participants wore parachutes while the other 11 donned backpacks that contained no parachutes. All 23 leapt from either a plane or a helicopter. The jumpers were assessed shortly after hitting the ground for death or major trauma, and most were reevaluated 30 days later.

The authors wrote, "We have performed the first randomized clinical trial evaluating the efficacy of parachutes for preventing death or major traumatic injury among individuals jumping from aircraft. Our groundbreaking study found no statistically significant difference in the primary outcome between the treatment and control arms." Indeed, all members of both cohorts were fine.

The researchers further note, "A minor caveat to our findings is that the rate of the primary outcome was substantially lower in this study than was anticipated … [subjects] could have been at lower risk of death or major trauma because they jumped from an average altitude of 0.6 m [just under 2 feet] on aircraft moving at an average of 0 km/h." As the reader suspected, the aircraft were parked on the ground.

The researchers also said, "Opponents of evidence-based medicine have frequently argued that no one would perform a randomized trial of parachute use. We have shown this argument to be flawed, having conclusively shown that it is possible to randomize participants to jumping from an aircraft with versus without parachutes (albeit under limited and specific scenarios)."

By the way, no participants actually deployed their parachutes—if you throw around square yards of fabric and feet of strings, somebody could get hurt. 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

MARCH

1969 Heat Pollution

"In the U.S. it appears that the use of river, lake and estuarine waters for industrial cooling purposes may become so extensive in future decades as to pose a considerable threat to fish and to aquatic life in general. The discharge of waste heat into the natural waters is coming to be called thermal pollution. What has aroused ecologists is the ninefold expansion of electric-power production that is in prospect for the coming years with the increasing construction of large generating plants fueled by nuclear energy. In Britain, where streams are small, water is scarce and appreciation of aquatic life is high, the favored artificial device for getting rid of waste heat from power plants has been the use of cooling towers."

"To a Quasar"

"Twinkle, twinkle, little quasar,
Candidate for Occam's razor:
  Are you near or are you far?
  Are you nebula or star,
Emitting all that energy
Like any normal galaxy?

Is your message from the dark
Sent by positron or quark?
  Spectrum lines, though
    rather faint,
  Tell us only what you ain't.
What strange phenomenon's
  involved
In this enigma, yet unsolved?
Stanley A. Bell, Laguna Hills, Calif."

The writer was inspired by John Updike's poem in the January 1969 issue and the article on quasi-stellar objects by Geoffrey Burbidge and Fred Hoyle in the December 1966 issue.

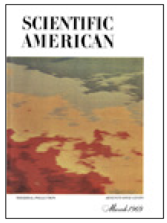
1919 Hating Daylight Saving

"When we were informed that a rider attached to the Agricultural Appropriation Bill aimed to kill the Daylight Saving Act, we experienced a distinct shock. When we learned that this opposition was mainly due to the farmers, our astonishment grew apace. They do rise early, to be sure, but the early morning work is taken up with chores. Much of the field work cannot be done until after the dew is off the ground. Last year farmers had difficulty with hired men who insisted on quitting work according to the new summer time. And strange to say the cows stubbornly refused to come home when the sun was high in the skies. However, there was an actual saving in lighting bills and consequently a saving of coal, which we cannot afford to ignore."

Akeley Film Camera

"While doing extensive scientific work in the jungles of Africa, Carl E. Akeley of the staff of the New York Museum of Natural History found the usual type of motion-picture camera inadequate and unreliable for the varied uses of field work. He conceived the principle of the present camera which bears his name. Briefly, the Akeley camera is a one-man camera, in the sense that its operator can carry the camera, magazines, and tripod himself, and set them up without assistance. Twin lenses are employed on the Akeley camera, one for the film and the other for the finder. This arrangement permits of watching the picture on the ground glass, right side up, while operating the camera. Thus the operator can always tell whether his picture is in focus—indeed, he sees exactly what the film is recording at all times. For filming rapidly moving objects, such as motor boats [*see illustration*], airplanes, athletes, and so on, there can be no doubt that the Akeley camera is in a field by itself."

1919: The new Akeley high-speed camera in operation.



1969

1919

1869

1869 The Panama Canal

"The Hon. Caleb Cushing has returned from the capital of Colombia, the most northern of the South American republics, whither he was sent by the Department of State, and the draft of a treaty he there negotiated for the right of way of a ship canal across the Isthmus of Darien, or Panama, is now before the Senate for ratification. The project of uniting the two oceans by a cut across the Siamese-twin ligature that unites the two great western continents and divides the two great oceans is not a new or a modern one.

In 1843 the French government sent out Messieurs Napoléon Garella and J. de Courtines to make explorations. They reported in favor of a canal passing under the dividing ridge of the Ahogayegua by a tunnel 17,390 feet long. With the disastrous expedition of Lieut. Strain [of the U.S. Navy, 1854], probably all or most of our readers are familiar. A railroad tunnel scarcely 20 feet wide is possible, while one to accommodate ships is a feat at which even modern engineering may stand aghast. A canal, however, is proposed now, and one without tunnels."

The Panama Canal was not opened until 1914.

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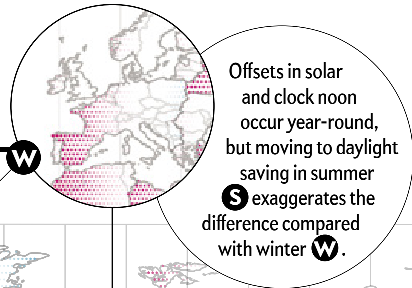
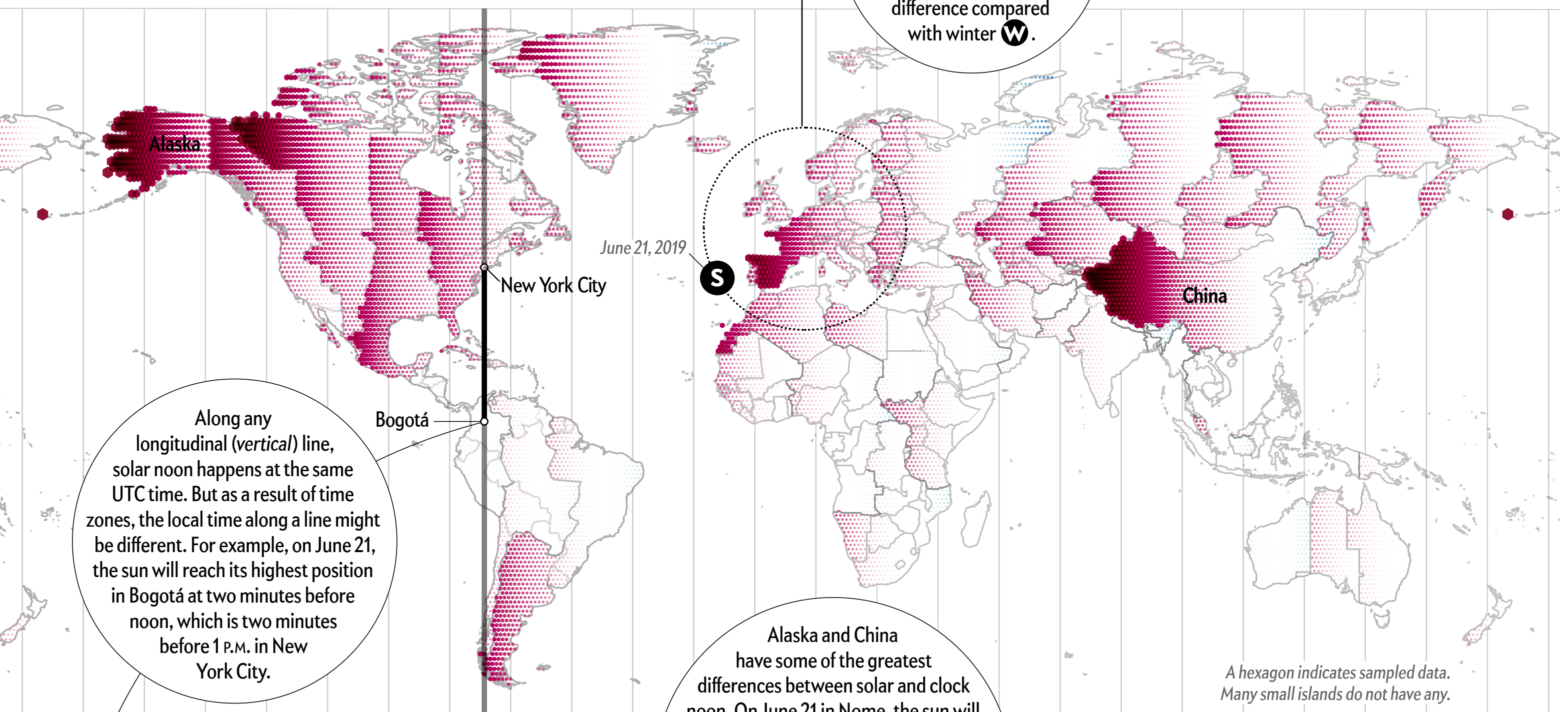
By Nadieh Bremer



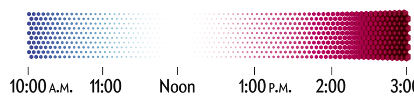


Noon It's Not

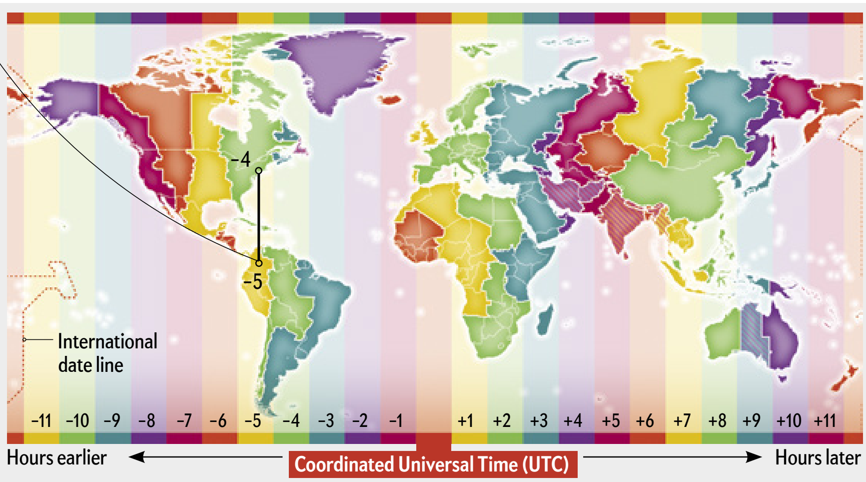
In many places, the sun reaches its highest point in the sky well after 12 o'clock

Local Time When the Sun Is Highest Overhead

June 21, 2019 (summer solstice)



Centuries ago cities designated 12 P.M. as the moment the sun reached its apex overhead, known as solar noon. But by the late 1800s it had become inconvenient for nearby municipalities to use slightly different times. Countries adopted time zones so large regions would be in sync (*multicolor map*). This practice creates offsets, however, between solar noon and clock noon. The offsets map (*blue* and *red*) reveals how much later (*red*) or earlier (*blue*) solar noon happens compared with clock noon on the summer solstice. In most places, the sun peaks later than 12 P.M.—which also means our clocks say sunrises and sunsets are later than our ancestors experienced. The offset pattern is similar in winter but less pronounced because daylight saving time, observed by many nations, exaggerates the shift (*inset map of Europe*).



Tinkering with Time Zones

A region has the smallest disparity between solar noon and 12 o'clock if it follows the Coordinated Universal Time (UTC) zone it falls in. Western Australia, for example, aligns almost perfectly with UTC+8. In that situation, solar noon occurs at 12 P.M. in the UTC zone; it tends to be slightly ahead (*blue on offsets map*) in the eastern region and slightly behind (*red on offsets map*) in the western region. Still, for diverse reasons, many countries' regions are ahead of this natural time zone. Some may want to have sunlight later in the evening or to stay at the same time as an important neighboring country.

In crosshatched regions, the UTC observed is not in full hours (for example, India is UTC+5:30).

SOURCE: OPENSTREETMAP (*time zone data*)