SPOOKY ACTION CONFIRMED
Quantum weirdness passes a definitive test

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ANATOMY OF A SUPERVOLCANO
What triggers the world's biggest eruptions

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PLUS

SILENT NO MORE
Could gene therapy cure deafness? PAGE 72

SPONGE CITIES
A new way to flood-proof urban areas PAGE 80

DECEMBER 2018
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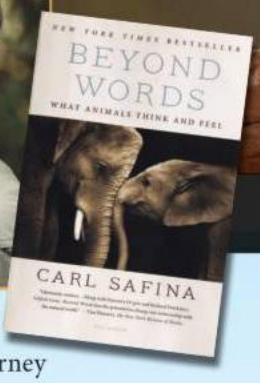
Lions, Tigers and Tradewinds

A PRIVATE JET EXPEDITION

HOSTED BY *Carl Safina*



Conservationist and writer Carl Safina will host this journey throughout, offering insights on wild lands and wildlife, and humans' relationship to the living world. Author of seven books, including *Beyond Words: What Animals Think and Feel*, Dr. Safina's work has been awarded the MacArthur, Pew, and Guggenheim Fellowships, among others.

"Join me and Bushtracks Expeditions' president David Tett as we take a great-cat-sized bite out of a great swath of two continents. And, we will also experience parts of the Middle East and the Indian Ocean. Our itinerary promises lands and luxuries, coasts and comforts, lions and tigers and maybe even bears. This is an itinerary for the curious, for the seeker, for those willing to get the greatest view of all—a view at ourselves not in the mirror but from the outside, looking in. There will be an enormity of concepts to explore, and things to see and enjoy. I hope to see you at boarding!"

Carl Safina

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ON THE COVER

Lab-grown meat, ubiquitous augmented reality and advanced medical diagnostics are on this year's list of 10 world-changing emerging technologies. *Scientific American* editors produced the annual report in partnership with the World Economic Forum and a Steering Group of experts from academia and industry. **Image by Mark Ross Studios.**

Photograph by Harsha Vadlamani

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ON THE WEB

Maternal Health
Preeclampsia can be treated if detected early in pregnancy, yet screenings are out of reach for many women. A simple blood test could change that.
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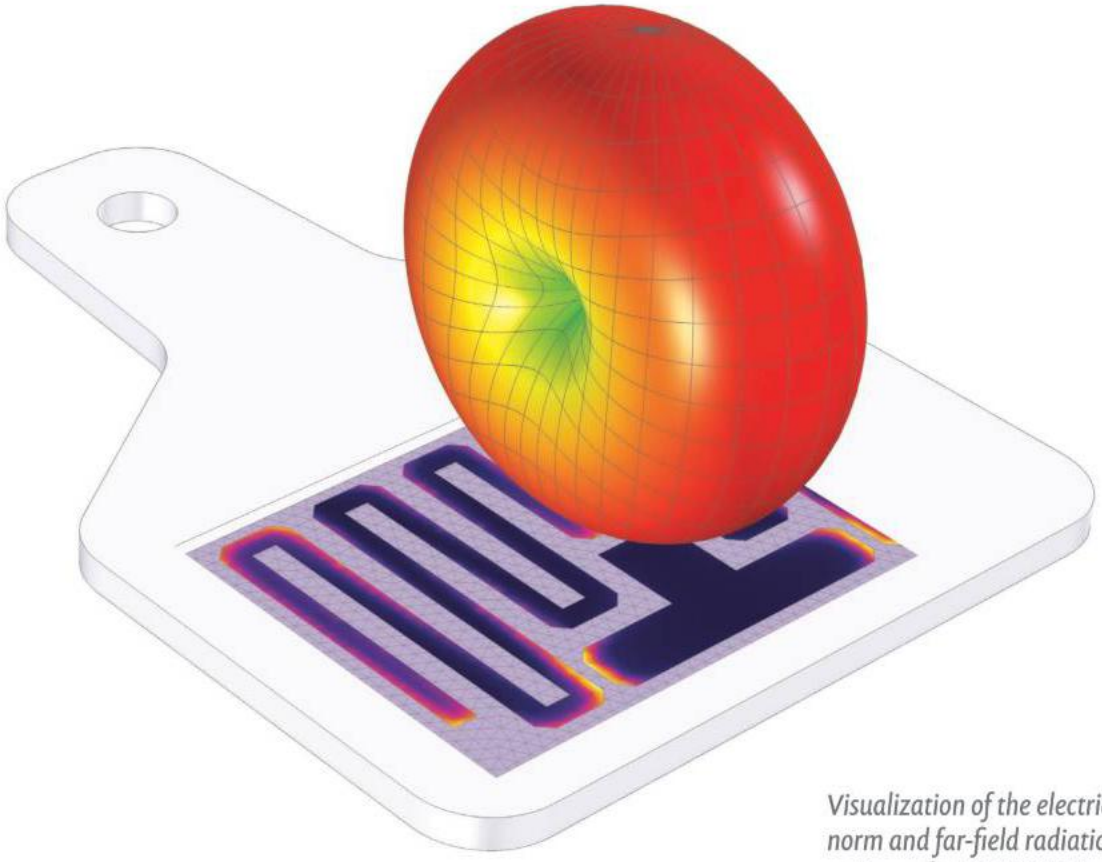
Smartphones, smart homes, smart...healthcare?



Visualization of the electric field norm and far-field radiation pattern of a UHF RFID tag.

RFID tags are used across many industries, but when it comes to healthcare, there is a major design challenge: size. If wearable RFID tags are too big and bulky, they could cause patient discomfort. Or, if the tag is for a biomedical implant, it has to be smaller than a grain of rice! Design engineers can optimize the size of an RFID tag for its intended purpose using RF simulation.

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

Tech That Will Shape the World

"The advocate of industry and enterprise, and journal of mechanical and other improvements": that mission visually underscored the logo of our very first issue, dated Thursday, August 28, 1845. In the latest installment of *Scientific American*'s delivery on that promise, we bring you this month's cover story, "Top 10 Emerging Technologies of 2018," a collaboration between *Scientific American* and the World Economic Forum's Expert Network.

What's an "emerging" technology? It must be a potentially disruptive solution that is poised to change the world. It must be drawing increasing investment or showing other signs of being ready to erupt globally in the next three to five years. It must offer significant benefits for societies and economies—although our specialist authors don't shy away from noting possible downsides in their articles about each innovation.

The selection process started about a year ago, when we began soliciting great ideas. Each year, we tap *Scientific American*'s editorial team and Board of Advisers, the Forum's knowledgeable networks, and others for nominations. Then a Steering Group of global authorities in multiple fields begins a thorough process of winnowing the list; they further investigate each submission and share insights in the group discussions. Special thanks to our Steering Group and my co-chair Bernard S. Meyerson of IBM, to Rigas Hadzilacos and Oliver Cann of the Forum, and to our many contributors. You can see the results unfold on page 28.

For another expert perspective, we turn to quantum physicists Ronald Hanson and Krister Shalm and their feature on "Spooky Action." The bizarre phenomena of quantum entanglement, where particles can retain a "spooky" connection even when far apart, is challenging to justify against our intuitive picture of nature. The effect has been seen in many experiments—yet each has also contained loopholes that have made it impossible to entirely rule out that any other effect could be at work. At last, they write, loophole-free tests confirm that quantum entanglement can't be explained away. Entangle your mind, starting on page 58.

Dispersed, unconnected bits—this time of fossilized bone—are the problem in "Needle in the Haystack," by researchers Thomas Higham and Katerina Douka (*page 40*). As the authors describe, in Denisova Cave in Siberia a novel combination of techniques is allowing scientists to comb through large quantities of unidentified fragments for clues about when, where and how human species interacted with one another. Hope you enjoy making the many other science and technology connections throughout the issue; as always, we welcome your thoughts. SA

Illustration by Nick Higgins


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August 2018

"To teach evolution effectively, the sequence of topics should be changed. The first should be ecology and then genetics."

BRIAN MYRES *CYPRESS COLLEGE*

EVOLUTION OF EDUCATION

In "Bringing Darwin Back" [Special Education Report 2018], Adam Piore discusses how a majority of American teachers do not fully teach evolutionary theory. He also reports on groups promoting strategies for preparing teachers to do so in communities that are biased against the subject.

To teach evolution effectively and productively, the sequence of topics should be changed. The first should be ecology and then genetics, with the latter's last chapter covering evolution. Integrating evolution with those two subjects would show students that evolution is needed for ecological adaptation and that the way for it to occur over the long term is through natural selection for those traits that are adaptive at a given time. And it should be impressed on them that evolution is an absolute necessity because the planet is always changing and that for a living system to be successful it must also change.

I doubt that any students would profess to not "believe" in genetics and ecology. And they could be asked if they think that humans are "apart from nature" or "a part of nature." I think many would accept that they are a part of nature and have evolved because the evidence is overwhelming.

BRIAN MYRES *Professor emeritus of biology, Cypress College*

As a retired biology teacher with 20 years of experience teaching evolution in high school, I have found an ideal way to present the topic: I begin my three-day lesson by announcing that the earth itself has embedded a key part of biology in its record. It has documented the natural process of evolution at work in *all* life-forms on the planet. I then ask the kids to define "evolution." Some do so accurately; a few proclaim that it says people come from monkeys. I then define it: "Evolution is simply a natural change in the design of species over time, in response to changes in their environment." That's it! The kids don't complain about something so simple.

I then spend two days outlining exactly how species change over time in response to the environment, including through natural selection. I give the students graphic slides showing organisms changing. I challenge them to identify what long-term changes would make sense in an organism if its environment, for example, got colder or warmer. They discover for themselves why organisms get bigger, or smaller, or smarter, or more colorful.

Kids are exquisitely sensitive to their peers. As they logically progress through the examples as a group, they become hesitant to voice any religious objection to a process so obvious and rationally innocent as the realization that species change over time in response to their environment. As a result, when I finally introduce them to the evidence that people, too, have evolved in design over time, they get it.

FRANK GREGORIO *Manassas, Va.*

UNCERTAIN MATTER

In "Is Dark Matter Real?" Sabine Hossenfelder and Stacy S. McGaugh compare two explanations for how stars orbit in galaxies and galaxies orbit in clusters: a long-assumed theory involving invisible particles having mass (dark matter) and theories that change the mathematical description of gravitational forces (modified gravity).

Einstein tells us that gravity is only an apparent force that results from the curvature of spacetime and that mass causes such curvature. Might it be that things other than mass (dark energy, for one) can cause it as well? Could dark energy's distortive effects on galactic scales result in a kind of local "bubbling" of spacetime?

KEITH BACKMAN *Bedford, Mass.*

I find it surprising that the authors have nothing to say about the influence of the darkest of the dark: black holes. In particular, the lack of density peaks in a galactic core might be affected by the presence of a central black hole, which could gorge itself on the dark matter distribution.

PETER J. TURCHI *Santa Fe, N.M.*

THE AUTHORS REPLY: Regarding Backman's question: According to Einstein's theory of gravity, all kinds of energy and mass cause spacetime to curve. Dark energy does affect the curvature, but it does not do so in the right way to give rise to the effects attributed to dark matter. Actually "dark energy" and "dark matter" are just names that physicists have given to what they conclude is necessary to explain the observations, and they have different properties. Dark energy is the stuff that causes the accelerated expansion of the universe. Its influence is negligible inside of galaxies.

In response to Turchi: The center of the Milky Way hosts a supermassive black hole that weighs in at about four million solar masses and that heats up surrounding gas as it falls in. Mind-boggling as that is, neither its gravitational influence nor the hot gas has much of an effect on the overall motion of the galaxy. The central black hole really plays a role for only the innermost regions of the galaxy, and the mass of the hole is tiny compared with the mass of dark matter needed to explain our observations.

SPEAKING FOR THE TREES

"Capture That Carbon," by Madison Freeman and David Yellen [Forum], discusses carbon capture, utilization and storage

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(CCUS), in which carbon captured from the smokestacks or removed directly from the air is turned into useful products or something that can be stored long term.

It should now be clear to all who follow the trends in climate change that we have long since passed the point where simply reducing emissions will be enough to solve the problem. The authors cite the difficulty of securing the investment funds needed to fully develop CCUS technologies to the level necessary to have the desired effect.

But there is another very low-tech, well-established approach that could be implemented immediately: forestry management. By ensuring that a new tree is planted for every mature tree cut, lumber going into construction could effectively be stored carbon. A critical element of this method is, of course, ensuring that all cut mature trees are replaced. One of the most destructive trends in the current situation is the conversion of tropical forest into pastureland or other agricultural use.

The technology of forest management is available right now. But we do need to change the economic value placed on forests in all regions. They could make an important contribution to sustaining a habitable planet.

PAUL M. MARTIN *Springfield, Mass.*

IMMODEST PROPOSAL

In "That's Life" [Anti Gravity], Steve Mirsky notes a study asserting that it "found no reports of primary data relating to health aspects of the use of sex robots." In response, I would like to point out that absence of evidence is not evidence of abstinence—or even evidence for absence.

DAN BARKER *Atlanta*

ERRATA

"Is Dark Matter Real?" by Sabine Hossenfelder and Stacy S. McGaugh, should have referred to the theory of particle dark matter predicting many more small dwarf galaxies than are observed rather than fewer. Further, the units for the graph in the box "A Problem for Dark Matter" should have been given as meters per second squared rather than meters per second.

Stephen Ornes's "Art by the Numbers" should have said that there will never be a finite number of primes rather than a countable number.

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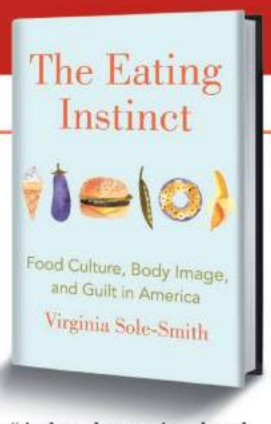

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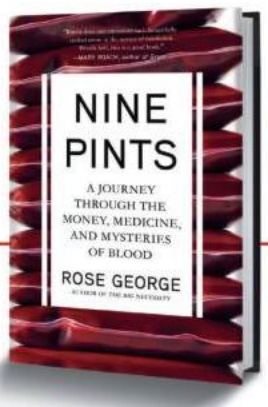

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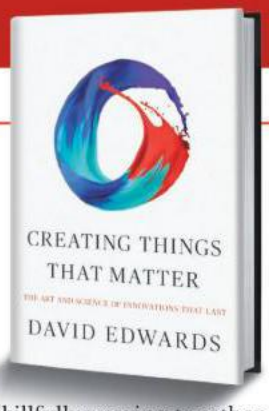

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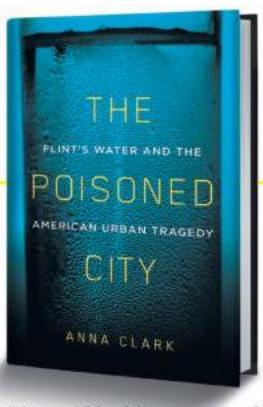

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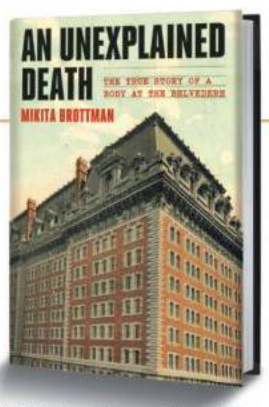

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Rethinking the "Anthropocene"

A popular name for our era perpetuates misperceptions about humans and nature

By the Editors

Alarming news, arriving almost daily, about rising temperatures, melting glaciers, species diebacks, radioactive waste, oceans contaminated with plastic, and other calamities has seared in our minds the staggering impact that humanity now has on our planet. In 2000 atmospheric scientist Paul Crutzen encapsulated these concerns into a single word, the "Anthropocene," which he proposed as the geologic name of an era dominated by the human race. Geologists cannot agree on when the Anthropocene began, and stratigraphers are still debating whether it is in fact a geologic era at all. Even so, the term has riveted public attention and sparked impassioned arguments about the relationship between humans and the natural world.

Several scholars in the humanities criticize the name itself, however, arguing that it perpetuates long-standing misconceptions about this relationship. Replacing "Anthropocene" with a name that focuses instead on its underlying causes might be more conducive to helping us tackle them.

One problem with the term is hubris: naming a geologic era after ourselves suggests a certain awe at our own magnificence. And sociologist Eileen Crist holds that it was such an anthropocentric worldview that got us into this predicament in the first place. When scientists discuss possible responses to a rapidly warming planet, they almost always accept the dominion of humans over all other species, Crist and others charge, imagining that the enlightened among us can sagaciously steer planet Earth onto a sustainable pathway without major disruptions to our modern ways of life.

A second indictment is that "Anthropocene" implicitly blames the entire human race for a crisis caused by a relative few. Surely the "Man of the Hole," the last survivor of an uncontacted hunter-gatherer tribe in the Brazilian Amazon, bears less responsibility for our present predicament than, say, former Secretary of State Rex Tillerson, who was CEO of ExxonMobil. The tribe's carbon emissions are essentially zero, whereas ExxonMobil is the fifth largest carbon emitter in the world, according to the Carbon Majors Report.

Yet another critique is that the "Anthropocene discourse" tends to hold not only all humans but *human nature* responsible for this predicament. That makes little sense to anthropologists, who point out that people have repeatedly figured out how to live within their ecological means and even thrive. Social scientists and others contend, however, that the environmental issues we face derive not from human nature but from culture: specifically, a socioeconomic configuration that arose in Europe in the second half of the past millennium. Giving the period a name that focuses on its actual historical and cultural roots, they say, would help us understand what happened, remind us that it is a choice—not an inevitability—and perhaps offer a way forward that does not require sacrificing the glorious wealth of life that surrounds us.

To this end, thinkers have suggested an astonishing variety of alternative names. The most widely accepted is "Capitalocene," first proposed by human geographer Andreas Malm, who locates the origins of the "era of capital" in the use of coal to fuel factories in 19th-century England. In contrast, geographer and historian Jason W. Moore contends that the Capitalocene arose in 15th-century Europe with an economic system predicated on perpetual territorial expansion. Expanding to the New World and moving on to colonies and dominions in Asia, Africa and Australia, capitalism established global systems of manufacturing and trade that consumed nature at unprecedented rates and is only now bumping up against planetary boundaries. Philosopher Donna Haraway has proposed another name that looks to the future: "Chthulucene" (from the Greek *chthonos,* meaning "of the earth"), an age in which we humans teach ourselves to live in full and rich harmony with our fellow beings.

These thinkers seek not so much to dethrone the concept of the Anthropocene as to—perhaps by taking a page from the idea of the Chthulucene—enrich the ongoing discussion between scientists and society to support us all in making the difficult choices ahead. We welcome that idea. Working collaboratively, the natural sciences and the humanities can help us break through thought barriers and generate fresh ideas. To quote Albert Einstein: "We cannot solve our problems with the same thinking we used when we created them." SA

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Illustration by Raz Latif

Kendall Jones is a doctoral researcher at the University of Queensland in Australia. **James Watson** is a professor in the School of Earth and Environmental Sciences at the University of Queensland.

The Last of the Ocean Wilderness

Just 13 percent of the ocean remains largely untouched by human activity

By Kendall Jones and James Watson

The ocean covers more than 70 percent of our planet, an area of over 160 million square miles. It is so immense that explorers once thought there was no way to cross it. When our ships were advanced enough to do so, naturalists then thought it impossible for humans to ever exhaust fisheries or drive marine species to extinction.

They were wrong.

Commercial fishing now covers an area four times that of agriculture, and much of that expanse has been rendered completely unsustainable. We have depleted 90 percent of formerly important coastal species. Large fish have been harvested so heavily that they are virtually wiped out in many places. Indeed, studying once vital fish habitats such as coral reefs has been compared to trying to understand the Serengeti by studying termites and locusts while ignoring the wildebeest and lions.

Some may hope that there are immense areas still untouched, given that humans do not live on the ocean and we need specialized ships to go far beyond the coast. But that is incorrect. In a study published this summer in *Current Biology,* we used fine-scale global data on 15 human stressors to the ocean—including commercial shipping, sediment runoff and several types of fishing—to show that Earth's "marine wilderness" is dwindling. Just 13 percent of the ocean remains as wilderness, and in coastal regions, where human activities are most intense, there is almost no wilderness left at all. Of the roughly 21 million square miles of marine wilderness remaining, almost all is found in the Arctic and Antarctic or around remote Pacific island nations with low populations.

These remnants of wilderness are home to unparalleled marine life, sustaining large predators and high levels of genetic diversity. The lack of human impact can also make them highly resilient to rising sea temperatures and coral bleaching—stressors that cannot be halted without globally coordinated efforts to reduce emissions.

In an era of widespread marine biodiversity loss, wilderness areas also act like a window into the past, revealing what the ocean looked like before overfishing and pollution took their toll. This is crucial information for marine conservation. If we are to restore degraded areas to their former state, we need to know what to aim for.

What concerns us now is that most wilderness remains unprotected. This means it could be lost at any time, as advances in technology allow us to fish deeper and ship farther than ever before. Thanks to a warming climate, even places that were once safeguarded because of year-round ice cover are now open to fishing and shipping.

This lack of protection stems in large part from international environmental policies failing to recognize the unique values of wilderness, instead focusing on saving at-risk ecosystems and avoiding extinctions. This is akin to a government using its entire health budget on emergency cardiac surgery, without preemptive policies encouraging exercise to decrease the risk of heart attacks occurring in the first place.

If Earth's marine biodiversity is to be preserved in perpetuity, it is time for conservation to focus not only on the E.R. but also on preventive health measures.

Our *Current Biology* paper comes with a plea. As we develop international conservation agreements, it is crucial that we recognize the unique values of wilderness and set targets for its retention. Without further action, wilderness areas will likely be lost forever—something President Lyndon B. Johnson urged us to avoid when he signed the Wilderness Act in 1964. "If future generations are to remember us with gratitude rather than contempt," Johnson observed, "we must leave them more than the miracles of technology. We must leave them a glimpse of the world as it was in the beginning." SA

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Illustration by Sija Hong

ADVANCES

Whisky researchers are at the forefront of the science of food-fraud detection.

GETTY IMAGES

INSIDE

FOOD SCIENCE

Whisky Fakers

Scientists are developing better methods for detecting liquor and food fraud

Whisky auctioneer Isabel Graham-Yooll was examining a seller's collection in London last year when she noticed some of the liquors were slightly off-color—and several bottles seemed a little too full. She called the police, who arrested the seller for fraud. If the case goes to court, prosecutors may be able to count on more than just Graham-Yooll's knowledge of fine whiskies; emerging laboratory techniques could help identify the liquors in question.

Whisky researchers are finding themselves at the forefront of the burgeoning science of food-fraud detection. The spirit is a handy test substance because of its complexity: its main components—water and barley or other cereals—and its production method create unique chemical and biological signatures. And the time whisky spends in a wood cask helps to impart its golden color and unique aromas. "If [a new testing] technique works for whisky, then we can be sure it works for other spirit categories," says Shona Harrison, the analytical services manager of the Scotch Whisky Research Institute (SWRI) in Edinburgh, whose work is funded by several liquor companies. Harrison and other researchers are fighting food and beverage fraud on multiple

fronts—from monitoring global trade data to adapting laboratory-detection tools for use in the field.

Fakes are often a response to sudden bursts of demand for a particular product. Counterfeit Scotch, for example, is most common in places where legitimate suppliers cannot keep pace with consumers' thirst for the liquor. And in the past couple of years a New Zealand honey called mānuka experienced a spike in popularity that was followed by a glut of bogus mānuka on the market.

Copper whisky stills

Slapping high-end labels on bottom-shelf commercial whisky, honey or other products primarily harms the owner of the high-end brand. But when fraudsters replace the product consumers think they are buying with something else altogether, it can sicken or even kill people; this happened in India last year when six people died and 30 more fell ill from methanol poisoning after drinking black-market liquor. Food fraud is also lucrative—criminals can pocket tens of thousands of dollars per shipment of counterfeit product, and the sentences for getting caught are much more lenient than those for trafficking illegal drugs.

Detecting bad batches of something already on store shelves may be too late. So food technologist Katharina Verhaelen of the Bavarian Health and Food Safety Authority and her colleagues developed software that monitors food-import data in Germany on a monthly basis and flags suspicious changes in product volumes or prices. The system helped to identify adulterated hazelnuts associated with a record price jump, Verhaelen's team reported in the December issue of *Food Control*.

Researchers are also using media reports to help detect and track counterfeit food. In a study published in November, supply chain researcher Yamine Bouzembrak of Wageningen University in the Netherlands and his colleagues took a public health alert program called the Medical Information System (MedISys), which scans online news and records potential cases of food contamination, and repurposed it for detecting cases of fraud. As of late September, they had identified and confirmed 5,174 separate food-fraud incidents, Bouzembrak says, and were set to meet with several European authorities at the November FoodIntegrity Conference in Nantes, France. They planned to discuss incorporating the updated tool, MedISys-FF, into early-warning systems for food contamination.

As methods for monitoring food fraud in the market have developed, so has commercial technology for detecting it at the molecular level. At a conference in 2017 Harrison encountered a portable spectrometer—a device that splits light shone through a liquid into its component wavelengths and measures their intensities to identify compounds inside. The customized device allowed minimally trained users to measure trace levels of sugars that are useful for verifying a wine's identity. Harrison realized she could also use it to help distinguish whiskies based on their chemical characteristics, a task that otherwise requires bulkier lab equipment. Harrison's institute, SWRI, bought one of the portable spectrometers to complement its existing profiling abilities.

Chemist David Ellis and his colleagues at the University of Manchester in England, who collaborate with the SWRI researchers, are now developing other spectroscopic methods for profiling Scotch. Whisky producers and distributors "seem particularly interested in 'through-bottle' methods at the moment," Ellis says. His group's technology might someday allow anyone to quickly screen bottles and decide whether to send them to the whisky authorities for a full analysis or whether it is safe to buy and enjoy them. —*Lucas Laursen*

LEON HARRIS *Getty Images (distillery)*; DAN RAFLA *Getty Images (Everest)*

BOTANY

High-Altitude Flora

Hardy plants adapted to life on Mount Everest

The upper slopes of Mount Everest are a punishing place for plant life: high levels of ultraviolet radiation scorch the mountain, temperatures regularly fall below freezing, and the icy, rocky terrain can hardly be called good soil. But now scientists have identified three new plant species capable of surviving this kind of place. Among the highest-elevation plants known to science, the specimens—collected decades ago but never studied until now—reveal unique adaptations to life on the roof of the world.

On May 25, 1952, a Swiss expedition gathered three plant samples on Everest at roughly 6,400 meters. (The summit, which was first reached the following year, is 8,848 meters.) The dried specimens were placed in an herbarium in Geneva and sat forgotten until 2017, when Cédric Dentant, a botanist at Écrins National Park in Gap, France, rediscovered them.

Dentant carefully analyzed the plants—each no more than a few centimeters long—and found several attributes that most likely contributed to their survival in such harsh surroundings, he reported in October in *Alpine Botany*. One of the plants had stems that burrowed into the ground, anchoring it in the unstable terrain; another had a cushionlike shape that limited heat and water loss; and two, according to notes made by the 1952 mountaineering team, grew in rock crevices, which are heated by sunlight and are often warmer than the surrounding alpine environment. "We're facing the limit of life," Dentant says, referring to the extreme conditions in which these plants grew.

Scientists nearly missed out on studying these high-altitude plants, says Sonja Wipf, an alpine plant ecologist at the WSL Institute for Snow and Avalanche Research SLF in Davos, Switzerland. "Not because they were growing on inaccessible rocky ledges," says Wipf, who was not involved in the new research, "but because they were 'buried' in an herbarium." —*Katherine Kornei*


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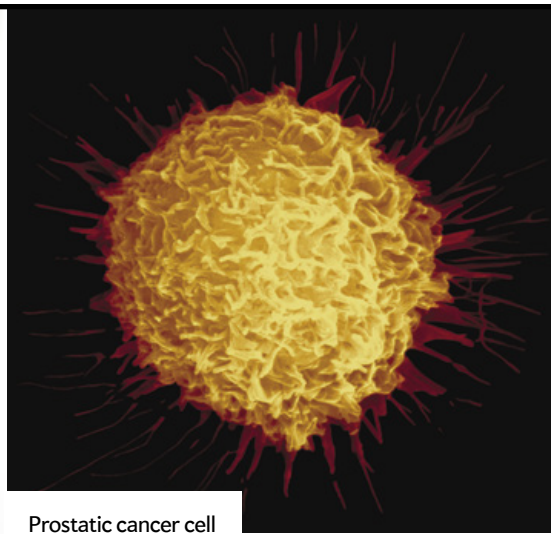
Protein-identifying apparatus



Prostatic cancer cell

ANDREA STARR *Pacific Northwest National Laboratory (apparatus);* SCIENCE SOURCE *(cancer cell)*

HEALTH

Molecular Microscope

New technology lets scientists peer inside single cells

Knowing how proteins behave inside individual human cells can tell us whether those cells will live, die or malfunction—information that can serve as an early warning of disease. But such detailed information is hard to come by because today's analytical methods require minimum samples of hundreds to thousands of cells. Now, however, researchers at Pacific Northwest National Laboratory (PNNL) have developed a "molecular microscope" for detecting and identifying proteins within samples of only a few cells—or even a single cell—and have used it to distinguish between diseased and healthy tissue.

The new apparatus can analyze tissue samples 500 times smaller than those needed for other protein-identification technologies. In one test, scientists used the tool to detect roughly 650 proteins in a single human lung cell. In another, they used it to inspect small samples of human pancreas tissue in a lab dish to determine if the tissue was diabetic or healthy. (Diseased pancreatic cells can block the production of insulin, causing type I diabetes.) The researchers have also employed the technology to identify thousands of proteins from small numbers of healthy human brain, lung, liver and uterus cells. They hope this approach will lead to more targeted and personalized treatments for diseases.

The system first collects tissue samples in minuscule wells etched into the surface of a glass chip. Then a robotic arm dispenses droplets of chemical reagents—for

ENVIRONMENT

Signal in the Noise

Signals from cell-phone towers help to predict imminent fog

Fog often leads to serious, costly collisions and accidents—particularly around airports, piers and highways. Monitoring visibility conditions in real-time could improve public safety and save tens of millions of dollars in the transportation sector alone. But conventional fog-detection systems—including satellites, visibility sensors and human observations—can suffer from poor spatial resolution, high cost or low sensitivity near the ground, where monitoring is most critical.

Now engineers Noam David and H. Oliver Gao, both then at Cornell University, have developed a way to use signal data from cell-phone towers to detect atmospheric conditions that are conducive to fog.

PAOLO TOFFANIN *Getty Images*

Wireless communications data are transmitted within networks of antenna towers as microwave radiation. And weather affects the strength of signals received at the towers. Thus, cellular data offer a low-cost, continuous means of fog monitoring.

David and Gao successfully employed this approach to predict fog in a swath of land around Tel Aviv, Israel, up to an hour before it appeared. They identified patterns in how microwave signals are modified in response to changes in temperature and humidity. In addition, based on how fog droplets attenuate the signals directly, the researchers showed they could detect fog at times when high-level clouds obscure satellite views. Unlike satellites, the method

extracting and isolating proteins—into each hollow. Scientists then use a device called a mass spectrometer to identify the proteins.

Until now, protein-identification technologies could provide only an overall view of larger samples rather than detailed information about the proteins in single cells or very small cell clusters. "We can now isolate and analyze the individual needles from the haystack, whereas before we had to analyze the needles and haystack together," says chemist Ryan Kelly. He and his colleague Ying Zhu, both then at PNNL, co-authored the study published this past summer in *Angewandte Chemie*.

The main reason that working with samples this small is difficult is because some material is lost during each processing step. The new system addresses this issue by using wells that minimize the surface area onto which proteins might stick. David Goodlett, a University of Maryland chemist who was not involved in the work, calls it an exciting step forward. The scientists have developed "an elegant solution to this problem," he says.

The researchers are now applying this technology to identify proteins in single tumor cells circulating in the bloodstream of patients with prostate cancer. The ability to detect such small details in these cells could help explain why some unhealthy tissues become resistant to drugs. —*Rachel Berkowitz*

also distinguishes between ground-level fog and low-level clouds. The research was detailed in studies published in January in the *Journal of Geophysical Research: Atmospheres* and online in August in *Natural Hazards*.

Cellular networks are deployed worldwide, which would make it easy to utilize this method in most regions. "In principle, we could already use existing infrastructure for day-to-day early detection of fog formation," David says. "Because system data can be received in real time, we can imagine short-term early warning against fog." He advocates rigorous testing in diverse parts of the world to probe the method's limitations.

The new work shows it is possible to detect subtle conditions that precede fog formation. Kelly Caylor, an environmental scientist at the University of California, Santa Barbara, who was not involved in the work, calls it "a substantial step forward. There's something remarkable and quite satisfying about finding so much signal in what would otherwise be considered noise." —*Rachel Berkowitz*

Two-spot octopus

ANIMAL BEHAVIOR

Rolling Octopuses

Cephalopods high on MDMA help to reveal the origin of social behavior

Several octopuses might have recently become the happiest individuals in their species' history when researchers gave them MDMA—the party drug often called Molly or Ecstasy. This may sound like a contender for an "Ig Nobel Prize," but the scientists behind the study, published in October in *Current Biology,* say tripping cephalopods can help us better understand the roots of sociability throughout the animal kingdom—including in people. "As human beings, we like to know where we came from," says Gül Dölen, a neuroscientist at the Johns Hopkins School of Medicine and co-author of the new paper. "MDMA is an amazing tool for studying social behaviors across multiple species."

MDMA (short for "3,4-methylenedioxy-methamphetamine") binds to transporter proteins in neurons, vastly increasing the availability of the signaling chemical serotonin. This flood of serotonin produces feelings of euphoria and sociability. Most research on the drug has been conducted in mice and rats, which respond similarly to how people do.

Rodents and humans diverged on the evolutionary tree around 75 million years ago, but a 500-million-year gulf separates us from octopuses. The cephalopods' invertebrate brains are vastly different from our own; they lack regions such as the cortex, basal ganglia and nucleus accumbens that we normally associate with complex interpersonal behaviors. Investigating how serotonin affects a creature so ancient and different from humans—far more so than, say, a rat—can illuminate whether the signaling chemical has always played a role in mediating friendly interactions or whether that function evolved more recently, Dölen says.

Dölen and her co-author Eric Edsinger, a research fellow at the Marine Biological Laboratory in Woods Hole, Mass., placed pairs of sober California two-spot octopuses—a typically antisocial species—in tanks together. One animal in each pair was secured under a mesh pot that allowed it to see, smell and touch the other octopus but prevented the two from fighting. As expected, the free-swimming octopuses chose to spend most of their time on the other side of the tank, as far as possible from the caged ones.

That completely changed when the uncaged octopuses were exposed to a tank containing dissolved MDMA and reintroduced to the experimental tank. Like humans at a rave, the drugged cephalopods relaxed their posture, moved their arms and somersaulted through the water as though they were dancing. They also spent significantly more time near their caged partners, sometimes attempting to touch them and even adopting a hugging posture around the mesh container.

The octopuses' raverlike reactions suggest that the human brain regions so closely associated with social bonding and affability may be evolutionary accidents rather than necessary elements, Dölen says. "This reiterates the importance of understanding function [at] the level of molecules," she adds. "Focusing on brain regions does not give us the whole story."

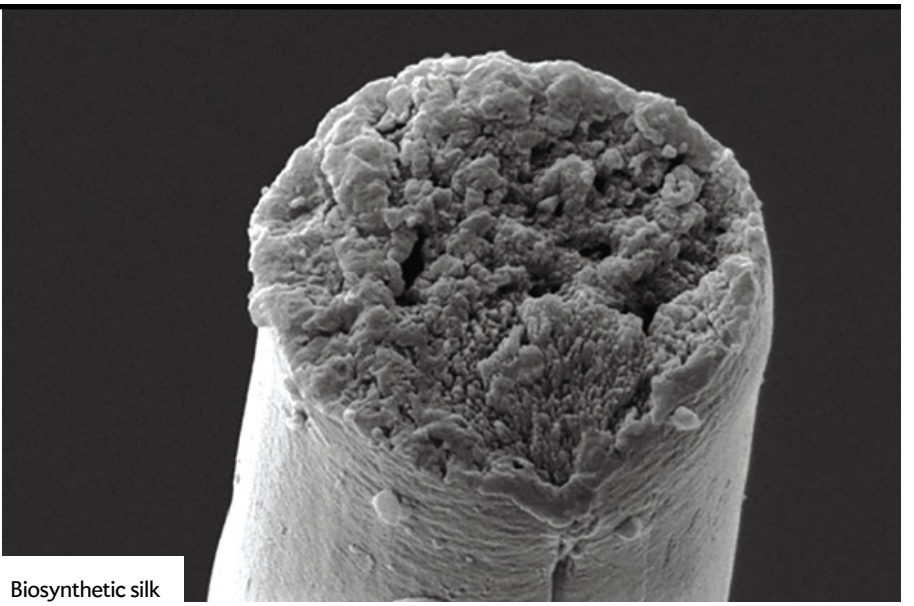
—*Rachel Nuwer*

MARK CONLIN *Getty Images*

SYNTHETIC BIOLOGY

Mimicking Spider Silk

Fibers made by engineered microbes are as strong and flexible as natural ones



Biosynthetic silk

CHRISTOPHER BOWEN *Washington University in St. Louis*

Spiders spin the stuff of engineers' dreams. Their silk is as strong as steel, stretchy, nontoxic and biodegradable. But spiders are not easy to farm. Each produces only a minuscule amount of silk, and some are cannibalistic. For decades scientists have tried to mimic the silvery strands to use for sutures, athletic gear and bulletproof vests, but their synthetic fibers have fallen short. Now a team has coaxed bacteria to produce silk as tough and elastic as the natural version.

Researchers have previously transplanted silk-making DNA from spiders into bacteria, silkworms, plants and even goats in an effort to mass-produce the substance. Until now, however, the best engineered fibers have been only half as strong as the real thing. The secret to spider silk's strength lies in large protein molecules composed of hundreds of strings of repeated amino acids encoded by similarly lengthy, repetitive DNA sequences. But "in general, nature does not like repetitive DNA and finds ways to get rid of it," says Fuzhong Zhang, a professor of energy, environmental and chemical engineering at Washington University in St. Louis. Spiders have figured out how to stabilize the large DNA—but in other creatures, such repeated units get snipped or changed.

To circumvent this problem, Zhang and his colleagues modified the spider DNA involved in producing silk proteins. Microbes engineered with this modified DNA make silk protein molecules with a unique "tag." The tags glue together two molecules to form the desired long chain and then fall off. The resulting proteins are longer than the largest natural proteins. The researchers made these proteins into a powder and mixed it into a solution that can be spun into fibers as strong as natural ones, they reported in September in *Biomacromolecules*.

Synthetic silk could be a sustainable alternative to petroleum-derived fibers such as nylon, Zhang says. But the challenge is producing it in sufficient quantities at low cost. The new approach may still face the same issue because the spinning solution is made with a corrosive and costly solvent, says Gregory Holland, a professor of chemistry and biochemistry at San Diego State University, who was not involved in the work. "The next step," Holland says, "is working on [a water-based] solution to see if similar high-performance fibers can be produced." —*Prachi Patel*

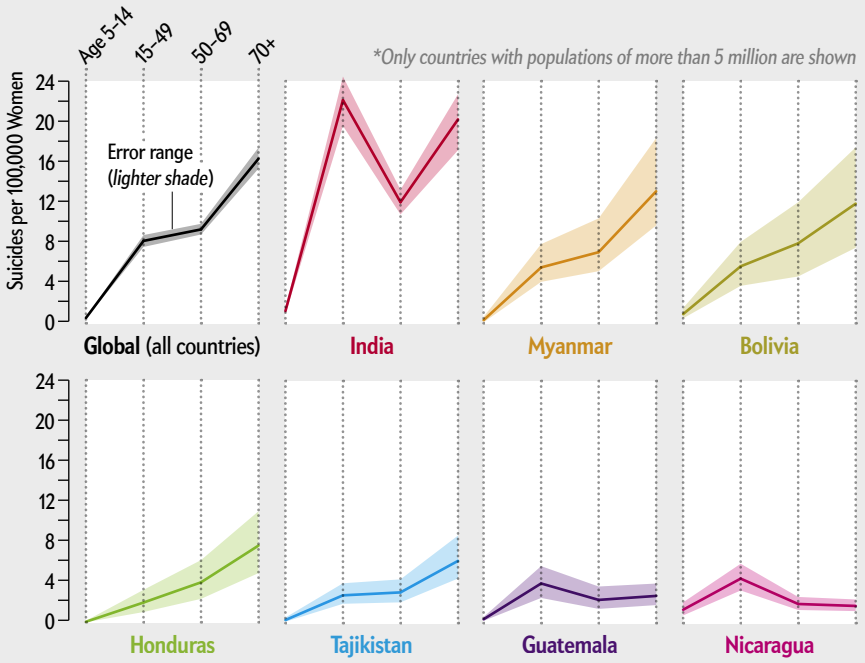
PUBLIC HEALTH

India Has a Female Suicide Crisis

The high rate may be driven by a disconnect between ambition and social acceptance

Women in India are committing suicide at an alarming rate. Research published in the October issue of the *Lancet Public Health* reveals that in 2016 they accounted for more than 36 percent of female suicide deaths globally, despite making up less than 18 percent of the world's female population. Suicide is the leading cause of death among Indian women ages 15 to 29, responsible for about 26 to 33 deaths per 100,000 women in that range. According to the Global Health Data Exchange, a database that tracks worldwide health trends and demographics, India has the highest suicide rate

Suicide Rates among Women in India and Sociodemographically Comparable Countries, 2016*



National suicide rates are typically linked with a country's sociodemographic index (SDI)—a measure of development derived from average income, educational attainment and fertility rate. Based on India's SDI, researchers found that the suicide rate among women there was almost three times higher than expected. Moreover, whereas suicide rates often increase with age, Indian women between 15 and 49 die from self-harm at a rate exceeding that of all other age groups. The graphs compare suicide rates by age group in countries with almost exactly the same SDI as India's. To avoid potential statistical anomalies, countries with populations of fewer than five million are excluded.

SOURCE: GLOBAL HEALTH DATA EXCHANGE

OLFACTION

Smelly Math

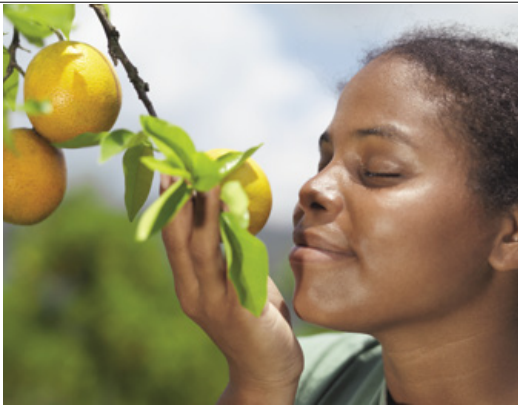
Scientists use geometry to map relations among odor molecules

The human nose finds it simple to distinguish the aroma of fresh coffee from the stink of rotten eggs, but the underlying biochemistry is complicated. Researchers have now created an olfactory "map"—a geometric model of how molecules combine to produce various scents. This map could inspire a way to predict how people might perceive certain odor combinations and help to drive the development of new fragrances, scientists say.

Researchers have been trying for years to tame the elaborate landscape of odor molecules. Neuroscientists want to better understand how we process scents; perfume and food manufacturers want better ways to synthesize familiar aromas for their products. The new approach may appeal to both camps.

One earlier strategy for mapping the olfactory system involves grouping odor molecules that have similar molecular structures and using those similarities to predict the scents of novel combinations. But that avenue often leads to a dead end. "It's not necessary that chemicals with the same chemical structures will be perceived similarly," says Tatyana Sharpee, a neurobiologist at the Salk Institute for Biological Studies in La Jolla, Calif., and lead author of the study, which appeared in August in *Science Advances*.

Sharpee and her colleagues analyzed odor molecules found in four familiar and unmistakable scents: strawberries, tomatoes, blueberries and mouse urine. The researchers calculated how often and in



MONTY RAKUSEN Getty Images

what concentrations certain molecules turned up together in these scents. They then created a mathematical model in which molecules that occurred together frequently were represented as closer in space and molecules that rarely did so were farther apart. The result was a "saddle"-shaped surface—a hallmark of a field called hyperbolic geometry, which

Graphic by Amanda Montañez

among young and middle-aged women for countries with similar sociodemographics.

The situation may be related to a clash between women's aspirations and the rigidity of their social environment, hypothesizes study author Rakhi Dandona, a professor of global health at the Public Health Foundation of India and the University of Washington. As India has developed, women have become better educated and more empowered, and arranged marriages have declined. Yet in many aspects of society, women still possess lower status and face barriers to opportunity. Dandona and other experts suspect this disconnect may drive some to despair. Suicide rates are especially high in southern Indian states, where development and social advances have accelerated. In contrast, Dandona says, suicide rates in the rural, more traditional northern states could be lower because women there may have "less knowledge that they could actually live a better life."

"Deaths that occur due to suicide are also a product of the method that is used," says Vikram Patel, a professor of global health at Harvard University, who was not involved in the *Lancet Public Health* study. In the West, women attempt suicide more often than men, but men typically use more lethal means, resulting in more deaths. In India, however, Patel says that men and women tend to use the same, more fatal, methods. —*Dana G. Smith*

obeys different rules from the geometry most people learn in school.

The researchers envision an algorithm, trained on this hyperbolic geometry model, that can predict the scents of new odor combinations—or even help to synthesize them. One of Sharpee's collaborators, behavioral neuroscientist Brian Smith of Arizona State University, wants to use this method to create olfactory environments in places devoid of natural scents.

Such a tool would be useful to scientists and odor manufacturers alike, says olfactory neuroscientist Joel Mainland of the Monell Chemical Senses Center in Philadelphia, who was not involved in the study. The ultimate goal is to know enough about how odors work to replicate natural smells without the natural sources, Mainland says: "We want to identify a strawberry flavor without worrying about replicating the ingredients that are in a strawberry." —*Stephen Ornes*

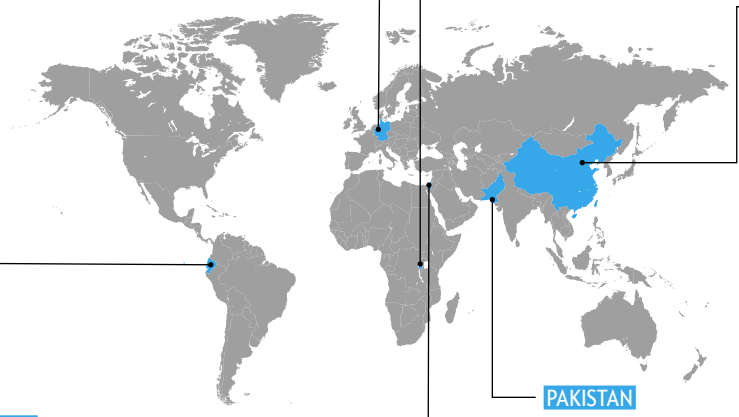
IN THE NEWS

Quick Hits

By Ankur Paliwal

GERMANY
Germany has launched the world's first hydrogen-powered trains in an effort to reduce its dependence on fossil fuels. The trains, which can reach speeds up to 140 kilometers per hour, have fuel cells that convert hydrogen and oxygen into electricity.

RWANDA
Rwanda is setting up its first research center for noncommunicable diseases, including diabetes and cancer. Such illnesses currently account for 46 percent of the country's total deaths by all diseases—a 100 percent increase from 2000.



ECUADOR
Scientists have identified a new hummingbird species in the Ecuadorian Andes. But very few of the birds exist, and the species is considered critically endangered. Its habitat is shrinking as nearby communities burn the native landscape to make way for cattle grazing.

CHINA
The Chinese government is requiring athletes who want to compete for the country in the 2022 Beijing Olympic Games to have their genomes sequenced. Officials say this practice is to screen for medical conditions that could affect the competitors' performance; some scientists have called it discriminatory.

ISRAEL
Scientists have discovered the world's oldest-known brewery in a cave near Haifa. They found residue from 13,000-year-old wheat- and barley-based beer that resembled porridge. The previous earliest known brewery was thought to be 5,000 years old.

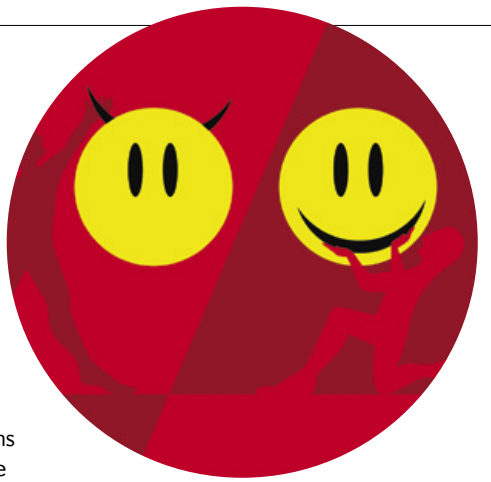
PAKISTAN
Researchers have detected the flesh-eating amoeba *Naegleria fowleri* in the domestic water supply of Karachi, Pakistan's most populous city. The metropolis of 15 million people has seen an alarming uptick in cases of a fatal type of encephalitis caused by the parasite.

For more details, visit www.ScientificAmerican.com/dec2018/advances

PSYCHOLOGY

Second Chances

First impressions about "bad" people are not set in stone



Common wisdom holds that negative first impressions are hard to shake—and some research backs this up. But such studies often unfairly compare impressions based on immoral deeds that are extreme and relatively rare (such as selling drugs to kids) with impressions based on kindnesses that are more common (such as sharing an umbrella). A new set of studies involving precisely balanced behaviors finds that people are more willing to change their mind about individuals who initially come off as selfish than about those they deem selfless.

In three of the experiments, 336 laboratory and online participants read about two people who each made a series of 50 decisions regarding how many electric shocks to give someone in exchange for money. One fictional subject required more money per shock than the average person did to inflict pain on others. The other's price-per-shock threshold was comparably lower than the average person's. Study participants read about each subject's decisions one at a time. Before seeing each decision, they predicted what it would be. After every three decisions the fictional subject made, participants rated the individual on a scale from "nasty" to "nice," then specified their confidence in the rating.

As expected, participants rated the person who gave shocks for a lower price as nastier than the higher-price shocker. But they expressed less confidence in the "nasty" ratings, and their predictions of how many shocks that person would give fluctuated more. In other words, their beliefs about the "bad" subject were more changeable. "A well-designed brain system would not write someone off completely at the first sign of trouble," says Molly Crockett, a psychologist at Yale University, who co-authored a paper about the new set of studies, published in October in *Nature Human Behaviour*. An open mind helps people forgive and form bonds, Crockett adds.

The test scenarios are a far cry from real-world interactions. Still, the experiment offers "a really elegant paradigm that drills down on a question that's so central to our everyday human life," says Peter Mende-Siedlecki, a psychologist at the University of Delaware, who was not involved in the study. Crockett suspects the findings about social impressions reflect a general mental process of absorbing more information in threatening situations. She describes the resultant social tendency as a double-edged sword: "It's very good for conflict resolution—but at the same time it could trap you in a bad relationship." —*Matthew Hutson*

Illustration by Thomas Fuchs

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Cultivating a Computer-Side Manner

There's a right way for doctors to integrate technology into patient care

By Claudia Wallis

I don't know if you've noticed this, but something has come between you and your doctor. It's there at every office visit, stealing the doc's attention and punctuating conversations with awkward silences and the light clicking of a keyboard. Yes, it's the computer, an omnipresent participant in the modern medical exam.

Electronic health records (EHRs)—and the computers that support them—crept onto the scene about 25 years ago, but they took off after getting a $19-billion boost in 2009 as part of the federal economic stimulus package. Several other countries, especially those with national health care systems, had already adopted EHRs, reaping the benefits of instant access to a patient's history, prescriptions, and much more. The U.S. was playing catch-up.

Alas, the rollout was excruciating. University of Chicago pediatrician Lolita Alkureishi vividly remembers the 2010 arrival of EHRs at the clinic where she sees patients. "It was like seeing the five stages of grief," says Alkureishi, who had volunteered to orient colleagues to the system. "People were angry and cursing at the computer. They were sad, lamenting the loss of paper charts. People were trying to bargain with me—saying, 'Could you just put in the orders for me?' Some finally accepted it, and some never got to that stage." Sadly, a number of veteran physicians took the arrival of EHRs as a cue that it was time to retire, recalls Neda Ratanawongsa, associate professor of internal medicine at the University of California, San Francisco.

The shift reshaped the doctor-patient relationship, says Elizabeth Toll, a pediatrician and internist at Brown University: "Prior to that I would have told you I had a job that revolved around people. Immediately thereafter I had a job that revolved around the computer. If you didn't pay 100 percent attention to the machine, you'd start making mistakes: you'd pick the wrong medicine or the wrong dose or send orders for the wrong test. I would often feel that the patient was slipping into second place." In fact, a 2017 study showed doctors spent twice as much time on clerical work—much of it after hours—as seeing patients.

Alkureishi decided to investigate the phenomenon, working with internist Wei Wei Lee, assistant dean of students at Chicago's Pritzker School of Medicine. They led a 2016 meta-analysis of 53 studies examining the impact of EHRs on patient-physician interactions. Six of the studies quantified EHR use and found it consumed, on average, 32 percent of a doctor visit. A 2017 study by Ratanawongsa found that health care providers spent 30.5 percent of a visit dividing their attention between patient and computer, another 4.6 percent silently tapping away and 33.1 percent in focused discussion with the patient.

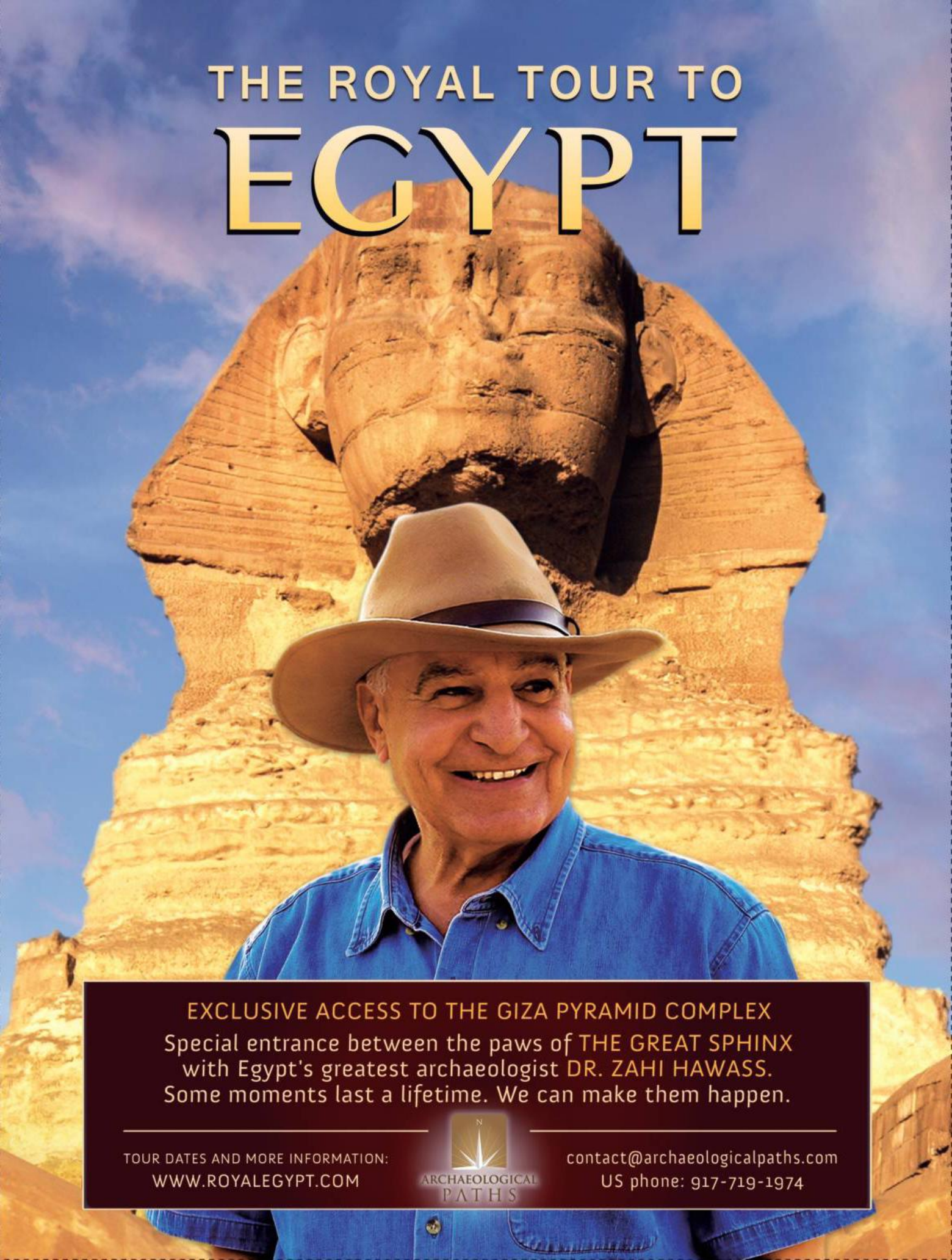
The meta-analysis identified both good and worrisome behaviors. Conversation was too often synchronized to typing pauses and subject to abrupt shifts, as the doctor worked through screens of required questions. Only about 10 percent of doctors shared the screen with patients, but when they did, patients liked it. One study found that when trauma patients were shown scans of their injuries on a tablet, they felt more involved in their care.

Based on their research, Lee and Alkureishi developed a set of "patient-centered" best practices for EHRs that are now taught to all Pritzker students and included in EHR training for medical staff. Among the tips: review patient records before the visit so you can begin the first "golden minute" with eye contact and conversation; position the computer in a "triangle of trust" where the patient can also see it; narrate data entry aloud so the patient can listen and comment; and disengage with technology when discussing sensitive matters. The authors also encourage using online videos and graphics as what Lee calls "a communication-enhancing tool" for patients. They have shared their ideas widely, including via a brief Doctor's Channel video.

One reason EHR systems were so disruptive in the U.S. is that they were designed with billing in mind, as opposed to simply patient care, as is the case in countries such as Sweden and the U.K. Newer systems are better, Ratanawongsa says, and integrated with tools for patients. At the same time, some practices are employing "medical scribes" as notetakers or employing a "team care" approach in which a nurse or assistant shares the record-keeping role. Making patients aware of ways to avoid letting technology hijack their visit also helps. If that starts to happen, speak up! SA

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*.

Illustration by Celia Krampien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A Meditation on Keyboard Shortcuts

They were Apple's brilliant innovation, and they *usually* make sense

By David Pogue

In the beginning, there was the keyboard. If you wanted to issue a command to your computer, you typed it. Then came the Apple Macintosh, which popularized the mouse as standard equipment. No longer would people have to memorize key commands! No longer was the computer a plaything of the geeky intelligentsia! The menus would list all available commands, and the mouse would choose them.

Even Apple, though, hedged its bets. Nestled on either side of the space bar were keys not found on any typewriter. They were modifier keys, to be used exclusively for keyboard shortcuts, aimed at those who still found tapping keys to be more efficient than mousing to the menu.

To this day, some people live by keyboard shortcuts—on Windows it's Control C for Copy, Control V for paste—and others use the mouse. Each looks at the other with disdain.

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

As a member of the former group, I think a lot about the mnemonics of keyboard shortcuts. Your English keyboard has 26 alphabet keys, plus four or five modifier keys. (Their names differ on Mac and Windows, but it's some combination of Shift, Alt/Option, Ctrl/Command, Control, Windows and sometimes Fn.)

These shortcuts have to trigger dozens of commands in an infinitude of programs. How can anyone keep them straight? It helps that Apple came up decades ago with simple combos for the most important functions across all programs. While pressing the Command key, you press the first letter of Print (P), Bold (B), Italic (I), Underline (U), New (N), Quit (Q) or Save (S). Microsoft later adopted the same sequences (using Ctrl instead of Command), so that they're now universal on all computers. Thank goodness for copycats—I mean, standards. But Apple also came up with Z for Undo, X for Cut, C for Copy and V for Paste. They're consecutive keys on the bottom row, but otherwise not so memorable.

Here's the logic that Macheads used to explain those mappings. "Well, Z, the last letter because it Undoes the *last thing* you've done. X for Cut because X looks like a pair of scissors. And V for Paste because it looks like the proofreading mark for 'insert.'" Well, okay.

Things break down when more than one command starts with the same letter. Most of the Windows logo keystrokes on a PC are straightforward: E for Explorer, L for Lock. But what about the Start Dictation command? It can't use S, because that's Search; can't use D, because that's Display Desktop. So we get Windows H—a letter that doesn't even appear in "Start Dictation."

I guess keyboard shortcuts are on my mind lately because of a massive mistake Apple made in 2015. It goes like this:

If there's one keyboard shortcut that's nearly universal, it's the space bar to *play or pause* a video or audio. It works on every video site (YouTube, Netflix, Hulu …), every editing program (Movie Maker, Final Cut, Premiere, Avid …), every photo app (Google Photos, Amazon Photos, Flickr, iPhoto, Windows Photos …).

But in 2015 Apple introduced a new Mac Photos app. In this program, the space bar did not mean "play video." There *was* no keyboard shortcut for "play video." Instead Apple had mapped the space bar for opening a photo thumbnail to see it at full size. To play a video, you had to move your hand from the keyboard to the mouse or track pad. This from the company that *invented* the space bar playback convention! (Fortunately, in the latest version of Photos, the space bar once again means "play/pause." Now, to open or close a photo, you press the Return key. It's taking me some time to adjust, but with therapy, I'm getting there.)

Truth is, you don't have to settle for the mappings Apple and Microsoft have come up with. You can change almost any Mac keyboard shortcut to whatever you want, and free programs let you do the same in Windows. These days it's *your* problem if the keystroke is awkward. But anything's better than lifting your hand to pick up the mouse. Who wants to do *that?*

SCIENTIFIC AMERICAN ONLINE
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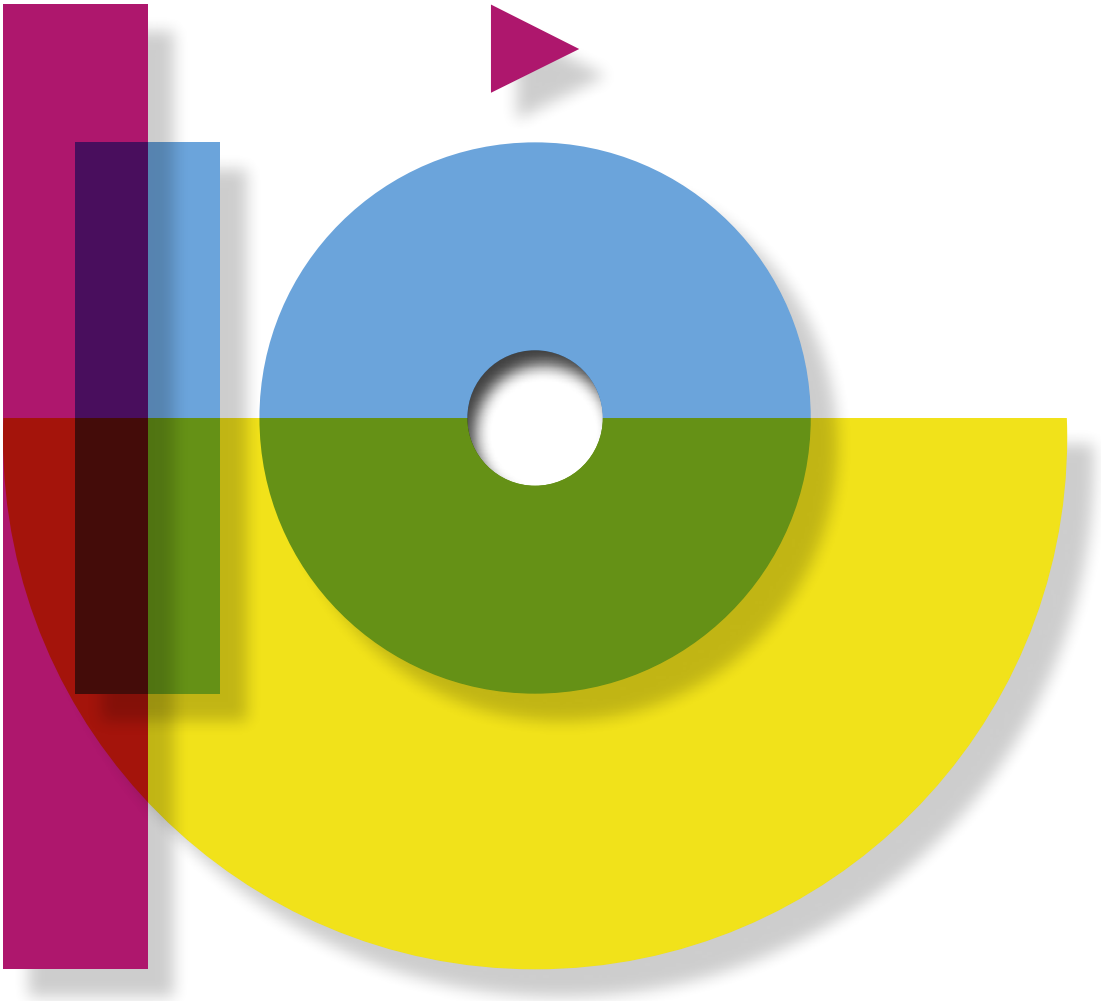


SPECIAL REPORT

TOP 10 EMERGING TECHNOLOGIES OF 2018

UNDERSTANDING THE LATEST INNOVATIONS—AND THEIR CHALLENGES—WILL HELP SOCIETY DETERMINE HOW TO MAXIMIZE THEIR BENEFITS

Illustrations by Vanessa Branchi

IN BRIEF

Artificial-intelligence technologies are being deployed to search for novel drugs and materials, as well as improve today's digital assistants. Soon virtual images will be overlaid on our physical world. And quantum computers are catching up to classical machines.

In health, advanced diagnostic tools are expanding the depth of precision medicine. Implantable, drug-making cells that escape detection of the immune system and nerve-stimulating therapies could both enhance the management and treatment of diseases.

To address the complex problems of society, researchers are growing meat from stem cells, while the gene-drive community develops rules to govern how species-altering tools get used. Light-controlled nanomaterials could boost the efficiency of solar cells.

How will technology change your life in the near future? Artificial intelligence will greatly hasten the design of innovative drugs and materials. Advanced diagnostic tools will enable increasingly personalized medicine. Augmented reality will be everywhere, overlaying information and animation on real-world images to help you with everyday tasks—and to help industry to operate more efficiently. If you get sick, doctors will be able to implant living cells in your body that will act like drug factories, treating what ails you. And you will be eating eat beef, chicken and fish grown from stem cells, greatly reducing the environmental impact of animal farming and sparing countless creatures from inhumane treatment.

These world-changing ideas, along with others that make up this year's list of "Top 10 Emerging Technologies," were selected by leading experts in fields such as biology, inorganic chemistry, robotics and artificial intelligence. The list is the result of an intensive selection process.

First, we cast a wide net, soliciting recommendations from innovators in the World Economic Forum's Global Future Councils and Expert Network communities, members of *Scientific American*'s advisory board and editorial staff, and others. Then, in a series of virtual meetings, a Steering Group evaluated how well the candidates met several criteria. The technologies had to have the ability to provide significant benefits to societies and economies and to do so in the next three to five years. They had to be potentially disruptive, able to alter industries or established ways of doing things. And they had to be in relatively early stages of development—not yet in widespread use but being studied by many groups, generating excitement among experts, attracting increasing investment and, ideally, being developed by more than one company. The Steering Group trimmed the initial list of more than 50 submissions in its first meeting and then compiled additional information to assess the roughly 20 candidates that remained. It made its final decisions after gathering more information in two further discussions.

—Mariette DiChristina and Bernard S. Meyerson

COMPUTER SCIENCE

AUGMENTED REALITY EVERYWHERE

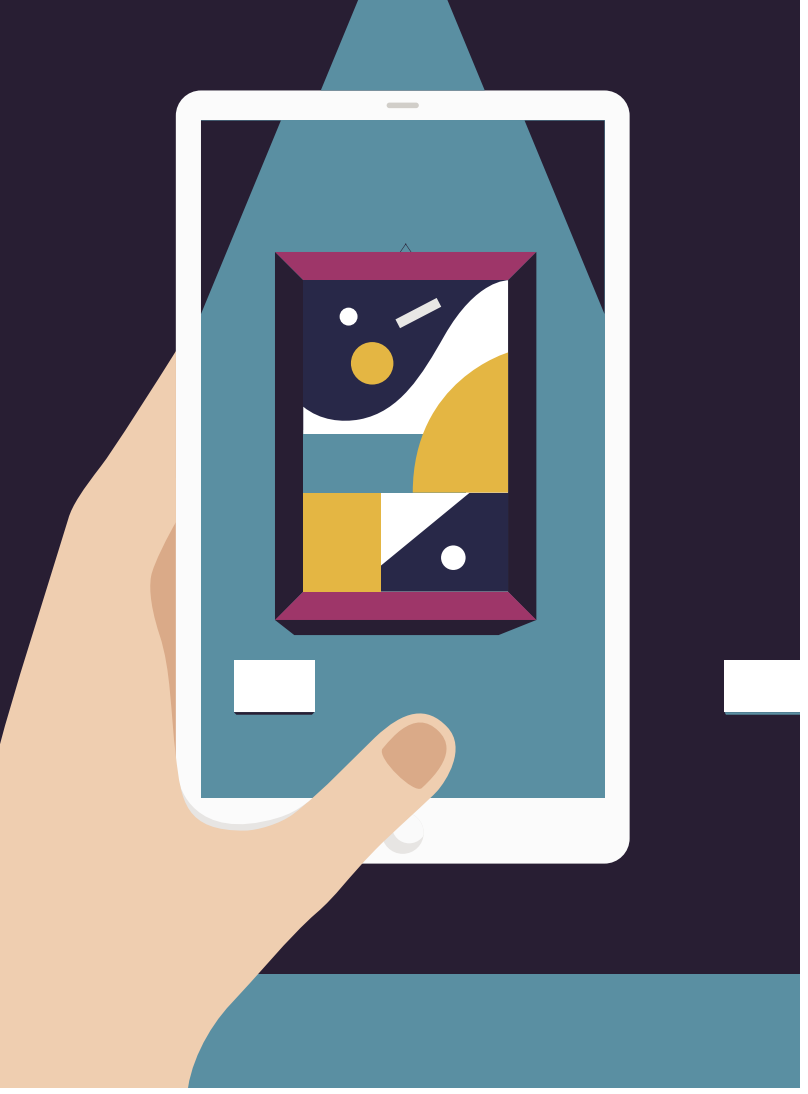
THE WORLD WILL BE OVERLAID WITH DATA

By Corinna E. Lathan and Andrew Maynard

Virtual reality (VR) immerses you in a fictional, isolated universe. Augmented reality (AR), in contrast, overlays computer-generated information on the real world in real time. As you look at or wear a device equipped with AR software and a camera—be it a smartphone, a tablet, a headset or smart glasses—the program analyzes the incoming video stream, downloads extensive information about the scene and superposes on it relevant data, images or animations, often in 3-D.

Two examples: the display that helps your car to back up safely and the popular game Pokémon GO. A multitude of consumer apps—including ones that translate street signs for foreign visitors, enable students to dissect virtual frogs and allow shoppers to see how a chair will look in their living room before they bring it home—also feature AR. In the future, the technology will enable museumgoers to conjure up guides resembling holograms; surgeons to visualize tissues underneath a patient's skin in 3-D; architects and designers to collaborate on their creations in novel ways; drone operators to control their remote robots with enhanced imagery; and novices to speedily learn new tasks in areas ranging from medicine to factory maintenance.

Easy-to-use software for designing apps should expand consumer offerings in the coming years. At the moment, though, AR is having its greatest impact in industry, where it is an integral component of the "Fourth Industrial Revolution," or "Industry 4.0": the systemic transformation of manufacturing through the integration of physical and digital systems to improve quality, lower costs and increase efficiency. Many companies, for instance, are testing its use on assembly lines. AR can deliver just the right information at the very moment it is needed (such as when a worker has to select one part over another)—thereby reducing errors, enhancing efficiency and improving productivity. It can also visualize stresses in equipment



and create real-time images of where problems lie.

Market analysts, such as ABI Research, IDC and Digi-Capital, believe that augmented reality is on the cusp of going mainstream. They expect the total market for AR, currently valued at about $1.5 billion, to grow to $100 billion by 2020. Major technology companies—including Apple, Google and Microsoft—are devoting large financial and human resources to both AR and VR products and applications. And venture capital is starting to roll in, with $3 billion invested in AR and VR in 2017—half of that amount in the fourth quarter alone. *Harvard Business Review* recently highlighted AR as a transformative technology that will affect all businesses.

Obstacles persist. At the moment, limitations of hardware and communication bandwidth pose barriers to scaling up for everyday use by consumers. For example, many existing museum and travel apps that use AR to enhance an experience have to be downloaded in advance. Even then, the quality of the graphics may not meet users' expectations. But the field is set to grow dramatically as cheaper, faster AR-ready mobile chips become available, more versatile smart glasses come to market and bandwidth increases. Then augmented reality will join the Internet and real-time video as an unexceptional part of our everyday lives.

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2

MEDICINE

ELECTRO-CEUTICALS

NERVE-STIMULATING THERAPIES COULD REPLACE DRUGS FOR MANY CHRONIC CONDITIONS

By Geoffrey Ling and Corinna E. Lathan

Electroceuticals—devices that treat ailments with electrical impulses—have a long history in medicine. Think pacemakers for the heart, cochlear implants for the ears and deep-brain stimulation for Parkinson's disease. One of these approaches is poised to become more versatile, dramatically improving care for a host of conditions. It involves delivering signals to the vagus nerve, which sends impulses from the brain stem to most organs and back again.

New uses of vagal nerve stimulation (VNS) have become possible in part because of research by Kevin Tracey of the Feinstein Institute for Medical Research and others showing that the vagus nerve emits chemicals that help to regulate the immune system. The release of a specific neurotransmitter in the spleen, for instance, quiets immune cells involved in inflammation throughout the body. These findings indicated that VNS might be beneficial for disorders beyond ones marked by disturbed electrical signaling, such as autoimmune and inflammatory conditions. It could be a boon for patients with those conditions because existing drugs often fail or cause serious side effects. VNS may be easier to tolerate because it acts on a specific nerve, whereas drugs generally travel throughout the body, potentially disrupting tissues beyond those targeted for treatment.

So far studies of inflammation-related applications are encouraging. VNS devices developed by SetPoint Medical (co-founded by Tracey) have proved safe in early human trials for rheumatoid arthritis, which causes painful, disfiguring inflammation of joints, and for Crohn's disease, which involves inflammation of the intestines. Additional trials for both are currently under way. The electroceutical approach is also being considered for other maladies that have an inflammatory component, such as cardiovascular disease, metabolic dysregulation and dementia, as well as for autoimmune disorders such as lupus, in which the vagal nerve itself becomes underactive. Preventing immune rejection of transplanted tissues is yet another potential application.

Most vagal nerve stimulators, including SetPoint's devices and those already in use for treating epilepsy and depression, are implants. Physicians usually place the device under the skin below the clavicle. Wires from the implant wrap around one branch of the vagus nerve and deliver electrical impulses to it at preset intervals; the frequency and other properties are programmed via an external magnetic wand. Today's implants measure about an inch and a half in diameter but are expected to become smaller and more finely programmable over time.

Noninvasive, handheld vagal nerve stimulators meant to ease cluster headaches and migraine have recently also gained FDA approval, although exactly how vagal nerve stimulation helps those conditions is unclear. The handheld devices deliver mild electrical stimulation to the nerve through skin on the neck or through the ear.

The vagus nerve is not the only one to be targeted by new electroceutical approaches. In late 2017 the FDA approved a nonimplanted device that eases opioid withdrawal by sending signals to branches of the cranial and occipital nerves through skin behind the ear. The device gained the FDA's nod after 73 patients suffering from opioid withdrawal saw a 31 percent or higher reduction in symptom severity.

The cost of implants and surgery could hamper widespread adoption of VNS therapy, although that problem should ease as the technology becomes less invasive.

Noninvasive, handheld vagal nerve stimulators meant to ease cluster headaches and migraine have recently gained FDA approval. Exactly how vagal nerve stimulation helps is unclear.

But cost is not the only challenge. Researchers still need to know more about how VNS produces its effects in each condition and how best to determine the optimal patterns of stimulation for individual patients. It is also possible that impulses targeted at the vagus nerve may affect surrounding nerves in undesirable ways.

Nevertheless, as more studies and trials examine the mechanisms and effects, VNS and other electroceuticals may ultimately be able to better manage a wide range of chronic conditions, potentially reducing the need to take medicine for millions of patients.

CHEMISTRY

3

MEAT GROWN FROM STEM CELLS

BEEF FOR DINNER—WITHOUT KILLING ANIMALS OR THE ENVIRONMENT

By G. Owen Schaefer

Imagine biting into a juicy beef burger that was produced without killing animals. Meat grown in a laboratory from cultured cells is turning that vision into a reality. Several start-ups are developing lab-grown beef, pork, poultry and seafood—among them Mosa Meat, Memphis Meats, SuperMeat and Finless Foods. And the field is attracting millions in funding. In 2017, for instance, Memphis Meats took in $17 million from sources that included Bill Gates and agricultural company Cargill.

If widely adopted, lab-grown meat, also called clean meat, could eliminate much of the cruel, unethical treatment of animals that are raised for food. It could also reduce the considerable environmental costs of meat production; resources would be needed only to generate and sustain cultured cells, not an entire organism from birth.

The meat is made by first taking a muscle sample from an animal. Technicians collect stem cells from the tissue, multiply them dramatically and allow them to differentiate into primitive fibers that then bulk up to form muscle tissue. Mosa Meat says that one tissue sample from a cow can yield enough muscle tissue to make 80,000 quarter-pounders.

A number of the start-ups say they expect to have products for sale within the next few years. But clean meat will have to overcome a number of barriers if it is to be commercially viable.

Two are cost and taste. In 2013, when a burger made from lab-grown meat was presented to journalists, the patty cost more than $300,000 to produce and was overly dry (from too little fat). Expenses have since fallen. Memphis Meats reported this year that a quarter-pound of its ground beef costs about $600. Given this trend, clean meat could become competitive with traditional meat within several years. Careful attention to texture and judicious supplementing with other ingredients could address taste concerns.

To receive market approval, clean meat will have to be proved safe to eat. Although there is no reason to think that lab-produced meat would pose a health hazard, the FDA is only now beginning to consider how it should be regulated. Meanwhile traditional meat producers are pushing back, arguing that the lab-generated products are not meat at all and should not be labeled as such, and surveys show that the public has only tepid interest in eating meat from labs. Despite these challenges, the clean meat companies are forging ahead. If they can succeed in creating authentic-tasting products that are also affordable, clean meat could make our daily eating habits more ethical and environmentally sustainable.

4

COMPUTER SCIENCE

BOTS THAT ARGUE AND INSTRUCT

NEW ALGORITHMS WILL ENABLE PERSONAL DEVICES TO LEARN ANY TOPIC WELL ENOUGH TO DEBATE IT

By Bernard S. Meyerson

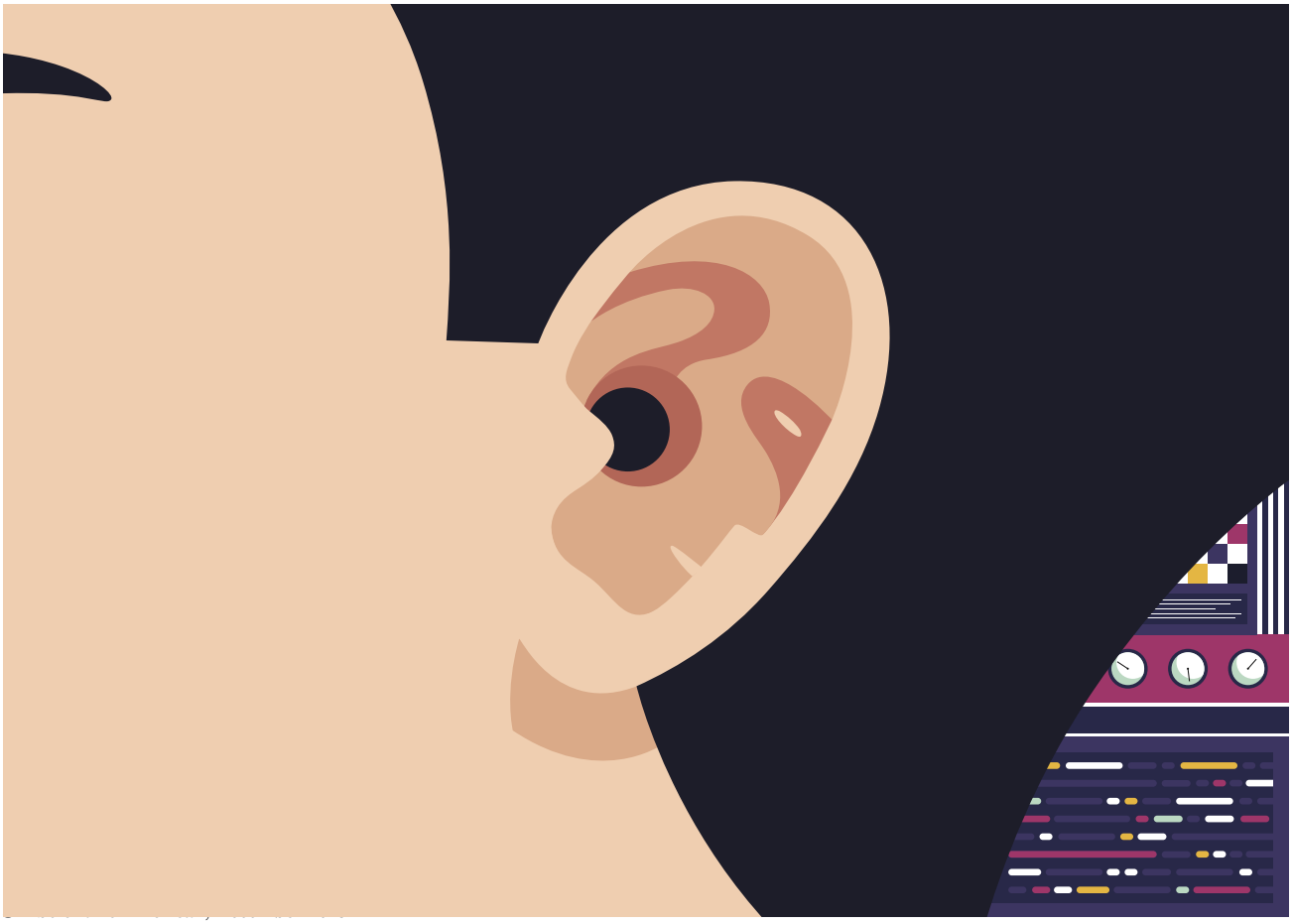
Today's digital assistants can sometimes fool you into believing they are human, but vastly more capable digital helpers are on their way. Behind the scenes, Siri, Alexa and their ilk use sophisticated speech-recognition software to figure out what you are requesting and how to provide it, and they generate natural-sounding speech to deliver scripted answers matched to your questions. Such systems must first be "trained"—exposed to many, many examples of the kinds of requests humans are likely to make—and the appropriate responses must be written by humans and organized into highly structured data formats.

That work is time-consuming and results in digital assistants that are restricted in the tasks they can perform. The systems can "learn"—their machine-learning capabilities allow them to improve their matching of incoming questions to existing answers—but to a limited extent. Even so, they are extremely impressive.

At a higher level of sophistication, technologies are now being developed to allow the next generation of such systems to absorb and organize unstructured data (raw text, video, pictures, audio, e-mails, and so on) from myriad sources and then autonomously compose cogent advice—or debate an opponent—on a subject they have never been trained to handle.

We have seen glimpses of this capability at Web sites offering chatbots that, out of the box, can answer natural-language questions covering a wide variety of data sets they have trained on. Such chatbots need relatively little or no training on specific questions or requests; they use a combination of preconfigured data and the emergent ability to "read" relevant background materials supplied to them. They do, however, require some training in recognizing words and intentions before they can give highly accurate responses.

In June my employer, IBM, demonstrated a more advanced version of the technology: a system carried on a debate with a human expert in real time without having prior training on the topic or the position to be



argued. Using unstructured data (including content from Wikipedia, some of which was edited for clarity), the system had to ascertain the relevance and veracity of the information and organize it into a reusable asset that it could call on to form coherent arguments supporting the position it had been assigned. It also had to respond to the arguments of its human opponent. The system engaged in two debates during the demonstration and was judged more persuasive in one of the two by a large group of spectators.

The enabling technology—which included software that could not only understand natural language but also handle the harder challenge of detecting positive and negative sentiment—was developed over more than five years and is still very much a work in progress. Nevertheless, the win by an unscripted AI system against an acknowledged human expert opens the door for countless related applications that could appear in the next three to five years, if not sooner. Such systems could, for instance, help physicians to quickly find research relevant to a complex case and then debate the merits of a given treatment protocol.

These intelligent systems will be useful only for assembling existing knowledge, not for creating it the way a bench scientist or an expert would. Still, as machines become increasingly intelligent, they raise the specter of job losses. It behooves society to provide the next generation with the skills it needs to tackle problems that require human ingenuity to solve.

BIOTECHNOLOGY

IMPLANTABLE DRUG-MAKING CELLS

THERAPIES CAN BE RELEASED IN THE BODY AS NEEDED—WITHOUT GETTING ATTACKED BY THE IMMUNE SYSTEM

By Sang Yup Lee

Many people with diabetes prick their fingers several times a day to measure blood sugar levels and decide on the insulin doses they need. Implants of pancreatic cells that normally make insulin in the body—so-called islet cells—can render this cumbersome process unnecessary. Likewise, cellular implants could transform treatment of other disorders, including cancer, heart failure, hemophilia, glaucoma and Parkinson's disease. But cellular implants have a major drawback: recipients must take immunosuppressants indefinitely to prevent rejection by the immune system. Such drugs can lead to serious side effects, including an increased risk of infection or malignancies.

Over several decades scientists have invented ways to enclose cells in semipermeable protective membranes that keep the immune system from attacking the implanted cells. These capsules still allow nutrients and other small molecules to flow in and needed hormones or other therapeutic proteins to flow out. Yet keeping the cells out of harm's way is not enough: if the immune system views the protective material itself as foreign, it will cause scar tissue to grow over the capsules. This "fibrosis" will prevent nutrients from reaching the cells, thereby killing them.

Now investigators are beginning to solve the fibrosis challenge. For instance, in 2016 a team at the Massachusetts Institute of Technology published a way to make implants invisible to the immune system. After producing and screening hundreds of materials, the researchers settled on a chemically altered version of a gel called alginate, which has a long history of safe use in the body. When they implanted islet cells encapsulated in this gel into diabetic mice, the cells immediately produced insulin in response to changing blood sugar levels—keeping them under control over the course of a six-month study. No fibrosis was observed. In separate work, the team later reported that blocking a particular molecule (the colony-stimulating factor 1 receptor) on macrophages, which are immune cells important in fibrosis, can inhibit scarring. Adding such a blocker should further enhance the survival of implants.

Several companies have formed to develop encapsulated-cell therapies. One of these, Sigilon Therapeutics, is advancing the technology developed at M.I.T. to design treatments for diabetes, hemophilia and a metabolic disorder called lysosomal storage disease. Pharmaceutical company Eli Lilly is partnering with Sigilon on the diabetes work. In other examples, Semma Therapeutics is also focusing on diabetes, using its own technology; Neurotech Pharmaceuticals has implants in clinical trials for glaucoma and various eye disorders marked by degeneration of the retina; Living Cell Technologies is running clinical trials of implants for Parkinson's and is developing therapies for other neurodegenerative conditions.

Today the cells being incorporated into capsules are drawn from animals or human cadavers or are derived from human stem cells. One day implantable cell therapies may include a broader array of cell types, including some engineered through synthetic biology—which reprograms a cell's genetics to make it perform novel functions, such as controlled, on-demand release of specified drug molecules into a tissue. These are still early days. Neither the safety nor the efficacy of encapsulated-cell therapy has been proved in large clinical trials, but the signs are encouraging.

6

ARTIFICIAL INTELLIGENCE

AI FOR RAPID MOLECULAR DESIGN

MACHINE-LEARNING ALGORITHMS ARE SPEEDING UP THE SEARCH FOR NOVEL DRUGS AND MATERIALS

By Jeff Carbeck

Want to design a new material for solar energy, a drug to fight cancer or a compound that stops a virus from attacking a crop? First, you must tackle two challenges: finding the right chemical structure for the substance and determining which chemical reactions will link up the right atoms into the desired molecules or combinations of molecules.

Traditionally answers have come from sophisticated guesswork aided by serendipity. The process is extremely time-consuming and involves many failed attempts. A synthesis plan, for instance, can have hundreds of individual steps, many of which will produce undesired side reactions or by-products or simply not work at all. Now, though, artificial intelligence is starting to increase the efficiency of both design and synthesis, making the enterprise faster, easier and cheaper while reducing chemical waste.

In AI, machine-learning algorithms analyze all known past experiments that have attempted to discover and synthesize the substances of interest—those that worked and, importantly, those that failed. Based on the patterns they discern, the algorithms predict the structures of potentially useful new molecules and possible ways of manufacturing them. No single machine-learning tool can do all this at the push of a button, but AI technologies are moving rapidly into the real-world design of drug molecules and materials.

An AI tool developed by researchers at the University of Münster in Germany, for example, repeatedly simulates the 12.4 million known single-step chemical reactions to come up with a multistep synthetic route—planning it 30 times faster than humans do.

In the pharmaceutical arena, an AI-based technology called generative machine learning is also exciting. Most pharmaceutical companies store millions of compounds and screen them for the potential to serve as new drugs. But even with robotics and lab-automation tools, this screening process is slow and yields relatively few hits. Further, the "libraries" collectively include only a tiny fraction of the more than 10^{30} theoretically possible molecules. Using a data set describing the chemical structures of known drugs (and drug candidates), as well as their properties, machine-learning tools can construct virtual libraries of new compounds that have similar, and potentially more useful, characteristics. This capability is starting to dramatically accelerate the identification of drug leads.

Close to 100 start-ups are already exploring AI for drug discovery. Among them are Insilico Medicine, Kebotix and BenevolentAI; the last recently raised $115 million to extend its AI technology to the discovery of drugs for motor neuron disease, Parkinson's and other hard-to-treat disorders. BenevolentAI is applying artificial intelligence to the entire drug development process—from the discovery of new molecules to the design and analysis of clinical trials meant to demonstrate safety and effectiveness in humans.

In the field of materials, ventures such as Citrine Informatics are using approaches similar to those of pharmaceutical makers and are partnering with large companies, including BASF and Panasonic, to speed innovation. The U.S. government is also supporting research into AI-enabled design. Since 2011 it has invested more than $250 million in the Materials Genome Initiative, which is establishing an infrastructure that includes AI and other computing approaches to accelerate the development of advanced materials.

Past experience teaches that new materials and chemicals can pose unforeseen risks to health and safety. Fortunately, AI approaches should be able to anticipate and reduce these undesirable outcomes. The technologies seem poised to markedly increase the speed and efficacy with which novel molecules and materials are discovered and brought to the market—where they may provide such benefits as improved health care and agriculture, greater conservation of resources, and enhanced production and storage of renewable energy.

7

MEDICINE

ADVANCED DIAGNOSTICS FOR PRECISION MEDICINE

A NEW GENERATION OF TOOLS COULD HELP END ONE-SIZE-FITS-ALL THERAPEUTICS

By Elizabeth O'Day and Habiba Alsafar

For most of the 20th century all women with breast cancer received similar treatment. Therapy has since become more individualized: breast cancers are now divided into subtypes and treated accordingly. Many women whose tumors produce estrogen receptors, for instance, may receive drugs that specifically target those receptors, along with standard postsurgery chemo-

therapy. This year researchers took a step closer to even more personalized treatment. They identified a significant fraction of patients whose tumors possess characteristics that indicate they can safely forgo chemo—and avoid its often serious side effects.

This march toward personalized, or precision, medicine for many disorders is being hastened by advances in diagnostic tools. These technologies can help physicians detect and quantify multiple biomarkers (molecules that signal the presence of a disorder) to divide patients into subgroups that differ in their susceptibility to a disease, prognosis or likelihood of responding to a specific treatment.

Early molecular diagnostic tools looked at single molecules—in the case of diabetes, for example, glucose. In the past decade, however, "omics" technology has progressed tremendously—in the ability to quickly, reliably and cheaply sequence an individual's entire genome or to measure levels of all the proteins (the proteome), metabolic by-products (the metabolome), or microbes (the microbiome) in a bodily fluid or tissue sample. Routine use of the technology has simultaneously begun to generate huge data sets that artificial intelligence can mine to discover new biomarkers useful for the clinic. This combination of high-throughput omics technology and artificial intelligence is ushering in a new era of advanced diagnostics that will transform the understanding and treatment of many diseases, allowing doctors to tailor therapies to the molecular profiles of individual patients.

Several advanced diagnostics are already in use for cancer. One, called Oncotype DX, examines 21 genes; it is the test that revealed that many women with breast cancer can avoid chemo. Another, called the FoundationOne CDx test, detects genetic mutations in more than 300 genes in solid tumors and indicates specific gene-targeting drugs that might be useful for a given patient.

Outside of cancer, one exciting tool applies to endometriosis, a frequently painful condition in which uterine tissue grows where it does not belong. Making the diagnosis typically involves surgery. A new, noninvasive saliva-based test from DotLabs can identify endometriosis by measuring a panel of small molecules known as microRNAs. And blood tests are being developed to help identify brain disorders—such as autism, Parkinson's and Alzheimer's—that are currently diagnosed via clinicians' subjective assessments of symptoms. Investigators are even exploring whether sequencing whole genomes, analyzing microbiomes, and measuring levels of hundreds of proteins and metabolites in healthy people can yield personalized guidance on how those individuals might prevent disease.

A word of caution: medical facilities and researchers using such intimate diagnostic tools must rigorously enforce safeguards for protecting patient privacy. Further, clear regulatory guidelines are needed for assessing the value of a biomarker as a diagnostic tool in a consistent way. Such guidelines will speed the introduction of new biomarkers into medical practice.

Even so, advanced diagnostics are beginning to dissolve the standard approach to diagnosing and treating disease. By steering patients toward the most effective treatments, they may even reduce health care spending. One day many of us may possess a personal cloud of biomarker data that will accumulate over time and inform our treatment no matter where we seek care.

8

BIOTECHNOLOGY

GENE DRIVE GETS SAFETY FEATURES

LIMITING RISK FOR A TOOL THAT COULD ALTER ENTIRE SPECIES

By Cynthia H. Collins

Research into a genetic engineering technology that can permanently change the traits of a population or even an entire species is progressing rapidly. The approach uses gene drives—genetic elements that pass from parents to unusually high numbers of their offspring, thereby spreading through populations rather quickly. Gene drives occur naturally but can also be engineered, and doing so could be a boon to humanity in many ways. The technology has the potential to stop insects from transmitting malaria and other terrible infections, enhance crop yields by altering pests that attack plants, render corals resistant to environmental stress, and keep invasive plants and animals from destroying ecosystems. Yet investigators are deeply aware that altering or even eliminating a species could have profound consequences. In response, they are developing rules to govern the transfer of gene drives from the laboratory into future field tests and wider use.

Investigators have been considering ways to exploit gene drive to fight diseases and other problems for decades. The effort got a boost in recent years from the introduction of CRISPR gene editing, which makes it easy to insert genetic material into specific spots on chromosomes. In 2015 several papers reported the successful spread of CRISPR-based gene drives in yeast, fruit flies and mosquitoes. One demonstration drove genes for resistance to the malaria parasite through a mosquito population, which, in theory, should limit the parasite's transmission. Another study interfered with female fertility in a different mosquito species.

This year a CRISPR gene-drive system was tested in mice by attempting to manipulate coat color. The procedure worked only in females. Even so, the results support the possibility that the technology could help eliminate or alter invasive mice or other mammalian populations that threaten crops or wildlife or transmit disease.

The Defense Advanced Research Projects Agency (DARPA) is among the investors who are enthusiastic about the technology. It has poured $100 million into gene-drive research aimed at fighting mosquito-borne disease and invasive rodents. The Bill & Melinda Gates Foundation has invested $75 million in a research consortium working on gene drive to combat malaria.

Despite all the promise, gene drives raise many concerns. Might they inadvertently jump to, and disrupt, other species in the wild? What are the risks of eliminating selected species from an ecosystem? Could malevolent parties use gene drives as a weapon to, say, interfere with agriculture?

In an effort to avoid such dire prospects, one team has invented a switch that must be turned on by delivery of a particular substance before the gene drive will work. In parallel, multiple groups of scientists are working on protocols to guide progression through each stage of gene-drive testing. In 2016, for instance, the U.S. National Academies of Sciences, Engineering, and Medicine reviewed the research and made recommendations for responsible practices. And in 2018 a large, international working group laid out a road map for handling research from lab studies through releases in the field. The group (some of whose meetings were attended by observers from DARPA, the Gates Foundation or other agencies) modeled its recommendations on gene drive's use to control malaria in Africa, where, it says, the public health benefit would probably be greatest.

Beyond limiting the risks of the technology itself, many investigators also want to avoid incidents and missteps that could lead to public or policy backlash. In a 2017 essay about the potential use of gene drive for eliminating pest mammals, Kevin M. Esvelt of the Massachusetts Institute of Technology and Neil J. Gemmell of the University of Otago in New Zealand fretted that an international incident could set back research by a decade or more. "For malaria alone," they predicted, "the cost of that delay could be measured in millions of otherwise preventable deaths."

ENGINEERING

FINDING TOXINS WITH PLASMONICS

LIGHT-ACTIVATED NANOMATERIALS ARE REVOLUTIONIZING SENSORS

By Javier Garcia Martinez

Writing in *Scientific American* in 2007, Harry A. Atwater of the California Institute of Technology predicted that a technology he called "plasmonics" could eventually lead to an array of applications, from highly sensitive biological detectors to invisibility cloaks. A decade later plasmonic technologies are a commercial reality, and others are transitioning from the laboratory to the market.

These technologies all rely on controlling the interaction between an electromagnetic field and the free electrons in a metal (typically gold or silver) that account for the metal's conductivity and optical properties. Free electrons on a metal's surface oscillate collectively when hit by light, forming what is known as surface plasmon. When a piece of metal is large, the free electrons reflect the light that hits them, giving the material its shine. But when a metal measures just a few nanometers, its free electrons are confined in a very small space, limiting the frequency at which they can vibrate. The specific frequency of the oscillation depends on the size of the metal nanoparticle. In a phenomenon called resonance, the plasmon absorbs only the fraction of incoming light that oscillates at the same frequency as the plasmon itself does (reflecting the rest of the light). This surface plasmon resonance can be exploited to create nanoantennas, efficient solar cells and other useful devices.

One of the best studied applications of plasmonic materials is sensors for detecting chemical and biological agents. In one approach, researchers coat a plasmonic nanomaterial with a substance that binds to a molecule of interest—say, a bacterial toxin. In the absence of the toxin, light shining on the material is reemitted at a specific angle. But if the toxin is present, it will alter the frequency of the surface plasmon and, consequently, the angle of the reflected light. This effect can be measured with great accuracy, enabling even trace amounts of the toxin to be detected and measured. Several start-ups are developing products based on this and related approaches—among them an internal sensor for batteries that allows their activity to be monitored to assist in increasing power density and charge rate and a device that can distinguish viral from bacterial infections. Plasmonics is also working its way into magnetic memory storage on disks. For instance, heat-assisted magnetic recording devices increase memory storage by momentarily heating tiny spots on a disk during writing.

In the medical field, light-activated nanoparticles are being tested in clinical trials for their ability to treat cancer. Nanoparticles are infused into the blood, after which they concentrate inside a tumor. Then light of the same frequency as the surface plasmon is shone into the mass, causing the particles to heat by resonance. The heat selectively kills the cancer cells in the tumor without hurting surrounding healthy tissue.

As new companies emerge to take advantage of plasmonics, they will need to ensure that their products are reasonably priced, reliable, robust, and easy to fabricate at scale and integrate with other components. Despite these challenges, the prospects look bright. The advent of metamaterials—synthetic nanoscale materials in which plasmons generate unusual optical effects—has enabled plasmonics researchers to use materials other than gold and silver, such as graphene and semiconductors. An analysis from Future Market Insights predicts that the value of the North American market for plasmonic sensor applications alone will grow from nearly $250 million in 2017 to nearly $470 million by 2027.

10

COMPUTER SCIENCE

ALGORITHMS FOR QUANTUM COMPUTERS

DEVELOPERS ARE PERFECTING PROGRAMS MEANT TO RUN ON QUANTUM COMPUTERS

By Alán Aspuru-Guzik

Within a few years quantum computers could catch up to or even outperform classical computers thanks to significant work on hardware and the algorithms to run on it.

Quantum computers exploit quantum mechanics to perform calculations. Their basic unit of computation, the qubit, is analogous to the standard bit (zero or one), but it is in a quantum superposition between two computational quantum states: it can be a zero and a one at the same time. That property, along with another uniquely quantum feature known as entanglement, can enable quantum computers to resolve certain classes of problems more efficiently than any conventional computer can.

This technology, while exciting, is notoriously finicky. A process called decoherence, for example, can disrupt its function. Investigators have determined that stringently controlled quantum computers that have a few thousand qubits could be made to withstand decoherence through a technique known as quantum error correction. But the largest quantum computers that laboratories have demonstrated so far—the most notable examples are from IBM, Google, Rigetti Computing and IonQ—contain just tens of quantum bits. These versions, which John Preskill of the California Institute of Technology named noisy intermediate-scale quantum (NISQ) computers, cannot perform error correction yet. Nevertheless, a burst of research on algorithms written specifically for NISQs might enable these devices to perform certain calculations more efficiently than classic computers.

Increased access to NISQ machines for users around the world has contributed greatly to this progress, enabling a growing number of academic researchers to develop and test small-scale versions of programs for the machines. An ecosystem of start-up companies focused on different aspects of quantum software is blossoming as well.

Researchers see particular promise in two kinds of algorithms for NISQs—those for simulation and for machine learning. In 1982 the legendary theoretical physicist Richard Feynman suggested that one of the most powerful applications of quantum computers would be simulating nature itself: atoms, molecules and materials. Many researchers, myself included, have developed algorithms to simulate molecules and materials on NISQ devices (as well as on the fully error-corrected quantum computers of the future). These algorithms could enhance the design of new materials for use in areas ranging from energy to health science.

Developers are also assessing whether quantum computers would be superior at machine-learning tasks, in which computers learn from large data sets or experience. Tests of a rapidly growing set of algorithms for NISQ devices have shown that quantum computers can indeed facilitate such machine-learning tasks as classifying information by categories, clustering similar items or features together, and generating new statistical samples from existing ones—for instance, predicting molecular structures likely to display a desired mix of properties. At least three research groups have independently reported progress in developing quantum versions of a machine-learning approach known as generative adversarial networks (GANs), which has taken the machine-learning field by storm in the past several years.

> An ecosystem of start-up companies focused on different aspects of quantum software is also blossoming.

Although a number of algorithms do seem to work well on existing NISQ machines, no one has yet produced formal proofs that they are more powerful than those that can be performed on conventional computers. These proofs are difficult and can take years to complete.

In the next few years researchers most likely will develop larger and more controllable NISQ devices, followed by fully error-corrected machines with thousands of physical qubits. Those of us working on algorithms are optimistic that algorithms for NISQ will be effective enough to achieve an advantage over state-of-the-art conventional computers, although we might have to wait until fully error-corrected machines are available.

MORE TO EXPLORE

The Top 10 Emerging Technologies of 2017. Scientific American and World Economic Forum, June 26, 2017.

FROM OUR ARCHIVES

The Promise of Plasmonics. Harry A. Atwater; April 2007.
Shock Medicine. Kevin J. Tracey; March 2015.
The Paradox of Precision Medicine. Jeneen Interlandi; April 2016.
Quantum Connections. Christopher R. Monroe, Robert J. Schoelkopf and Mikhail D. Lukin; May 2016.
Our Digital Doubles. Pedro Domingos; September 2018.

scientificamerican.com/magazine/sa

NEEDLE IN

ARCHAEOLOGY

A new technique for identifying tiny fragments of fossilized bone is helping to answer key questions about when, where and how human species interacted with one another

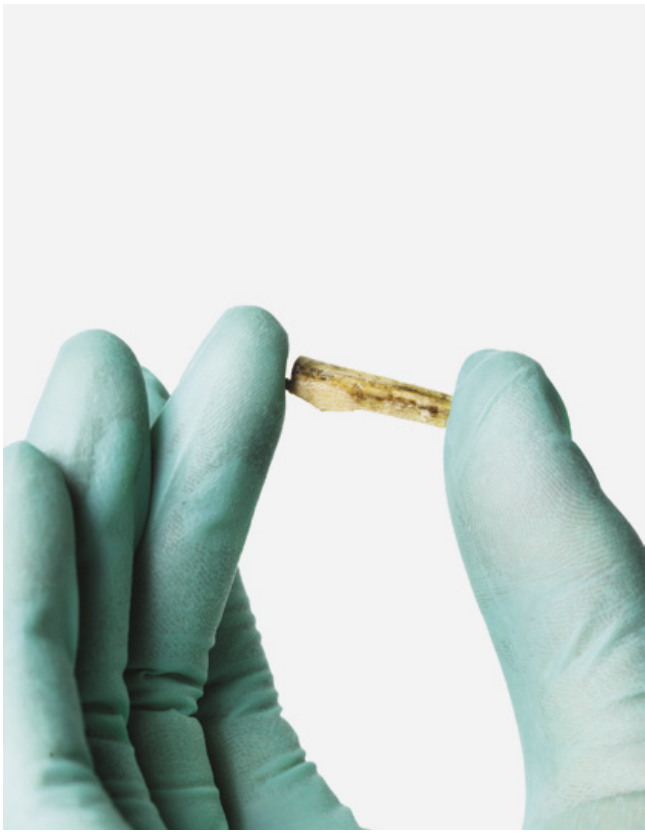
By Thomas Higham and Katerina Douka

Photographs by Christoffer Rudquist

FOSSIL SCRAPS may include precious human remains—the trick is picking them out.

THE HAYSTACK

IT IS ALWAYS A RELIEF TO ARRIVE AT DENISOVA CAVE in southern Siberia. After a bumpy 11-hour drive southeast from Novosibirsk, across the steppe and through the foothills of the Altai Mountains, the field camp suddenly appears around a bend in the dirt road, and all thought of the long journey evaporates. Steep-sided valleys, swift-running rivers and the traditional wood houses of the local Altai people dominate the landscape; golden eagles soar overhead. A couple of hundred meters away, the limestone cave itself, perched high above the Anui River, beckons with the promise of some of the most exciting research under way in the field of human origins.



BONE FRAGMENT from Denisova Cave in Siberia is the latest specimen to be identified as a member of the human/great ape family using zooarchaeology by mass spectrometry (ZooMS).

Denisova Cave is at the center of a revolution in scientists' understanding of how our ancestors in the Paleolithic, or Old Stone Age, behaved and interacted. Our species, *Homo sapiens,* originated in Africa hundreds of thousands of years ago. When it eventually began spreading into Europe and Asia, it encountered other human species, such as the Neandertals, and shared the planet with them for millennia before those archaic species disappeared. Scientists know these groups encountered one another because people today carry DNA from our extinct relatives—the result of interbreeding between early *H. sapiens* and members of those other groups. What we do not yet know and are eager to ascertain is when and where they crossed paths, how often they interbred and how they might have influenced one another culturally. We actually have quite a few important archaeological sites from this transitional period that contain stone tools and other artifacts. But many of these sites, including Denisova, lack human fossils that are complete enough to attribute to a particular species on the basis of their physical traits. That absence has hindered our ability to establish which species made what—and when.

Now a technique for identifying ancient bone fragments, known as zooarchaeology by mass spectrometry (ZooMS), is finally allowing researchers to start answering these long-standing questions. By analyzing collagen protein preserved in these seemingly uninformative fossil scraps, we can identify the ones that come from the human/great ape family and then attempt to recover DNA from those specimens. Doing so can reveal the species they belong to—be it Neandertal, *H. sapiens* or something else. What is more, we can carry out tests to determine the ages of the fragments.

Directly dating fossils is a destructive process—one has to sacrifice some of the bone for analysis. Museum curators are thus usually loath to subject more complete bones to these tests. But they have no such reservations with the scraps.

The ability to directly date fossils found in association with artifacts is especially exciting with regard to

IN BRIEF

During the middle and later parts of the Stone Age, *Homo sapiens* spread out of Africa into Eurasia. Subsequently, archaic human groups across the region, including the Neandertals and Denisovans, disappeared.

Researchers are keen to understand the nature and extent of interactions among these groups during this transition. But many of the relevant archaeological sites from this period lack fossils that can be attributed to one species or another based on their anatomy.

Now a combination of techniques is allowing scientists to comb through large quantities of unidentified bone scraps and pick out human remains that can be dated and genetically sequenced. Already this method has yielded insights into interspecies dynamics.

Denisova and other sites we know sheltered multiple human species in the past. A number of researchers have argued that symbolic and decorative artifacts, which are proxies for modern cognitive abilities, are unique to *H. sapiens*. Others maintain that Neandertals and other species made such items, too, and may have even passed some of their traditions along to the *H. sapiens* they met. The ability to identify and date these fossil fragments means researchers can begin to reconstruct the chronology of these sites in far greater detail and elucidate a critical chapter of human prehistory.

MISSION IMPOSSIBLE

RUSSIAN ARCHAEOLOGISTS have been excavating Denisova Cave since the 1980s. But it was an announcement in 2010 that put the site on the map. That year scientists at the Max Planck Institute for Evolutionary Anthropology in Leipzig, Germany, reported on the results of their genetic analysis of a bone found at Denisova in 2008. The DNA they obtained from the fossil—a bit of finger bone—revealed a previously unknown type of hominin, or member of the human family, one that was as closely related to Neandertals as we are. The bone was from a young girl, initially dubbed "X woman," who belonged to a group of people that scientists now refer to as Denisovans. Since then, a handful of other hominin bones and teeth have been discovered among the excavated remains, both Denisovan and Neandertal.

Those discoveries at Denisova illustrated the powerful information that can be gleaned from fossils using modern genetic approaches, telling us not only about the presence of hitherto unknown species but also about the nature of their interaction with us. We know from genetic analysis, for instance, that Neandertals and modern humans interbred at least three times over the past 100,000 years and that Neandertals and Denisovans, as well as moderns and Denisovans, also mixed. As a result, the long-held view that *H. sapiens* moved out of Africa and simply wiped out such archaic populations has, in the blink of an eye, given way to a more complex scenario of interbreeding and gene flow between groups—a "leaky replacement" model of modern human origins. Yet most of the fossils at Denisova are so incomplete that we cannot discern which ones might belong to a human species. And the site has been notoriously difficult to date.

We got involved in the Denisova project six years ago through our expertise in chronology, particularly the use of radiocarbon dating to establish time frames for archaeological sites. For material from the Middle and Upper Paleolithic periods (broadly the time spanning 250,000 to 40,000 and 40,000 to 10,000 years ago, respectively), dating is hugely important because the sites themselves often lack distinctive tool types that are associated with tightly defined periods. We are working to provide a robust chronology at Denisova and other Paleolithic locations in Eurasia.

We were both at the site in 2014 attending a meeting of the Denisova team when we came up with an idea that we thought might help us build a more nuanced picture of the interactions that occurred among our species, Neandertals and Denisovans. One thing that was apparent at Denisova was that all the known

Thomas Higham is director of the Oxford Radiocarbon Accelerator Unit at the University of Oxford. His research focuses on the dating of bone at archaeological sites in Eurasia spanning the Middle and Upper Paleolithic periods.

Katerina Douka is an archaeological scientist at the Max Planck Institute for the Science of Human History in Jena, Germany. She is leading a team to discover fossils of Neandertals and Denisovans among collections of unidentified bone fragments from sites in Asia.

SERGEY ZELINSKY *Institute of Archaeology and Ethnography of the Siberian Branch of the Russian Academy of Sciences*

RESEARCHERS inspect archaeological deposits in Denisova Cave before taking samples for ZooMS analysis and radiocarbon dating.

Whose Bone Is It, Anyway?

With ZooMS, researchers can assign bone fragments to their proper taxonomic group. ZooMS analyzes collagen protein preserved in bone. An enzyme cuts the collagen into its component peptide chains. A mass spectrometer uses a laser to impart an electric charge to the peptides, which then race toward a detector that measures when each peptide strikes it. The resulting spectrum of values is a distinctive "fingerprint" that can be compared with a library of collagen fingerprints of known species to identify a mystery bone.

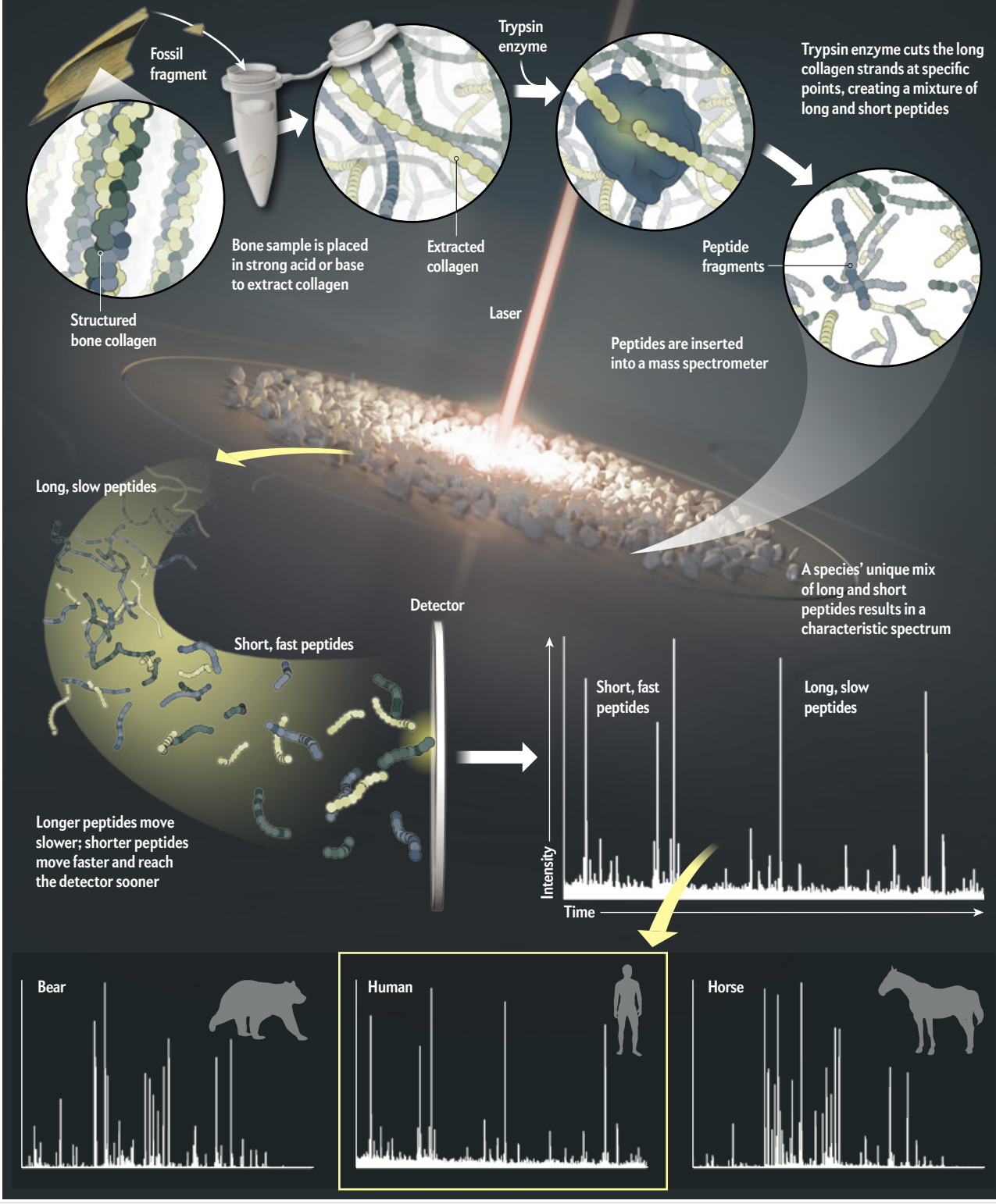


Illustration by Falconieri Visuals

hominin remains were absolutely tiny, just three to five centimeters long. The X woman finger bone, for instance, was about the size of a lentil and weighed less than 40 milligrams. A great proportion of bone material at the site was broken, principally because of the activity of predators such as hyenas, which den in caves to have their young and chew up bones while feeding. Since 2008 more than 135,000 bones have been excavated at Denisova, but 95 percent of them cannot be identified taxonomically, because they are too fragmentary. In contrast, the preservation of biomolecules in these fragments—including those molecules that make up DNA—is amazing: the two most complete ancient hominin genomes ever recovered come from Denisova fossils. What if, we wondered, there were a way of screening these many thousands of bone fragments at the site to find more human bones? If we could do this, perhaps we could generate more genetic and chronometric data or even find a new type of hominin lurking in the cave. It was then that we realized that we might be able to carry out exactly this kind of screening using ZooMS.

ZooMS, also called collagen peptide mass fingerprinting, allows investigators to assign fragments of bone to the proper taxonomic group by analyzing the proteins in bones. Bone collagen protein is made up of hundreds of small compounds called peptides that vary slightly among different types of animals. By comparing the peptide signatures of mystery bones against a library of such signatures from known animals, it is possible to assign the unidentified bones to the correct family, genus and sometimes species. First developed by Michael Buckley, now at the University of Manchester, and Matthew Collins of the University of York, both in England, ZooMS has been employed for more than a decade to identify the animal bones at archaeological sites. It is relatively cheap, costing around $5 to $10 per sample, and minimally destructive—it requires only around 10 to 20 milligrams of bone for analysis. It is also rapid; one person can screen hundreds of bones a week.

To our knowledge, no one had used ZooMS to search for human bones before. But we figured we had a shot. Even small fragments should be potentially useful, we reasoned, because the bone collagen and DNA preservation in Denisova is unsurpassed, given its stable and very low average annual temperature of below zero degrees Celsius. We knew we would not be able to get species-level identification with ZooMS. The collagen peptide signatures of human species and the great apes are too similar to discriminate. But no great apes are known to have roamed this part of the world during the Paleolithic. So if we could identify a piece of bone as belonging to a member of the group that comprises great apes and humans—together known as Hominidae—we could be fairly certain that it belonged to a human of some kind and subject it to genetic analysis that could provide the species identification.

Ancient DNA expert Svante Pääbo of the Max Planck Institute for Evolutionary Anthropology, who leads the Neandertal Genome Project and whose group published the Denisovan genome in 2010, was at Denisova for the 2014 meeting. We had not formally met Pääbo before, and we were keen to see what he thought of our idea for screening bone fragments and whether he would be interested in collaborating on that effort. He jumped at the chance and gave his immediate support. We then discussed our plan with Anatoly Derevianko of the Russian Academy of Sciences, who oversees work done at Denisova, and Michael Shunkov, director of the excavations. Both were interested. And so later that year we began the process of sampling a few thousand little fragments of, for all intents and purposes, "worthless" bones that had been recently excavated from the site.

In the abstract, it seemed like it would be quick work. In reality, we were faced with the massive job of painstakingly removing a minuscule sample of bone from each fragment for analysis, taking care not to touch the potentially valuable specimens with anything that might contaminate them. One of our students, Samantha Brown, who took on the project for her master's research dissertation, carried out much of this work, logging countless hours at our lab at the University of Oxford.

What we had found was not a Neandertal but an individual with a Neandertal mother and a Denisovan father.

Buckley collaborates with us on this project. Once we had 700 to 800 bone samples ready, Brown went to his lab to prepare and analyze them. The results were interesting: we had mammoths, hyenas, horses, reindeer, woolly rhinos—the full panoply of Ice Age beasts—but sadly, none of the peptide signatures corresponded with Hominidae. It was disappointing, but we decided to try a second batch to see whether we could locate even one human bone from the mass of fragments. Although we did not fancy our chances, we were hoping to be proved wrong.

Then one evening in the summer of 2015 we received an e-mail from Buckley. He had noticed that one of our samples, DC1227, had the characteristic peptide markers coding for Hominidae. We had a fragment of human bone—the proverbial needle in the haystack! We were ecstatic; our crazy idea seemed to have actually panned out.

Early the next day we went to our lab at Oxford to find the bone among the archived samples. We were somewhat deflated when we saw that the bone we had found was tiny even for a Denisova specimen—only 25

1

2

ANALYZING fossil fragments using ZooMS requires sawing off a 20-milligram sample from each tiny specimen (*1*). Other samples are prepared for radiocarbon dating (*2*).

millimeters long—which did not leave much for further studies. But given the exceptional biomolecular preservation of the Denisova remains, we believed that it would be enough to allow us to apply the techniques we wanted to use to find out as much about the bone as possible. We photographed it at high resolution, put it through a CT scanner, and drilled additional samples for dating and isotope analysis before Brown took the bone to Leipzig for DNA analysis in Pääbo's lab.

Several weeks later the dating results came back. The absence of any traceable radioactive carbon in the sample implied that our little bone was more than 50,000 years old. And before long, we learned from Pääbo that its mitochondrial DNA—which resides in the energy-producing organelles of cells and is passed down from mother to child—indicated that the bone came from an individual who had a Neandertal mother. We had found a hominin bone fragment hidden among thousands of "junk" bones and proved that the concept could work. Pääbo's team was planning to extract the much more informative nuclear genome from the bone, which now went by the site fossil I.D. "Denisova 11," or "Denny," as we nicknamed it. In the meantime, we decided to test our approach at another site.

US VS. THEM

VINDIJA CAVE in Croatia is a key site for understanding late Neandertals in Europe. For many years radiocarbon dates indicated that Neandertals there might have survived until 30,000 years ago, providing evidence for a potential overlap phase with anatomically modern humans, who arrived in the region by 42,000 to 45,000 years ago. Such a lengthy coexistence hinted that rather than being driven to extinction by modern humans, the Neandertals had been assimilated into their population. While reassessing the Vindija chronology, we decided it might be interesting to use ZooMS to assess the unidentified bones from the site. Previous work on the more complete bones from Vindija had shown that cave bears dominate the remains, accounting for some 80 percent of the bones, so we were not expecting to find the variety and breadth of fauna that we had detected at Denisova. Cara Kubiak, then another of our students, took on the project.

Surprisingly, the 28th sample out of the 383 we analyzed yielded a peptide sequence consistent with Hominidae. Later, Pääbo's team confirmed it genetically as a Neandertal. This bone was around seven centimeters long and, intriguingly, exhibited cut marks and other signs of human modification. Neandertal bones sometimes bear these markings, which may well be evidence of butchery and cannibalism.

The specimen, known as Vi-*28, turned out to be pivotal for our chronology work. Historically, archaeologists and preparators treated the bones from Vindija with conservation products to protect them. That practice makes radiocarbon dating very difficult because these products add carbon to the bone. Unlike

other human bones from the site, Vi-*28 was not conserved; misidentified as an animal bone, it had eluded treatment—a boon for us. Radiocarbon dating of Vi-*28 revealed that it belonged to a Neandertal from more than 47,000 years ago. This finding, published in 2017, along with dates we obtained from other Neandertals, showed that they disappeared from Vindija more than 40,000 years ago, before modern humans arrived at the site. The earlier dating results suggesting that they had persisted until at least 30,000 years ago were a fiction, influenced by contaminating carbon that had not been effectively removed. ZooMS again had proved its worth.

Other teams have had great success with the technique, too. In 2016 Frido Welker, now at the Natural History Museum of Denmark, and his colleagues reported that they had used ZooMS to identify 28 previously unrecognized hominin fossils among the unidentified bone fragments from the famed site of Grotte du Renne in the Burgundy region of France. Decades ago researchers working there found Neandertal bones in association with an array of surprisingly sophisticated artifacts, including bone tools, as well as pendants and other body ornaments—elements of a so-called Châtelperronian culture that is said to be transitional between the Middle Paleolithic and the Upper Paleolithic. The discovery ran counter to the long-held idea that *H. sapiens* alone was capable of such ingenuity. In so doing, it touched off an enduring debate over whether the Neandertals were truly associated with the advanced artifacts or whether the archaeological levels at the site had been disturbed somehow, mixing Neandertal bones with later artifacts left behind by *H. sapiens*.

The 28 bone fragments Welker and his colleagues identified as human using ZooMS all clearly came from the same layer as the advanced tools and ornaments. When they had the bones sequenced, the results were unequivocal: the specimens were Neandertal, not *H. sapiens*. The work lends considerable support to the notion that Neandertals did indeed make the Châtelperronian and other transitional industries and that they were cleverer than they have often been given credit for.

A HYBRID CHILD

THROUGHOUT OUR WORK at Vindija, we continued to analyze samples from Denisova in the hope that we could add more human fossils to our collection. Our efforts yielded two more Hominidae hits: DC3573, which turned out to belong to a Neandertal from more than 50,000 years ago, and DC3758, a 46,000-year-old bone that unfortunately does not preserve any ancient DNA. More than 5,000 bone fragments have now given us a total of five hominin bones that might have languished in obscurity forever if not for ZooMS.

But the most exciting development was yet to come. In May 2017 we were at the Max Planck Institute for Evolutionary Anthropology and met with senior members of Pääbo's lab, including Matthias Meyer and Janet Kelso. We wanted to know about the status of Denisova 11 and whether they had managed to retrieve nuclear DNA, which would give us a much more detailed picture of who Denisova 11 was.

It is not often in science that one receives completely jaw-dropping news, but Meyer and Kelso delivered exactly that. The nuclear DNA, they said, was curiously split: half was consistent with a Neandertal, and the other half appeared to be derived from a Denisovan. They thought Denisova 11 was a 50–50 hybrid. To exclude all possibility of error, the team was running the samples again to verify this astonishing result. Several months later the final data confirmed this initial finding. The mitochondrial DNA had given us only half of the picture. What we had found was not a Neandertal but an individual with a Neandertal mother and a Denisovan father—a first-generation hybrid, in the parlance of geneticists. The Denisova team announced this astounding discovery in the September 6 *Nature*, in a paper led by Viviane Slon of the Max Planck Institute for Evolutionary Anthropology.

We know now from the DNA that Denisova 11 was a female who probably lived around 90,000 to 100,000 years ago. And bone-density analysis generated from the CT scan we performed allowed our colleague Bence Viola of the University of Toronto to tentatively estimate her age at death at a minimum of 13 years old. Her Denisovan father himself had a distant Neandertal relative several hundred generations back. Of course, we can never know how these unions came about in prehistory, only that they did. Neither can we establish how Denisova 11 died, just that her remains were probably deposited in the cave sediment by a predator, possibly a hyena.

We will never know whether she died and was ceremonially buried by her loved ones, only to be scavenged by the hyena later, or lost her life to a predator. For tens of millennia this minute piece of her body lay undisturbed in the cave and might well have remained there for many more years, had it not been for the cutting-edge science that has allowed us to breathe life into her story. We are hopeful that ZooMS will help us unlock many more such secrets archived in bone. SA

MORE TO EXPLORE

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FROM OUR ARCHIVES

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Sacred Groves

Indian villagers are reviving an ancient tradition to enjoy the ecological benefits it confers

By Madhav Gadgil

Photographs by Harsha Vadlamani

PONAD KADYA sacred grove is one of tens of thousands of such protected refuges in India. They provide shelter to many rare species of flora and fauna and often serve as water sources for local villages.

Madhav Gadgil founded the Center for Ecological Sciences at the Indian Institute of Science in Bengaluru, India. His research helped to establish the country's first biosphere reserve in the Nilgiri Mountains. He has received many awards, including the Padma Bhushan and the Tyler Prize for Environmental Achievement.

IT WAS THE MIDDLE OF MARCH IN 2014. WE WERE SITTING UNDER A MAHUA (*MADHUCA longifolia*) tree in the hilly, forested heartland of India, breakfasting on locally grown rice, bean sprouts and fish curry. From time to time the fleshy, sugary petals of mahua flowers showered down on us, so we ended our meal with a refreshing sweet dish. My hosts were Gond tribals, residents of Mendha village in the Indian state of Maharashtra, who had declared a quarter of a century earlier that they, and they alone, would manage the region's rich natural resources. As a field ecologist, I had been working alongside them ever since, helping to design strategies for managing their biodiversity resources. On that day I was looking forward to visiting the seven patches of forest they had identified for setting up as new sacred groves, covering more than 12 percent of their 1,800-hectare community forest.

A legacy of prehistoric traditions of nature conservation, sacred groves are patches of forest that rural communities in the developing world protect and revere as sacrosanct. Deeply held spiritual beliefs ensure that not a tree is felled nor a creature harmed within its boundaries. (In times of dire need, such as if a village burns down, permission may, however, be sought of the grove's deities to extract a limited quantity of wood for reconstruction.) Treasure troves for naturalists, the groves often serve as the last refuge for magnificent and ancient trees, as well as for species of lianas, medicinal plants, macaques, deer, birds, lizards, frogs and other creatures that have become rare elsewhere in the landscape.

Originally widespread in the Old World, sacred groves were reported in Greek and Sanskrit classics but were essentially wiped out in Europe by the arrival of Christianity and its attendant anthropocentrism. The Christian church, with its towering pillars and soft light filtering in through colorful stained-glass windows, is said to evoke the sacred groves of yore. Such protected copses are still found in parts of the Middle East, Africa and Asia.

Over almost half a century I have explored a great many sacred hills, river origins, river stretches, ponds and groves in India, Bhutan and Japan. I have witnessed sacred groves being destroyed but also being preserved, revived or even newly established in the face of the active hostility of the developmental state. An ecological crisis in the Indian subcontinent, brought about by relentless commercial exploitation of natural resources, is prompting a vibrant revival of these sacred spaces. This assertion of ancient values of reverence for nature, too often derided as primitive superstition, represents the most hopeful news about Indian ecology to emerge in decades.

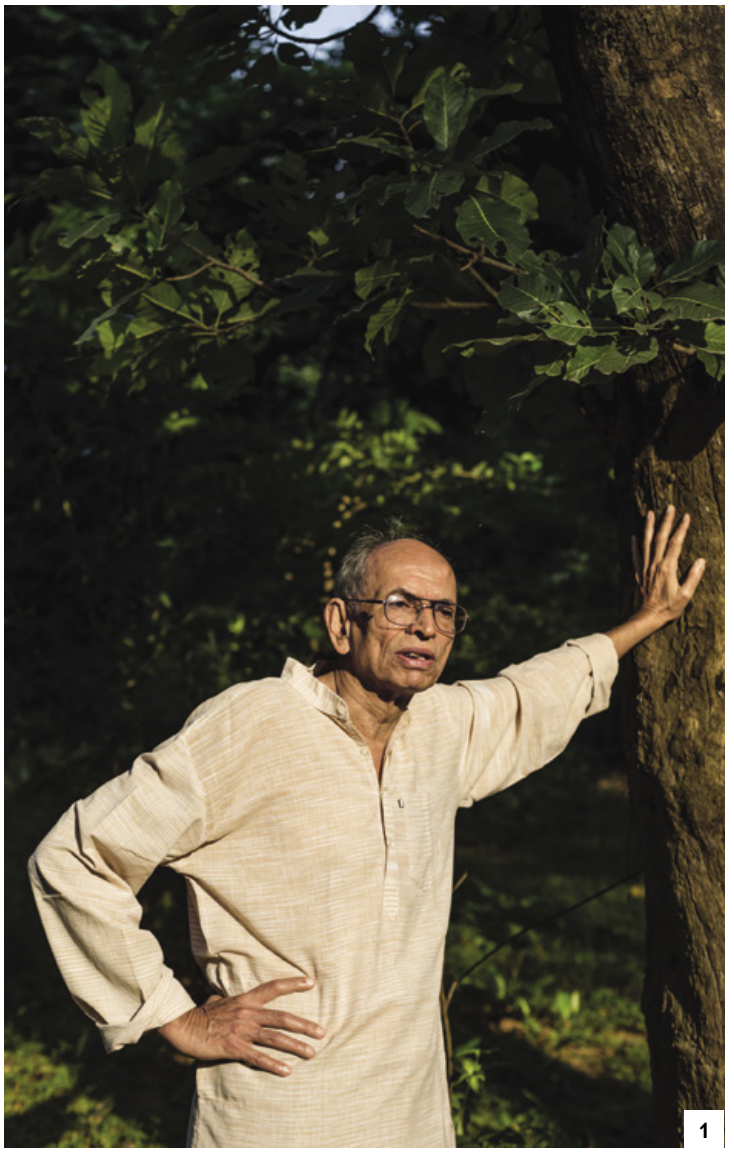
Conventional conservation follows a top-down strategy modeled on Yosemite National Park, whose establishment in 1890 followed the forcible expulsion of the Native Americans who lived there. As journalist Mark Dowie described in 2009 in *Conservation Refugees,* this Western concept of a wilderness free of humans was imposed around the world. Large conservation agencies, partnering with governments in developing countries, created protected areas for charismatic creatures such as tigers and lions by expelling millions of humans from the forests and savannas in which they had lived for hundreds of years or longer. Not only did these evictions cause immense suffering, they also proved counterproductive as a conservation strategy. In many cases, the locals had nurtured the forest and protected its biodiversity in ways that became clear only in hindsight—such as by

IN BRIEF

Sacred groves are patches of primeval forest that some rural communities protect as abodes of deities. Such "ecosystem people" draw their livelihoods from nearby resources and value nature for the ecological services it provides.

Colonial resource extraction devastated the ancient network of sacred groves in India. Thousands of groves survived, however, and some are being newly established because of the ecological benefits that communities derive from them.

Empowering ecosystem people to protect their environment could be key to preserving such pristine spaces. India's Forest Rights Act of 2006, which grants communities rights to manage neighboring forests, is a significant step to this end.



MADHAV GADGIL (*1*) leans against a mahua tree protected by the people of Mendha village in the state of Maharashtra. The mahua (*2*) is sacred to many forest dwellers and villagers of central and eastern India, who eat its nutritious flowers and brew from these an alcohol used in religious ceremonies. India's forest department tends to eradicate mahua trees, however, replacing these with commercial species.

controlled burning that removed invasive shrubs or helped to regenerate seeds of valuable trees.

In recent years, however, a radically different, bottom-up conservation strategy is gaining ground worldwide. About 40 percent of the earth's wildlife-rich forests are still defended by the local groups who live in and around them. As this story indicates, empowering such "ecosystem people"—who live close to nature and can directly observe and appreciate the manifold benefits it confers—could be the most effective way to protect what remains of the planet's biodiversity.

ROAMING THE WESTERN GHATS

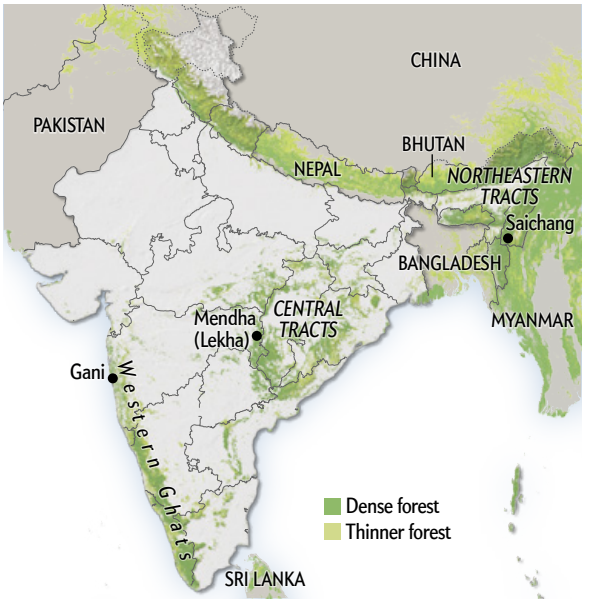
MY LOVE AFFAIR with sacred groves began in August 1971. Soon after returning to India with a doctoral degree from Harvard University, I set out on a field trip with my former botany teacher, V. D. Vartak. We trekked into the northern Western Ghats, a chain of hills running along the western edge of the Indian peninsula. I had grown up in these parts, and I got progressively depressed at the sight of the barren, eroded hills that had been covered with tropical rain forest until the early 1960s. Suddenly we were confronted with a five-hectare patch of luxuriant evergreen forest, within which towered four trees of dhup (*Canarium strictum*)—the northernmost representatives of a species characteristic of the southern Western Ghats, 500 kilometers away. Vartak explained that this grove, named Dhuprahat, had survived because it was sacred to a local mother goddess—and that several other such remnants of primeval vegetation were scattered all over the Western Ghats.

On returning, I read up on sacred groves. Though mentioned frequently in literature on cultural and religious beliefs, I could find no systematic investigations of the phenomenon, let alone studies from an ecological or social science perspective. The reigning hypothesis among conservationists was that they represented lingering elements of nature worship prevalent in all supposedly primitive societies; they had no secular functions but persisted purely because of superstition. That hypothesis implied that sacred groves should be concentrated at religious sites such as mountain peaks or sources of rivers.

It seemed more plausible to me that whereas sacred groves

Forests of South Asia

Sacred groves are scattered all over the India but are found mostly within forested areas such as the Western Ghats, the Himalayas, and the northeastern and central hill tracts. These refugia shelter numerous species of trees, lianas, medicinal plants, animals, birds, lizards, snakes, frogs and other creatures that have become rare everywhere else in the landscape.



may receive protection through religious beliefs, the system is grounded in secular benefits, such as securing freshwater sources. According to this hypothesis, sacred groves would not be restricted to particular kinds of habitats but would be distributed throughout the entire range of habitat types. I set out to collect primary field data to test this prediction.

It was a fascinating experience: trekking through the northern Western Ghats, finding villages with significant patches of sacred groves, making notes on their size, botanical composition, animal life and location in relation to topography, settlements and cultivation and talking to local people about their traditions, beliefs and ecological knowledge. The hospitable villagers readily granted my request to share their meals and to shelter under their roofs for the night.

The resulting data clearly showed that people perceived and valued the ecosystem services that the sacred groves offered and were continuing to protect them because they wished to avail themselves of these benefits. At the same time the groves protected water sources, they served as refugia for animals exploited outside the sacred groves. One notable example of the latter involved the Jenu Kurubas of Nilgiri Hills. Their name means "harvesters of honey," which they collected by setting fires under the hives of the wild rock bees wherever they found them—except in the network of sacred groves in their region. They were fully aware that the taboo on harming the hives inside the sacred groves ensured continued persistence of the rock-bee populations.

COLONIAL HUBRIS

THE PEOPLE OF MENDHA and the Jenu Kurubas believe that they are part of a community of beings, comprising not only humans but also mountains, rivers, trees, animals and birds. These nonhuman community members benefit them in many ways; hence, humans must reciprocate through restrained use, even veneration and total protection. Such a feeling must have prevailed in all early cultures, such as those of hunter-gatherers, who live by it to this day.

The need to protect the wilderness would have become all the more urgent when people took to cultivating plants and radically modifying the original ecosystems. Agriculture began in northern India around 6,000 years ago. Initially patches of forest most likely were cleared for planting, being abandoned after two or three years in favor of a fresh site, in a process known as shifting cultivation. Indologist D. D. Kosambi surmised that the practice of always protecting specific parts of the forest from clearance as sacred groves—and of never cutting valued trees such as mahua (or members of the keystone resource genus *Ficus*)—probably arose at this time. Maintenance of sacred groves was integrated into land-use practices even as permanent fields began to replace shifting cultivation.

Along with settled agriculture came the first city-states. The Indus Valley civilization gave way around 3,500 years ago to Vedic kingdoms. According to an interpretation of the epic Mahabharata by anthropologist Irawati Karve, these early states expanded their frontiers across the Gangetic basin by burning forests to evict hunter-gatherers and to create more fields for pasture and taxation. With cultivation extending across the plains, a resource crunch showed up. The evidence, albeit patchy, suggests that soil fertility and possibly rainfall declined, whereas leaf manure, fruit trees, wild game and other forest resources became scarce. Studies by historian Romila Thapar indicate that Jainism and Buddhism, religions that preached vegetarianism or other forms of restraint in consumption, arose at this time—in direct response to the ecological crisis. These faiths bolstered the local tradition of protected groves. Gautama Buddha himself was born in the sacred grove of Lumbini about 2,600 years ago. Sufi Islam, which spread across the Indian subcontinent in the 10th century, also supported these conservation practices.

The conquest of India by the East India Company, which began in 1757, almost wiped out these millennia of ecological adaptation. Early British travelers described India as an ocean of trees, but the company proceeded to rapidly "enclose the commons." Fields, streams, ponds and other resources were seized from villagers and became state property, many being handed over to English-style landlords who agreed to pay exorbitant taxes extorted from the (now landless) laborers and sharecroppers. The landlords expunged most sacred groves on their holdings to expand fields. Subsequently the state appropriated virtually all forests with the claim of managing them in an enlightened scientific fashion. Community control and accompanying conservation measures were declared to be thoroughly illegitimate.

Especially fierce criticism was reserved for the practice of shifting cultivation, prevalent in the central Indian forested belt, of which Mendha was a part. Locals pleaded in vain that the practice was nondestructive: the cleared patches were left to

Map by Mapping Specialists

"Who owns this forest? Not the government, nor any of us. The real owners are not yet born. We are merely custodians."

—Dukku Chamaru Tofa

ELDER OF THE GOND TRIBE in central India, Dukku Chamaru Tofa upholds ancient traditions of nature conservation that are common to hunter-gatherers and shifting cultivators worldwide.

regrow for up to 15 years. Moreover, they always left all mahua trees, which they considered sacred, intact. Under British rule, the entire forest, including the huge, ancient mahua trees, was being razed to the ground to facilitate the harvesting of timber.

By 1860 Indian forests had been substantially depleted, and moves to moderate the pace of their destruction led to the appointment of an inspector general of forests, German botanist Dietrich Brandis. (The British had little expertise in forestry, having long consumed the forests of their own isles.) Admiring the excellent community-based management of Indian villagers, Brandis lamented the decimation of the once extensive network of sacred groves and asked that a substantial part of forest be left in charge of the people. Although they reluctantly agreed, the colonial rulers did not implement this provision until around 1930 and that, too, on a very limited scale. Instead the forest department grew into the biggest landlord of all, eventually controlling more than a fifth of the country's land. Community rights over forests were abolished.

Derecognition of their ancient rights meant that villagers could no longer prevent outsiders getting in and ruthlessly exploiting resources from their commons. The resource regime had changed from "community control" to "open access." Elinor Osrom, who won a Nobel prize in economics in 2009 for her research, demonstrated by a remarkable combination of theoretical, field and experimental studies that the open-access common-property regime is subject to abuse. Restrained utilization or complete protection of common-property natural resources becomes possible only in the presence of firm community control.

ECOSYSTEM PEOPLE

DESPITE THE IMPOSITION OF an open-access regime, communities in the central forested tract of India continued to manage their forests well until independence in 1947. Mahatma Gandhi, who led the struggle for independence, had consistently pleaded for respecting and empowering India's village communities. His vision was, however, rejected in toto by the government of independent India, which proceeded to further consolidate the forestry establishment. As a result, the disempowerment of Indian village communities gathered pace.

In February 1972 I received a plea for help from the people of Gani, a village in the Western Ghats, who were shocked by the state forest department marking trees for felling in their sacred grove. Reaching the village posthaste, I saw their grove of 15 hectares, all of it in a primeval state: never had there been any felling within it in human memory. Its ancient trees, laden with climbers, soared up to 40 meters in height, with the most majestic specimen, a ficus locally called garud, having a girth of 15 meters. But all the surrounding region had been completely deforested, so that the grove was the people's only source for dead wood or leaf litter for manuring the paddy fields and, apart from the village well, the only perennial water source. Armed with these facts, I met the most senior forestry officer in the state. He granted the request since it was coming from me but dismissively remarked that such groves were nothing but "stands of overmature timber."

In terms first used by Raymond Dasmann, one of the founders of modern environmentalism, the people of Gani were "ecosystem people," and the chief of the forestry department belonged to the class of "biosphere people." Ecosystem people largely depend on their own muscle power and that of their livestock to gather and

process most of the resources they consume, which comes from within an area of roughly 50 square kilometers around their homesteads. Living in such close proximity with their resource base, ecosystem people fully understand and appreciate the bounty that nature confers. Biosphere people, on the other hand, have extensive access to additional sources of energy such as fossil fuels, which enables them to transport and transform large quantities of materials from all over for their use. Their ecological footprints are tens or hundreds of times higher than those of the ecosystem people. The biosphere people see distant rural locales merely as sources of timber, mineral ores or hydroelectric power or—at best—as tourist resorts. To them, ecosystem people are either a source of cheap labor or a hindrance to accessing the resources they need or want. They disregard the ecosystem services valued by the locals.

The ruling classes in India, as in across the world, are biosphere people, and they claim that they manage society for the common good. The reality is quite different, as I saw in my early fieldwork in the then remote, narrow Ambi Valley in the Western Ghats. The villagers cultivated rice in the valley and practiced shifting cultivation on the hill slopes. While clearing forest patches for cultivation, they left intact extensive tree growth of mango and myrobolan that brought them a small but regular income. When dam construction began in the 1950s, however, motor vehicles began to enter the valley, confronting the peasants, who until then had seen little cash, with the market economy. Charcoal merchants told them that because they would be relocated soon, they might as well sell the trees on their hill slopes. They brought along Hindu priests from the nearby city of Pune, who assured the villagers that they would perform appropriate ceremonies to placate the offended deity and build a pretty little temple to house it.

Huge mango and myrobolan trees, each worth hundreds of rupees, were sold for as little as half a rupee. The reserve forests on top of the hill, controlled by the state, were also wiped out by the charcoal merchants in collusion with corrupt forest officials. In the end, the villagers displaced by the dam were never adequately rehabilitated. Most were forced to relocate onto the now thoroughly denuded hill slopes, to eke out a living as best they could. The plentiful water stored in the dam serves the organized industries of Pune and the holders of irrigated lands to the east. The cost of all the environmental degradation was, in the short run, thrust on the villagers of Ambi Valley. In the long run, of course, the entire society is the loser.

For me, these experiences strengthened the hypothesis that, six millennia since the inception of sacred groves in the Indian subcontinent, spiritual beliefs were no longer sufficient to ensure their survival in the face of sustained assault from commercial interests. Since independence, India has displaced tens of millions of people from forests and fields to make room for mines, dams and other development projects. If the sacred groves are to survive, I surmised, the ecosystem people must be able to retain access to the ecological services they offer. If the hegemony of biosphere people destroys the possibility of such benefits, the villagers would have little motivation to protect the groves—which would then be wiped out.

SECULAR GROVES

ALONG WITH ANTHROPOLOGIST B. Mohan Reddy and Natabar Shyam Hemam, both then at the Indian Statistical Institute, I tested this hypothesis in the 1990s in the states of Manipur and Mizoram in the foothills of the eastern Himalayas. Elders told us that in the past, up to 30 percent of land and water were fully protected as sacred sites. Certain valued resources such as *Aquilaria,* with its fragrant wood, or bamboo were harvested with great care. When the British established control over this region in the early 20th century, however, they assigned the ownership of all land to various tribal chiefs, reducing the rest of the populace to sharecroppers. Many of these chiefs forcibly liquidated the forests to make a quick buck.

WOMEN OF MENDHA, including Jaiyawanta Dayaram Duga (*1*), Jaiyawanta Dewaji Kadap (*2*), Sangita Vasant Atala (*3*) and Bhagrita Kisan Halmi (*4*), played a leading role in protests against a stone quarry that was damaging forests and threatening a sacred site, the Jaitur Pen. A women's cooperative named after Danteshwari, the community's supreme goddess, now runs the quarry.

Even greater damage followed in the 1950s, when missionaries converted the entire tribal society of many of the northeastern states to Christianity. Their hostility to "pagan" beliefs led to the destruction of the large network of sacred groves and ponds. (Sacred ponds are water bodies, often within sacred groves, in the vicinity of which only one human activity is permitted: the taking of drinking water, which is typically pure and free of pathogens.) Significantly the tiny Buddhist country of Bhutan, nestled among India's northeastern states, never came under colonial rule or missionary influence and still harbors a network of sacred groves that is estimated to cover 20 percent of its land surface.

As the sacred groves were cleared, however, people began to realize they had fulfilled a number of valued ecosystem services, in particular as firebreaks. The fires that they set to clear plots for shifting cultivation stopped when they reached these dense, drippy patches of rain forest. In consequence, a few years after the demise of sacred groves, several villages, such as Saichang of the Gangte tribe in Manipur, reinstituted protection to forest patches. These refugia are no longer regarded as inviolable as abodes of spiritual beings. Even so, the system of community-based vigilance and protection is identical to that of earlier times, and they are still called *gamkhap* (in the Gangte language), like the sacred groves of yore. These findings strengthened my conviction that even if spiritual beliefs give way to secular ones, sacred groves could survive if ecosystem services reached the ecosystem people.

FOREST RIGHTS

FOR THE PEOPLE of the central forested tract of India, the tide began to turn in the 1980s. A spirited struggle—"Save the Forest, Save the People"—broke out to assert the forest rights of local communities. The people of Mendha—which locals call "Mendha (Lekha)" because of its proximity to a larger village, Lekha—played a leading role. Their first success, small but significant, came in 1991, when a cooperative society that the women had formed obtained rights to manage a stone quarry that was threatening a sacred site in the community forest. The movement continued to spread and gather strength until it culminated in the passage of the Scheduled Tribes and Other Traditional Forest Dwellers (Recognition of Forest Rights) Act of 2006. Professing to undo the injustice that began in the British regime, the act conferred not only individual but also, and more important, community rights over certain areas. These included the right to protect, regen-

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erate, or conserve and manage local resources such as bamboo.

In 2009 Mendha and its neighbor, Marda, became the first villages in India to win community rights over their common forest. At long last, they were able to exclude outsiders and to ensure that insiders exercise due restraint in harvesting natural resources. I was fortunate to be present during their discussions for formulating regulations for sustainable resource use. The preface to their management plan includes a quotation from an elder, Dukku Chamaru Tofa, capturing a sentiment that is at the core of sustainability: "Who owns this forest? Not the government, not the village, nor any of us. The real owners are those not yet born. We are merely custodians, entrusted with the privilege of taking only what we need while leaving the heritage intact for future generations." The villagers also resolved to identify areas to be set up as new sacred groves, called *pen geda* (in the Gondi language)—but incorporating the scientific wisdom that these should encompass the full range of ecological habitats and species.

Although the forest bureaucracy is dragging its feet on ceding control, thus far 3,600 villages in Maharashtra have obtained community rights to neighboring forests. Just as exciting, across Gadchiroli District, where Mendha lies, efforts are under way to create a Mahasangh, a federation of village councils. This promises to be a fascinating experiment in cooperative efforts to protect natural resources on a broad scale. At a meeting of representatives of some 200 village councils this past February, they resolved to set up around 10 percent of their community forest resource areas as newly constituted sacred groves.

So there is ever stronger support for my belief that sacred groves will be preserved, revived or even newly created. That will require empowering the ecosystem people to fight back against the economically and politically powerful interests that want to grab timber, minerals, land and water for consumption by the biosphere people. Across the globe, similar grassroots movements are gaining ground. Local peoples are opposing tar sands extraction in Canada, oil pipelines in the U.S., dams in Brazil, mines in New Guinea and the replacement of rain forest with palm oil plantations in Indonesia. These grassroots defenders of the environment are being forcibly suppressed, but they are also winning significant battles.

After our breakfast in Mendha in March 2014, my hosts and I spent the day visiting the new sacred groves. Some had magnificent forest stands of arjun (*Terminalia arjuna*) and bondara (*Lagerstroemia microcarpa*), as on the rather inaccessible Saheban Metta Hill. Others had been chosen to provide a secure habitat for sloth bears and yet others to represent rocky outcrops and other special habitats. This was a fitting culmination of my romance with sacred groves of India, begun almost half a century earlier. SA

MORE TO EXPLORE

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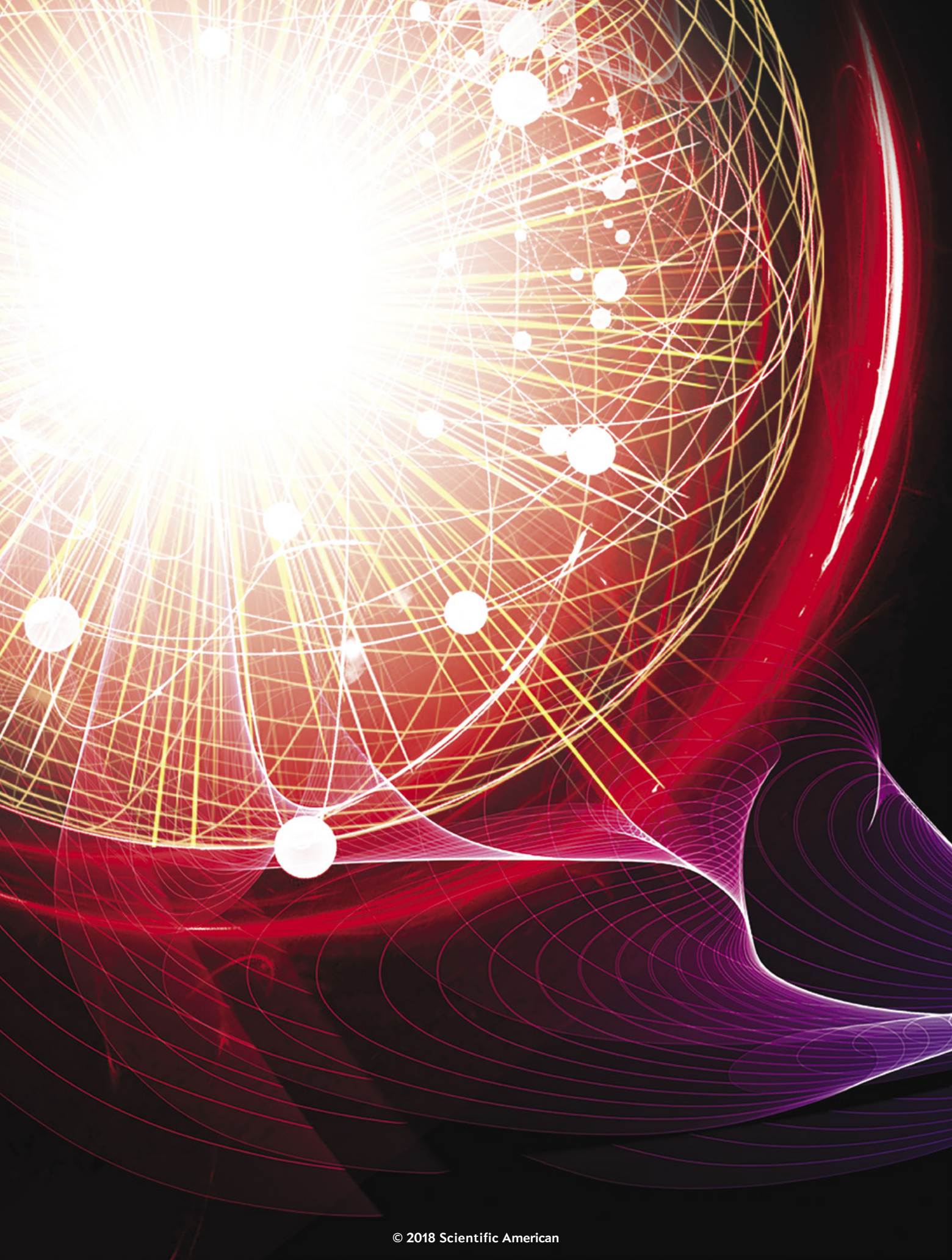
scientificamerican.com/magazine/sa

SACRED POOL in Kathani River near Mendha. Such water bodies are typically protected by prohibition of all human activity, other than the collection of drinking water, in their vicinity.



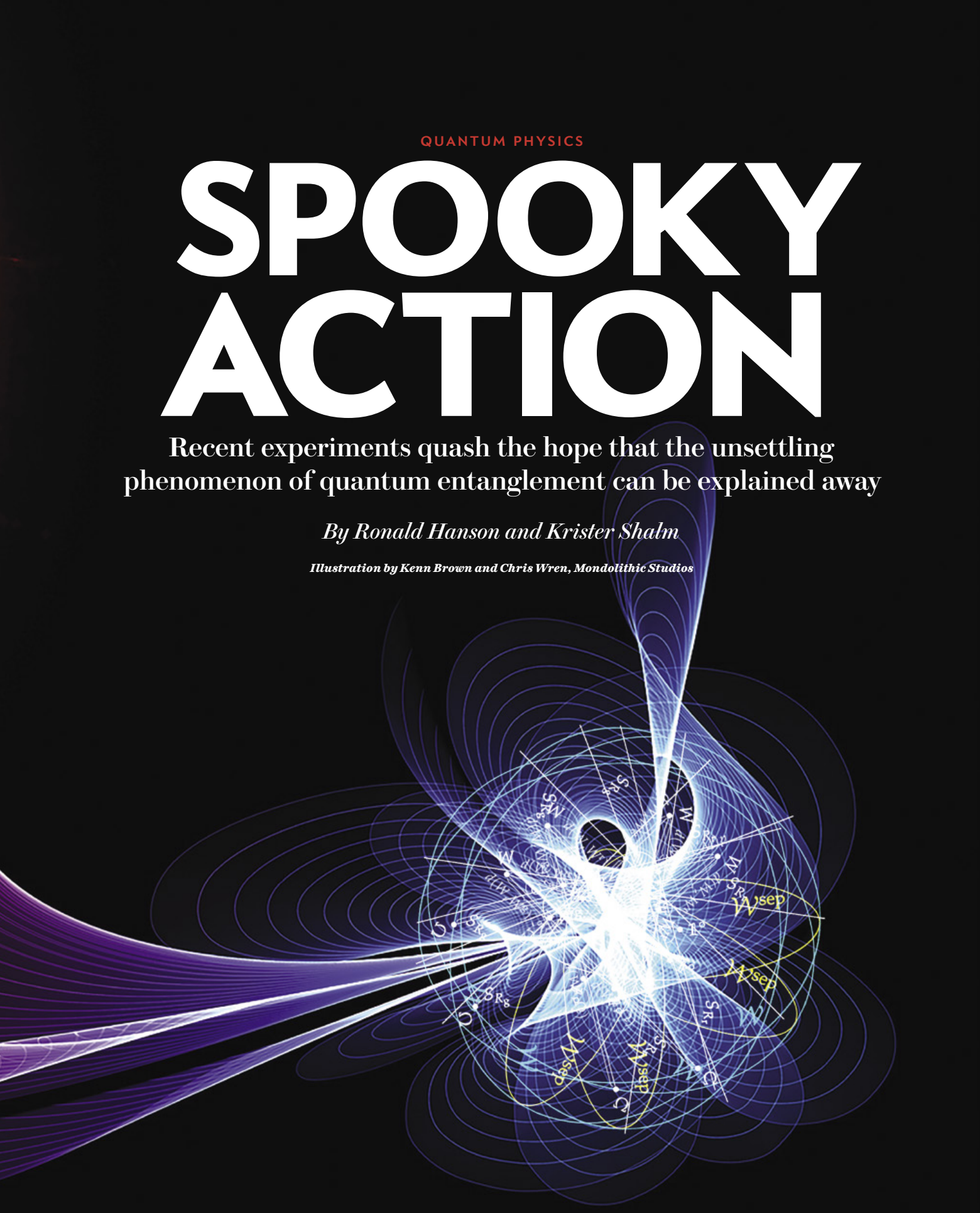
QUANTUM PHYSICS

SPOOKY ACTION

Recent experiments quash the hope that the unsettling phenomenon of quantum entanglement can be explained away

By Ronald Hanson and Krister Shalm

Illustration by Kenn Brown and Chris Wren, Mondolithic Studios



Ronald Hanson is a physicist at Delft University of Technology and scientific director of its QuTech research center, a collaboration with the Netherlands Organization for Applied Scientific Research (TNO), focused on quantum computing and quantum Internet technology.

Krister Shalm is a physicist at the National Institute of Standards and Technology and the University of Colorado Boulder, where he develops tools to test foundational issues in quantum mechanics.

Not all revolutions start big. In the case of quantum mechanics, a quiet one began in 1964, when physicist John Bell published an equation. This equation, in the form of a mathematical inequality, proposed a test to address deep philosophical questions that troubled many of the early founders of quantum mechanics.

The issue was whether particles separated by vast distances could retain a connection so that measurements performed on one affect the other. According to classical physics, this should be impossible. But under quantum theory, it happens all the time. Through his equation, Bell proposed a way to determine whether the universe could actually be that strange.

Over the past half a century his simple equation has profoundly changed the way we think about quantum theory. Today many of the quantum technologies that physicists are inventing owe their beginnings to Bell's test. Yet it was not until 2015, more than 50 years after Bell proposed his inequality, that scientists were able to verify the predictions of Bell's theorem in the most complete manner possible. These experiments close a quest that has spanned generations and mark the start of a new era in developing quantum technologies.

HIDDEN VARIABLES

TO UNDERSTAND BELL'S EQUATION, we must go back to the roots of quantum mechanics. This set of rules describes the behavior of light and matter at the smallest scales. Atoms, electrons, photons and other subatomic particles act differently from things we experience in our everyday lives. One of the major deviations is that these small particles exist in uncertain states. Take an electron's spin, for example. If an electron whose spin is sideways passes through a magnetic field oriented up and down, half the time it will veer upward and half the time it will veer downward, but the outcome is truly random. Compare this to a coin flip. We might think that flipping a coin is equally random, but if we knew precisely the mass of the coin, how much force was used to flip it and all the details about the air currents hitting it, we would be able to predict exactly how the coin would land. Electron spin is different, however. Even if we had perfect knowledge about all the properties of the electron and its spin before it passes through the magnetic field, quantum fuzziness prevents us from knowing which way it will go (we can, however, calculate the *probability* of it going up or down). When scientists actually measure a quantum system, though, all these possibilities cease to exist somehow, and a single outcome is decided—the electron ends up having a spin that is oriented either up or down.

When physicists formulated quantum theory in the early 20th century, some of its founding members, such as Albert Einstein and Erwin Schrödinger, felt uncomfortable with the fuzziness of quantum states. Perhaps, they thought, nature is not really fuzzy, and a theory that goes beyond quantum mechanics could exactly predict the behavior of particles. Then it would be possible to foresee the outcome of a measurement of the spin of an electron in the same way it is possible to know exactly how a coin will land if you have enough information.

Schrödinger introduced the idea of entanglement (*Verschränkung* in German) to describe quantum fuzziness spread across two or more particles. According to quantum theory, properties

IN BRIEF

In 1964 physicist John Bell discovered that the phenomenon of quantum entanglement—where two particles can retain a "spooky" connection even when far apart—leads to a mathematical conflict with our intuitive picture of nature.

Since Bell's proposal, experimenters have staged many versions of his test. Most results seemed in agreement with the existence of entanglement. Yet each of these experiments has contained loopholes that make it possible for "hidden variables" to act behind the scenes, producing results that masquerade as entanglement.

Finally, in 2015, several groups conducted the first loophole-free Bell tests, ruling out any local hidden variable explanation.

of particles can be entangled such that their joint value is precisely known, but the individual values remain completely uncertain. An analogy would be two dice that, when rolled, would each yield a random result but together always add up to 7. Schrödinger used the idea of entanglement in a famous thought experiment in which the fuzziness of the state of an atom becomes entangled with a cat being dead or alive. Surely any cat is either dead or alive and not in an absurd limbo in between, Schrödinger reasoned, and therefore we should question the notion that atoms can be fuzzy at all.

Einstein, with his collaborators Boris Podolsky and Nathan Rosen (known together as EPR), took the argument a step further by analyzing two entangled electrons that are far apart. Imagine that the spins of the particles are entangled such that when measured along the same orientation, opposite values will always result. For instance, if scientists measure one electron spin and find it to be pointing up, the other will point down. Such correlations are certainly surprising when the electrons are far enough apart that it is impossible for them to communicate at the speed of light before their individual spins are measured. How does the second particle know that the first one was up? Einstein famously called this synchronization "spooky actions at a distance."

The EPR analysis of this case, published in 1935 in a now classic paper, started from two very reasonable assumptions. First, if scientists can predict a measurement outcome with certainty, there must be some property in nature that corresponds to this outcome. Einstein named these properties "elements of reality." For example, if we know that an electron's spin is up, we can predict with certainty that if it travels through an appropriate magnetic field it will always be deflected upward. In this situation, the electron's spin would be an element of reality because it is well defined and not fuzzy. Second, an event in one place cannot instantaneously affect a faraway event; influences cannot travel faster than the speed of light.

Taking these assumptions, let us analyze two entangled electrons held at distant places by two people, Alice and Bob. Suppose Alice measures her electron spin along the z direction. Because of the perfect anticorrelation, she immediately knows what the outcome will be if Bob measures his electron spin along z as well. According to EPR, the z component of Bob's electron spin would thus be an element of reality. Similarly, if Alice decides to measure the spin along the x direction, she would know with certainty the outcome of a measurement on Bob's electron spin along x. In this case, the x component of Bob's electron spin would be an element of reality. But because Alice and Bob are far apart, Alice's decision to measure along the z direction or the x direction cannot influence what happens at Bob's. Therefore, to account for the perfect anticorrelations predicted by quantum theory, the value of Bob's electron spin must be perfectly predictable both along the z direction and the x direction. This appears to contradict quantum theory, which states, through the so-called Heisenberg uncertainty principle, that the spin can have a well-defined value along a single direction only and must be fuzzy along the others.

This conflict led EPR to conclude that quantum theory is incomplete. They suggested that it might be possible to resolve the contradiction by supplementing the theory with extra variables. In other words, there might be a deeper theory that goes beyond quantum mechanics in which the electrons possess extra properties that describe how they will behave when jointly measured. These extra variables might be hidden from us, but if we had access to them, we could predict exactly what would happen to the electrons. The apparent fuzziness of quantum particles is a result of our ignorance. Physicists call any such successor to quantum mechanics that contains these hidden variables a "local hidden variable theory." The "local" here refers to the hidden signals not being able to travel faster than the speed of light.

BELL'S TWIST

EINSTEIN DID NOT QUESTION the predictions of quantum mechanics itself; rather he believed there was a deeper truth in the form of hidden variables that govern reality. After the 1935 EPR paper, interest in these foundational issues in quantum mechanics died down. The possibility of hidden variables was seen as a philosophical question without any practical value—the predictions of theories with and without hidden variables appeared to be identical. But that changed in 1964, when Bell startlingly showed that in certain circumstances hidden variable theories and quantum mechanics predict different things. This revelation meant it is possible to test experimentally whether local hidden variable theories—and thus Einstein's hoped-for deeper truth of nature—can really exist.

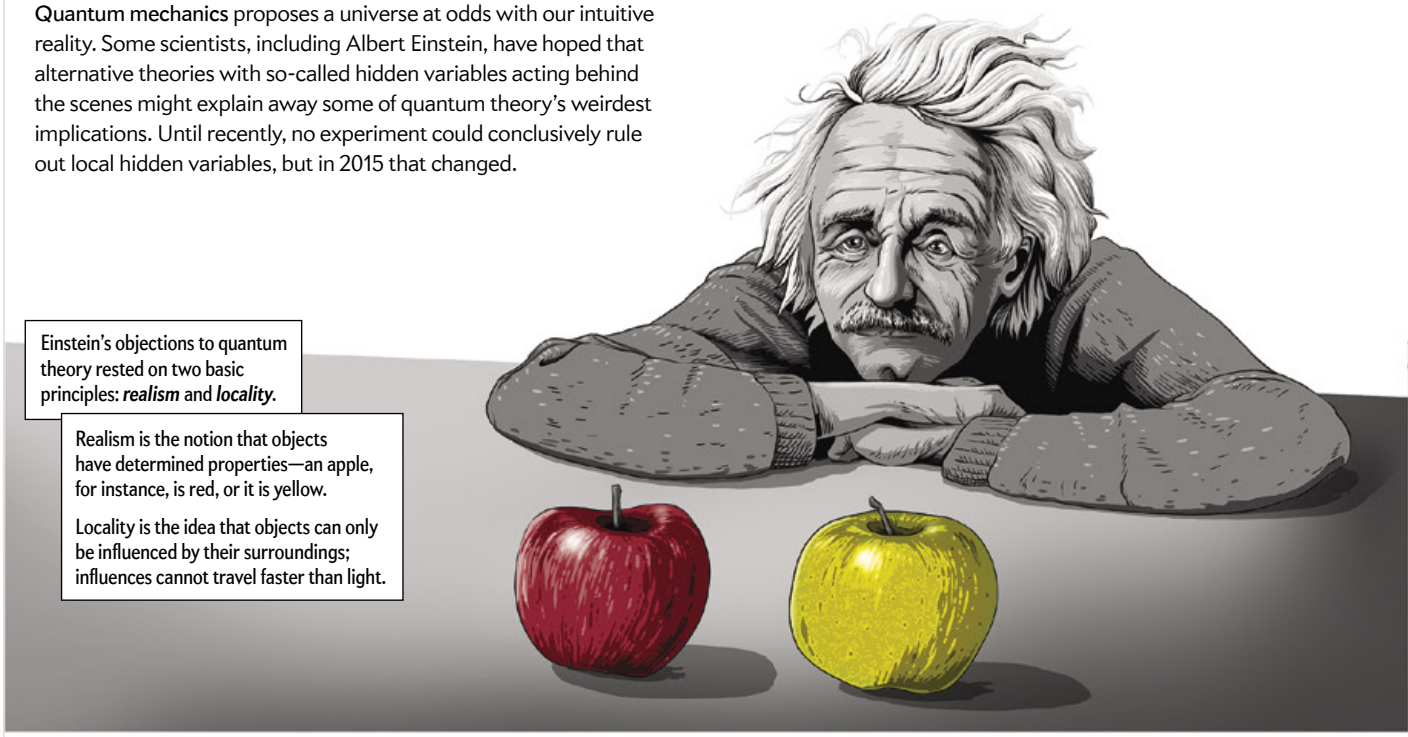
Bell analyzed the EPR thought experiment but with one twist: he let Alice and Bob measure their electron spins along any possible direction. In the traditional experiment, Alice and Bob must measure along the same direction and therefore find that their results are 100 percent correlated—if Alice measures up, then Bob always measures down. But if Alice and Bob are sometimes measuring along different axes, sometimes their outcomes are not synchronized, and that is where the differences between quantum theory and hidden variable theories come in. Bell showed that for certain sets of directions, the correlations between the outcomes of Alice and Bob's measurements would be stronger according to quantum theory than according to any local hidden variable theory—a difference known as Bell's inequality. These differences arise because the hidden variables cannot influence one another faster than the speed of light and therefore are limited in how they can coordinate their efforts. In contrast, quantum mechanics allows the two electrons' spins to exist jointly in a single entangled fuzzy state that can stretch over vast distances. Entanglement causes quantum theory to predict correlations that are up to 40 percent stronger.

Bell's theorem completely changed physicists' thinking. It showed a mathematical conflict between Einstein's view and quantum theory and outlined a powerful way for experimentally testing the two. Because Bell's theorem is a mathematical inequality that limits how high correlations can be under any local hidden variable theory, experimental data that exceed these bounds—in other words, that "violate" Bell's inequality—will show that local hidden variable theories cannot describe nature.

Soon after Bell's publication, physicists John Clauser, Michael Horne, the late Abner Shimony and Richard Holt (known as CHSH) found similar inequalities that were easier to test in experiments. Researchers performed the first trials in the late 1960s, and since then experiments have come closer and closer to the ideal of Bell's proposed setup. The experiments have found correlations that violate Bell's inequality and seemingly cannot be explained by local hidden variable theories. Until 2015, though, all experiments necessarily relied on one or more additional assumptions because of imperfections in the setups.

Closing All the Loopholes

Quantum mechanics proposes a universe at odds with our intuitive reality. Some scientists, including Albert Einstein, have hoped that alternative theories with so-called hidden variables acting behind the scenes might explain away some of quantum theory's weirdest implications. Until recently, no experiment could conclusively rule out local hidden variables, but in 2015 that changed.



Einstein's objections to quantum theory rested on two basic principles: ***realism*** and ***locality***.

Realism is the notion that objects have determined properties—an apple, for instance, is red, or it is yellow.

Locality is the idea that objects can only be influenced by their surroundings; influences cannot travel faster than light.

Yet the theory of quantum mechanics suggests that reality is much weirder than that.

According to quantum mechanics, a particle can be in two states at the same time.

For example, a quantum apple …

Particles can even be entangled with one another. That is, if you look at one apple and find it red, the other instantly becomes yellow.

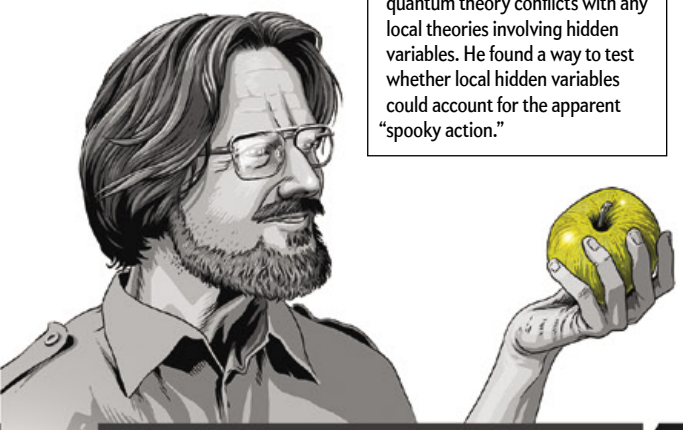
Entanglement exists no matter the distance between particles.

Einstein refused to accept this concept, calling it "spooky actions at a distance."

He claimed there must be local hidden variables, unknown to observers, that control this entanglement because otherwise influences must be traveling faster than light.

Illustration by Matthew Twombly

In 1964 John Bell discovered that quantum theory conflicts with any local theories involving hidden variables. He found a way to test whether local hidden variables could account for the apparent "spooky action."



The Bell test: Two observers would make separate measurements of two supposedly entangled particles. Bell calculated the maximum amount of correlation that could arise between the two observers' findings if local hidden variables limited by the speed of light were at work.

Experimenters soon got to work putting the test into action. But two loopholes left some leeway for hidden variables.

1. Locality loophole
The measurement stations are close enough to allow communication with each other at sub–light speed during a test.

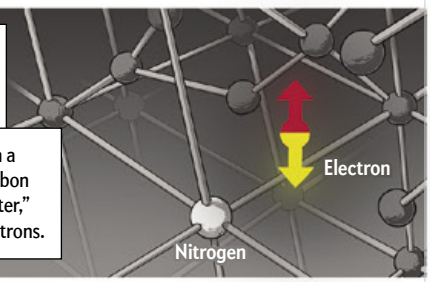
2. Detection loophole
The detectors are only able to measure some but not all the entangled particles.

In 2015 several groups of scientists devised versions of the Bell test that close both loopholes.

One, at the Delft University of Technology, starts with two tiny diamonds.

In the nearly perfect carbon lattice of a diamond, there exists a flaw, the occasional nitrogen atom.

In some places, next to such a nitrogen atom there is a carbon atom missing, a "defect center," which acts as a trap for electrons.

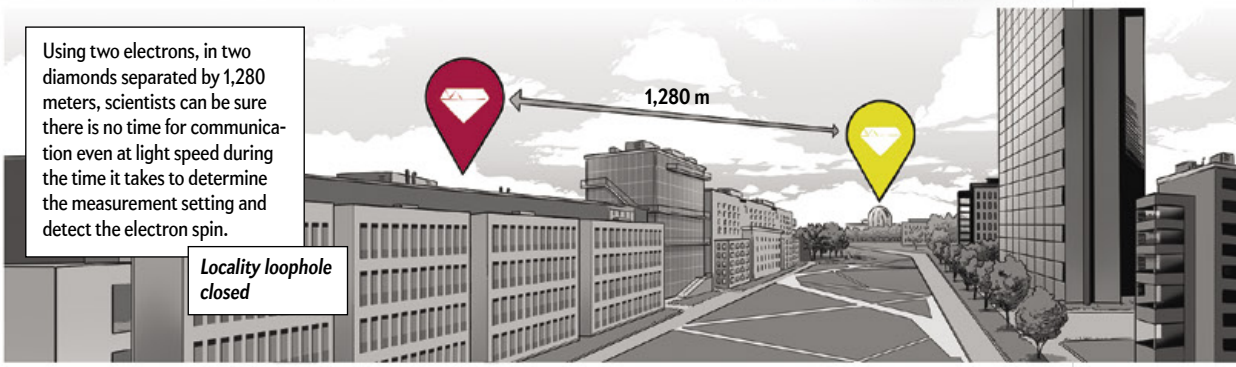


Electrons have a spin . . .

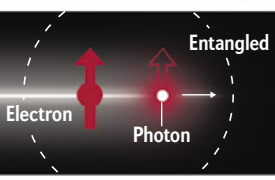
Or in a *superposition*, both up and down.

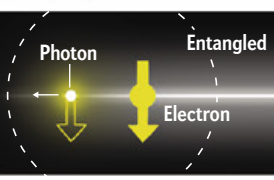
Using two electrons, in two diamonds separated by 1,280 meters, scientists can be sure there is no time for communication even at light speed during the time it takes to determine the measurement setting and detect the electron spin.

Locality loophole closed



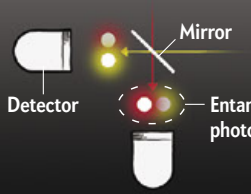
Scientists use lasers to excite the electrons, which then emit photons that are entangled with the spin of the electrons.





Those photons travel across campus until they meet each other at detectors.

When the photons meet, they become entangled. By extension, their distant respective electrons—which are easier to detect and measure than photons—also become entangled.



Detection loophole closed

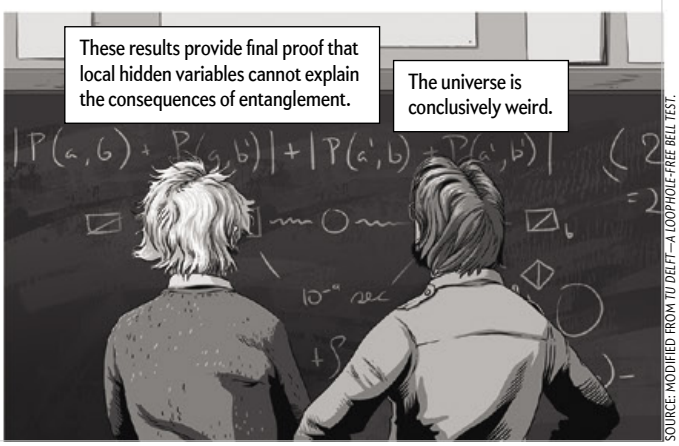
For the first time, a loophole-free Bell test

At Delft, scientists ran 245 trials in which a pair of electrons 1,280 meters apart were entangled. They measured the particles in every case and found 80 percent were correlated—significantly more than would be possible with local hidden variables.

Experiments in the U.S., Austria and Germany found similar results.

These results provide final proof that local hidden variables cannot explain the consequences of entanglement.

The universe is conclusively weird.



SOURCE: MODIFIED FROM *TU DELFT—A LOOPHOLE-FREE BELL TEST.*
TEXT BY MICHEL VAN BAAL AND GRAPHICS BY SCIXEL. TU DELFT, 2015

These assumptions provide loopholes that local hidden variable theories could in principle use to pass the test.

In virtually all such experiments in the 20th century, scientists generated entangled photons at a source and sent them to measurement stations (standing in for Alice and Bob). The Alice and Bob stations each measured their respective photon along one of two orientations, noting its polarization—the direction in which the photon's electric field oscillates (polarization can be thought of as the spin of a photon). The scientists then calculated the average correlations between the two stations' outcomes and plugged those into Bell's equation to check whether the results violated the inequality.

TESTS WITH CAVEATS

THE FIRST SERIES OF EXPERIMENTS used fixed measurement directions. In these cases, there is ample time for hidden variables (using knowledge of the measurement directions on either side) to influence the outcomes. That is, hidden signals could tell Bob which direction Alice used to measure her photon without traveling faster than light. This so-called locality loophole means that a hidden variable theory could match the quantum correlations. In 1982 French physicist Alain Aspect and co-workers performed a test where the photons were sent to opposite ends of a large room and their polarization measured. While these entangled photons were in flight, the polarization angle of the measurement device changed periodically. In the late 1990s Anton Zeilinger, now at the University of Vienna, and his colleagues further improved this strategy by using truly random (as opposed to periodic) polarization-measurement directions. In addition, these measurement directions were determined very shortly before the measurements took place, so hidden signals would have had to travel faster than light to affect this experiment. The locality loophole was firmly closed.

These experiments had one drawback, however: photons are hard to work with. Most of the time the tests got no answer at all, simply because the photons were not created in the first place or were lost along the way. The experimenters were forced to assume that the trials that worked were representative of the full trial set (the "fair sampling assumption"). If this assumption was dropped, the results would not violate Bell's inequality. It is possible that something different was happening in the trials where photons were lost, and if their data were included, the results would not be in conflict with local hidden variable theories. Scientists were able to close this so-called detection loophole in this century by giving up photons and using matter, such as trapped ions, atoms, superconducting circuits and nuclei in diamond atoms, which can all be entangled and measured with high efficiency. The problem is that in these cases the particles were all located extremely close to one another, leaving the locality loophole open. Thus, although these Bell tests were ingenious, they could all, at least in principle, be explained by a local hidden variable theory. A Bell test with all the loopholes closed simultaneously became one of the grandest challenges in quantum science.

Thanks to rapid progress in scientists' ability to control and measure quantum systems, it became possible in 2015, 80 years after the EPR paper and 51 years after Bell's equation, to carry out a Bell test in the ideal setting, often referred to as a loophole-free Bell test. In fact, within a short span of time, four different groups found results that violated Bell's inequality with all loopholes closed—providing ironclad evidence against local hidden variable theories.

CLOSING THE LOOPHOLES

ONE OF US (Hanson) and his collaborators performed the first experiment to close all loopholes at the Delft University of Technology in the Netherlands using a setup [*see box on preceding page*] that closely resembles the original EPR concept. We entangled the spins of two electrons contained inside a diamond, in a space called a defect center, where a carbon atom should have been but was missing. The two entangled electrons were in different laboratories across campus, and to make sure no communication was possible between them, we used a fast random-number generator to pick the direction of measurement. This measurement was finished and locally recorded on a hard drive before any information from the measurement on the other side could have arrived at light speed. A hidden signal telling one measuring station which direction the other had used would not have had time to travel between the labs, so the locality loophole was firmly closed.

These strict timing conditions required us to separate the two electrons by more than a kilometer, about two orders of magnitude farther apart than the previous world record for entangled matter systems. We achieved this separation by using a technique called entanglement swapping, in which we first entangle each electron with a photon. We then send the photons to meet halfway between the two labs on a semitransparent mirror where we have placed detectors on either side. If we detect the photons on different sides of the mirror, then the spins of the electrons entangled with each photon become entangled themselves. In other words, the entanglement between the electrons and the photons is transferred to the two electrons. This process is prone to failure—photons can be lost between the diamonds and the mirror, just as in the earlier photon-based experiments. But we start a Bell trial only if both photons are detected; thus, we deal with photon loss beforehand. In this way, we close the detection loophole because we do not exclude the findings of any Bell test trials from our final results. Although the photon loss related to the large separation in our case does not limit the quality of the entanglement, it does severely restrict the rate at which we can conduct Bell trials—just a few per hour.

After running the experiment nonstop for several weeks in June 2015, we found Bell's inequality was violated by as much as 20 percent, in full agreement with the predictions of quantum theory. The probability that such results could have arisen in any local hidden variable model—even allowing the devices to have maliciously conspired using all available data—was 0.039. A second experimental run conducted in December 2015 found a similar violation of Bell's inequalities.

In the same year, three other groups performed loophole-free Bell tests. In September physicists at the National Institute of Standards and Technology (NIST) and their colleagues, led by one of us (Shalm), used entangled photons, and in the same month, Zeilinger's group did so as well. Not too long after, Harald Weinfurter of Ludwig Maximilian University of Munich and his team used rubidium atoms separated by 400 meters in a scheme similar to that of the Hanson group (the results were published in 2017).

Both the NIST and Vienna teams entangled the polarization

state of two photons by using intense lasers to excite a special crystalline material. Very rarely, about one in a billion of the laser photons entering the crystal underwent a transformation and split into a pair of daughter photons whose polarization states were entangled. With powerful enough lasers, it was possible to generate tens of thousands of entangled photon pairs per second. We then sent these photons to distant stations (separated by 184 meters in the NIST experiment and 60 meters in the Vienna experiment) where we measured the polarization states. While the photons were in flight toward the measurement stations, our system decided which direction to measure their polarization in such a way that it would be impossible for any hidden variables to influence the results. The locality loophole is therefore closed. The most challenging aspect of using photons is preventing them from being lost, as we must detect more than two thirds of the photons we create in our setup to avoid the detection loophole. Most conventional single-photon detectors operate at around 60 percent efficiency—a nonstarter for this test. But at NIST we developed special single-photon detectors, made of cold superconducting materials, capable of observing more than 90 percent of the photons that reach it. Thus, we closed the detection loophole as well.

Repeating these polarization measurements on many different entangled photon pairs more than 100,000 times per second, we were able to quickly accumulate statistics on the correlations between the photon polarization states. The correlations observed in both experiments were much stronger than those predicted by hidden variable theories. In fact, the probability that the NIST results could have arisen by chance is on the order of one in a billion (even less likely than winning the Powerball lottery), and the chances are even smaller for the Vienna experiment. Today our NIST group regularly uses an improved version of our setup to violate Bell's inequalities to a similar degree in less than a minute, and future improvements will speed this up by two orders of magnitude.

HARNESSING ENTANGLEMENT

THESE EXPERIMENTS FORCE US TO CONCLUDE that any local hidden variable model, such as those Einstein advocated, is incompatible with nature. The correlations between particles we have observed defy our intuition, showing that spooky action does indeed take place.

Our results also hint at the remarkable power contained in entanglement that we may be able to put to use. A near-term application where loophole-free Bell tests can be useful is in generating randomness. Random numbers are a critical resource in many cryptographic and security techniques. If you can predict the next number a random-number generator will produce, you can hack many financial and communications systems. A good source of randomness that cannot be predicted is therefore of vital importance. Two of the most common ways to generate randomness are through mathematical algorithms or using physical processes. With mathematical algorithms, if you know the conditions used as a "seed," you can often predict the output perfectly. With physical processes, a detailed understanding of the underlying physics of the system is required. Miss even a single detail, and a hacker can exploit or control the randomness. The history of cryptography is littered with examples of both types of random-number generators being broken.

Quantum mechanics has handed us a gift, though. It is possible to "extract" the randomness inherent in quantum processes to produce true randomness. The correlations measured in a loophole-free Bell test can be distilled into a certifiably random string. Remarkably, it is possible to hand part of the experimental apparatus (the generation of the entangled particles) to a potential hacker to control. Even in this extreme case, it is possible to produce numbers that are as random as nature allows. In early 2018 our team at NIST was able to use our loophole-free Bell setup to extract 1,024 truly random bits from 10 minutes of experimental data. These bits were certified to be random to better than a part in one trillion. In contrast, it would take a conventional random-number generator several hundred thousand years to acquire enough data to directly measure the quality of their randomness to this level. We are working now to incorporate our random-number generator into a public randomness beacon. This tool could act as a time-stamped source of random numbers that is broadcast over the Internet at fixed intervals and can be used in security applications by anyone who needs it.

On a more general level, the techniques developed in loophole-free Bell experiments may enable fundamentally new types of communications networks. Such networks, often referred to as a quantum Internet, can perform tasks that are out of reach of classical information networks. A quantum Internet could enable secure communication, clock synchronization, quantum sensor networks, as well as secure access to remote quantum computers in the cloud. Another goal is "device-independent cryptography," in which (in close analogy to the randomness beacon) users can validate the secrecy of a shared key through a violation of Bell's inequalities.

The backbone of a future quantum Internet will be formed by entanglement links precisely like the setups used to test Bell's inequalities with diamond defect centers, trapped atoms and photons. In 2017 our team at Delft demonstrated a method to boost the quality of remote entangled spins, and in 2018 we improved the entangling rates by three orders of magnitude. Based on this progress, researchers are working toward a first rudimentary version of a quantum Internet that is scheduled to be realized among a few cities in the Netherlands in 2020.

Eight decades ago when quantum theory was being written, skeptics chafed at its apparent contradiction with the centuries of physical intuition that had been developed; now four experiments have dealt the final blow to that intuition. At the same time, these results have opened the door to exploit nature in ways that Einstein and Bell could not have foreseen. The quiet revolution that John Bell kicked off is now in full swing. SA

MORE TO EXPLORE

Loophole-Free Bell Inequality Violation Using Electron Spins Separated by 1.3 Kilometres. B. Hensen et al. in *Nature,* Vol. 526; pages 682–686; October 29, 2015.

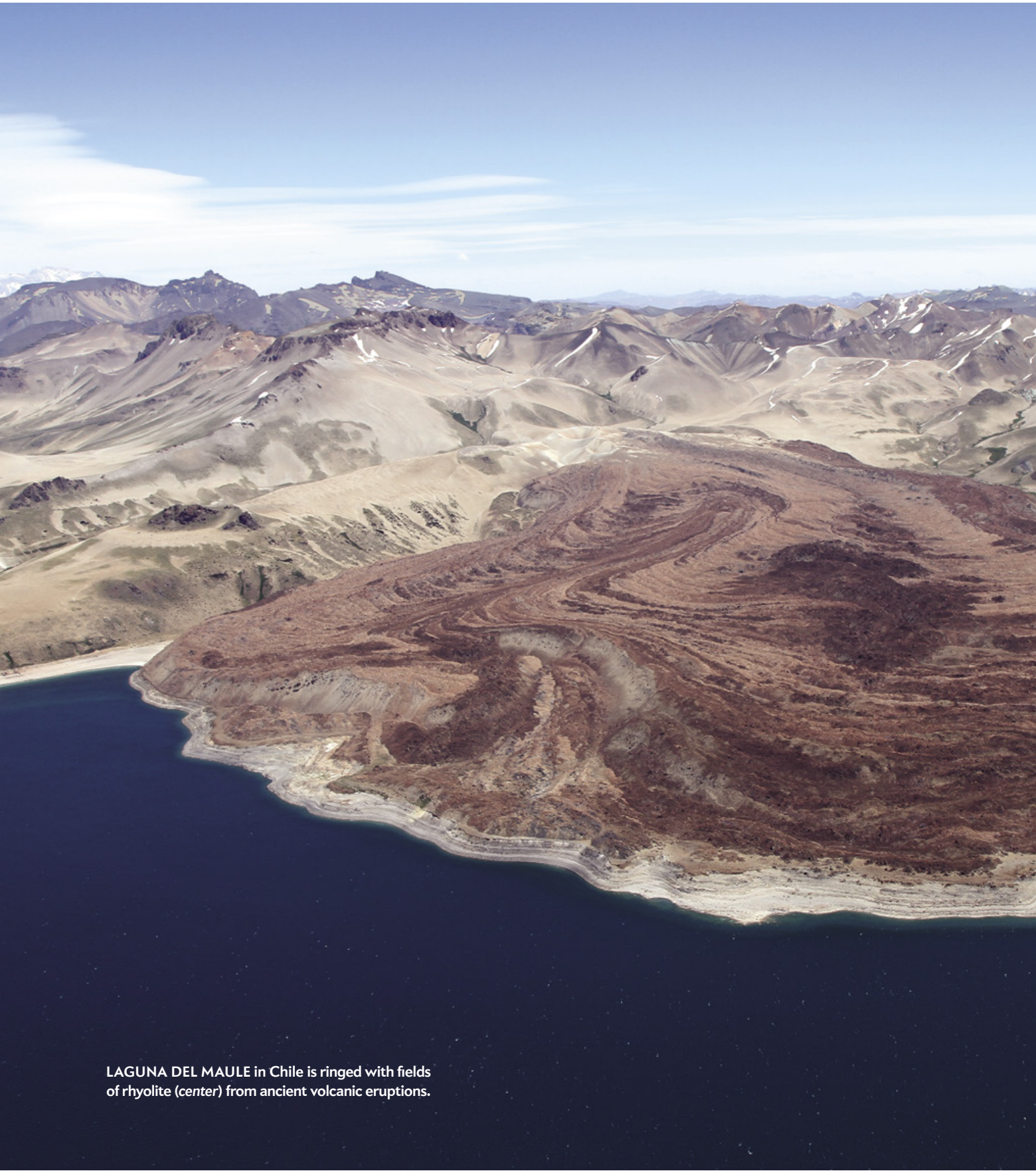
Significant-Loophole-Free Test of Bell's Theorem with Entangled Photons. Marissa Giustina et al. in *Physical Review Letters,* Vol. 115, Article No. 250401. Published online December 16, 2015.

Strong Loophole-Free Test of Local Realism. Lynden K. Shalm et al. in *Physical Review Letters,* Vol. 115, Article No. 250402. Published online December 16, 2015.

FROM OUR ARCHIVES

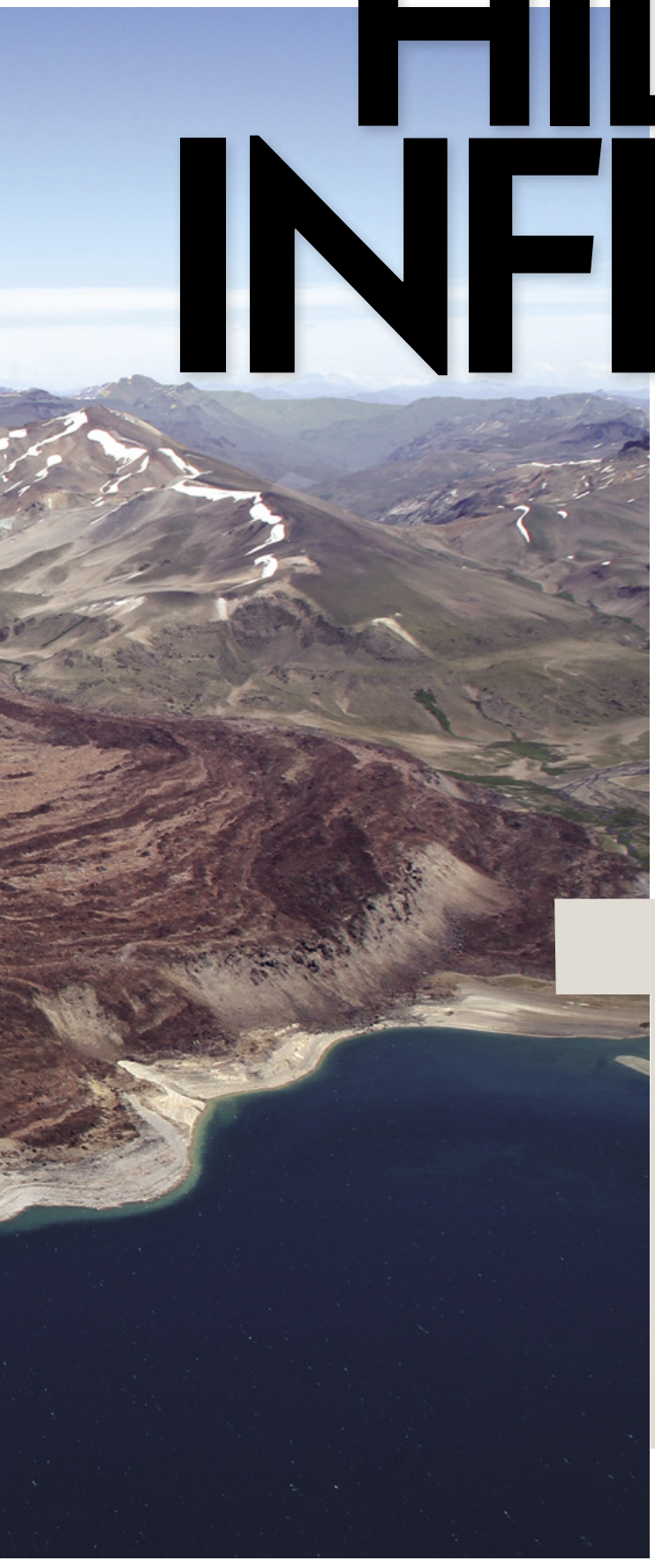
Black Holes, Wormholes and the Secrets of Quantum Spacetime. Juan Maldacena; November 2016.

scientificamerican.com/magazine/sa



LAGUNA DEL MAULE in Chile is ringed with fields of rhyolite (*center*) from ancient volcanic eruptions.

HIDDEN INFERNO



GEOLOGY

A supervolcano may be brewing underneath Chile, with a cold interior that is upending ideas about triggers of huge eruptions

By Shannon Hall

THE AIRBUS HELICOPTER BUCKED wildly in the frigid air hundreds of meters above the Chilean Andes. Every time it heeled over to turn, the helicopter dropped 20 meters, and the jagged peaks below seemed to rush up at Brad Singer through a gaping opening in the copter's side—the door had been removed to make photography easier. The jolts and the clear path to the ground did not make Singer, a geologist usually based on the flat land around the University of Wisconsin–Madison, feel very secure even though he was strapped into a seat. "It was like being in a big, loud open roller coaster," he recalls.

But the awe-inspiring scene far below, with its landmarks of a vast volcanic history, distracted him from his worries about falling. At one point, Singer and his colleagues flew over a pale pink lava flow that stretched across the stark landscape for 20 square kilometers—a footprint that could easily hold 25 Mount Kilauea summit craters. And that was only part of what the geologist had come to see. This volcanic region, known as Laguna del Maule, hosts about 50 lava flows and 70 ash deposits, ringed around a 54-square-kilometer icy blue lake. Only from above, says Singer, who has been exploring this area for the past 20 years, can you truly grasp the region's gigantic scale. Only then can you take to heart that Laguna del Maule hosts the world's largest collection of recently erupted rhyolite, a rock that, in its liquid magma form, can be particularly explosive and dangerous.

Geologists suspect that the flows and deposits are the handiwork of 25 to 30 different volcanoes over the past 20,000 years. This record is eerily like a place called Long Valley in California, where, in addition to a spate of what Singer calls "business as usual" explosions, a single enormous volcano blew a 500-square-kilometer pit in the land roughly 765,000 years ago. That geologic similarity, plus an ominous swelling of the ground at Laguna del Maule that began a decade or so ago, suggests the region might be capable of becoming the world's next supervolcano.

Supervolcanoes hold some of the most destructive forces on the planet. These eruptions send at least 1,000 cubic kilometers of rock and ash hurtling out of the earth at once—2,500 times more material than the devastating Mount St. Helens explosion in 1980. Underground maps of Laguna del Maule's magma chamber have recently indicated it has grown large enough to put that amount of material in the air, should it all blow at once. Even if Laguna del Maule lets off some of its steam in a series of smaller eruptions, the system looks like a good model for the ancient giants.

It also has one key feature all other known supervolcanoes lack: it is forming in front of our eyes. Until today, everything that geologists know about these behemoths has been gleaned from old rocks and ash deposits and other aftereffects—forensic work that allows them to reconstruct a few aspects of the explosions. But Laguna del Maule is rousing right now, offering the first live look at the way such catastrophes develop. "We have no human experience with these kinds of large supervolcanic eruptions," Singer says. (The prospect of human experience is a major concern for the several hundred thousand people who live in nearby cities and towns. While a supereruption does not seem likely any time soon, government agencies in Argentina and Chile are keeping a close eye on the region.)

Shannon Hall is an award-winning freelance science journalist based in the Rocky Mountains. She specializes in writing about astronomy, geology and the environment.

That up-close peek at Laguna del Maule, along with findings from older supervolcanoes, has already pushed scientists toward a surprising conclusion: the giant underground chambers of magma that fuel these monsters are not the hot vats of molten lava that researchers once imagined. Instead the mass is cold enough that it is often solid. The realization has presented volcanologists with a puzzle: for an eruption to occur, solid magma has to melt and rise rapidly, within a matter of decades, so geologists have been trying to explain how this sudden change from cold to superhot happens.

Recently Singer and some of his colleagues have seen signs that the cool magma reservoir may be hit by a sudden jolt of hot bubbles of water from below; in other volcanoes, scientists have found evidence that magma from a lower, hotter chamber bursts into the higher, chillier one. As researchers try to piece together these clues, the real-time observations at Laguna del Maule might help them explain our planet's biggest bangs.

A RISING POWER

THE FORCES UNLEASHED by historic supervolcanoes were staggering. Roughly 631,000 years ago, for example, one erupted in what is now Yellowstone National Park in the U.S., sending lethal waves of hot gas, volcanic rock, ash and toxic fog racing across the landscape. Those eruptions filled entire valleys with material so hot and heavy that it welded into cliffs that are as thick as 200 meters today. Afterward the sky was dark with ash that went on to fall across an enormous swath of North America, leaving a layer of debris that spanned a triangle stretching from today's Canadian border down to California and over to the Gulf of Mexico. At times the ramifications of a supervolcano can be felt across the globe. A few have created layers of ash so thick that scientists believe they blocked the sun's light and plunged the earth into a volcanic winter.

No supervolcano has erupted in modern history. But in 2008 Matthew Pritchard, a geophysicist at Cornell University, was scouring data from a satellite when he noticed a surreal signal emanating from the Chilean Andes. The data on his computer screen revealed a psychedelic tie-dyed bull's-eye. The ring pattern was typical for any changes in ground elevation. The odd

IN BRIEF

Enormous destructive forces are stored in supervolcanoes, whose explosions are big enough to reshape continents. Humanity has never seen this kind of eruption.

At Laguna del Maule, high in the Andes, a volcanic system is brewing that may reach supersize in our lifetime. Its magma reservoir is already big enough, and past eruptions hint at vast power.

Surprisingly, such giant explosions do not start with superhot melted rock but with masses that are practically solid. Scientists are uncovering triggers that can transform them in mere decades.

PRECEDING PAGES: ANGIE DIEFENBACH *U.S. Geological Survey*

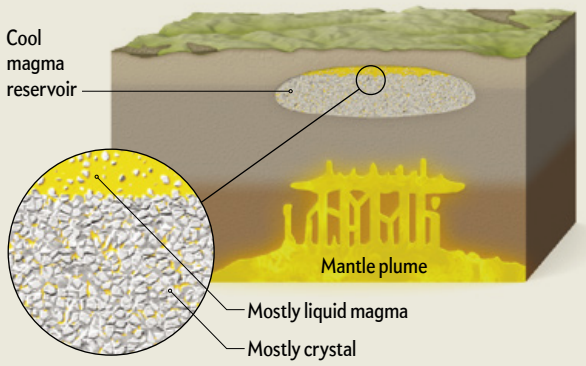
Map by Mapping Specialists

How Supervolcanoes Erupt

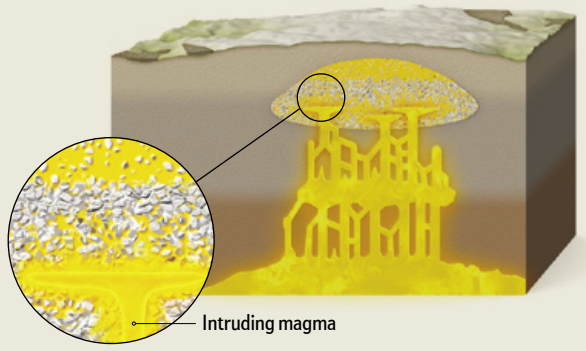
The planet's biggest volcanoes are not fueled by constantly seething cauldrons of magma. New findings indicate they have relatively cold hearts of nearly solid rock. Two different triggers, scientists theorize, could quickly heat that rock to explosive levels.

RISING PLUME

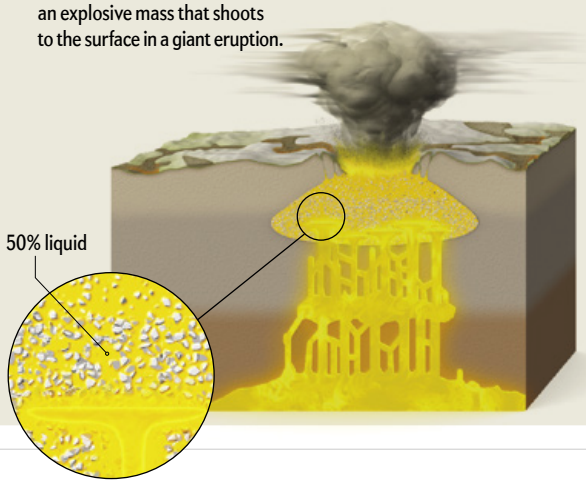
1 Some supervolcanoes, such as the behemoth underneath Yellowstone in the western U.S., sit above a plume of rising magma. Closer to the surface they have a cooler reservoir, mostly crystalline with a little hot liquid.



2 Molten material from the plume slowly moves upward over thousands of years, heating the upper reservoir when it contacts the chamber.

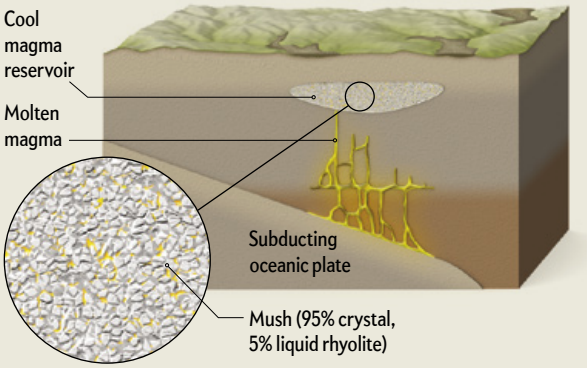


3 The heated crystals melt quickly, possibly within decades, forming an explosive mass that shoots to the surface in a giant eruption.

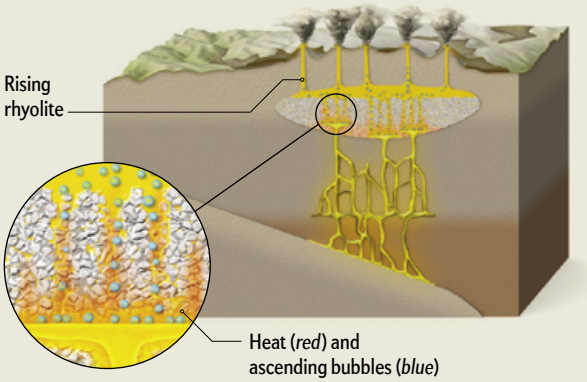


BURSTING BUBBLES

1 Volcanic regions such as Laguna del Maule in Chile lie atop two colliding plates of crust, which produce hot magma deep in the planet. Above, a reservoir of crystalline mush—with a sticky melted rock called rhyolite—waits.



2 Magma hits the reservoir, and the heat melts crystals there. As this melt rises in the chamber, it releases volatile fluids, mostly as bubbles of water. Within decades the heat and rising bubbles can force liquid rhyolite up and out, creating small eruptions.



3 Bubbles gather near the top of the reservoir, forcing more rhyolite into rock fractures. As melt gets near the top, its pressure drops, so bubbles expand rapidly. This can create large explosions that may reach supervolcanic levels.

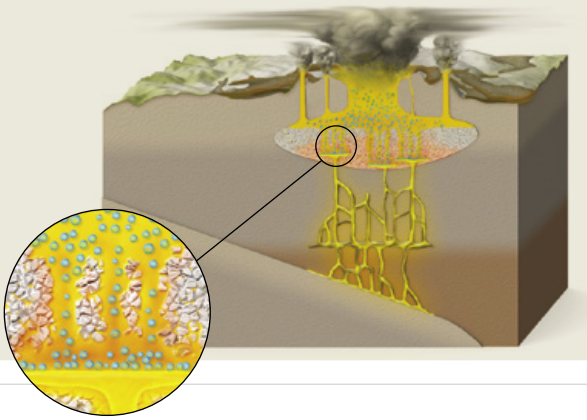


Illustration by Emily Cooper

thing was that rings such as these were usually located at the top of a single known volcano, but here the pattern was centered on a large region with hills and plateaus stretching about 400 square kilometers. Something unusual was happening. When Pritchard looked through earlier images, he found that the uplift, which must have begun between 2004 and 2007, was causing the ground to shoot upward by 20 centimeters a year. That is the largest rate of ground-level change anywhere in the world, 10 times larger than the "enhanced" uplift at Yellowstone that has occurred (and then stopped) a few times during the past several years.

That movement at Laguna del Maule, combined with the area's explosive record, has drawn a number of expeditions in recent years to determine if the area is indeed getting close to an eruption and if so how large it might be. In 2013 Singer began a five-year project to study the system's past and current state. Working with Chile's National Geology and Mining Service, he and his colleagues deployed about 50 sensors on the ground. They flew helicopters above the lake that carried instruments to scan the surface below. And they pecked away at ancient rocks with a shovel and a hammer, removing samples that they could further analyze in the laboratory.

All the data indicated that something very big was brewing under the surface. "I don't want to be an alarmist or anything, but it does suggest that there's a developing larger collection of magma underneath Laguna del Maule," says Judith Fierstein, a geologist at the U.S. Geological Survey's California Volcano Observatory in Menlo Park, Calif. Clues about underground structures gleaned from the way vibrations travel through them, as well as changes in gravity and electrical conductivity produced by different rock types, all suggest the region sits on top of a reservoir holding 450 cubic kilometers of explosive rhyolitic magma. If it all erupts, that amount of magma can transform into the 1,000 cubic kilometers of ash, rock and lava needed to meet the minimum supervolcano definition, Singer says.

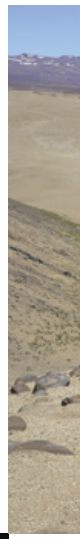
The magma does not all have to blow at once to be dangerous. Only 10 percent of that volume would produce an explosion about twice the size of Krakatoa, which, though not a supervolcano, killed 36,000 people in Indonesia when it blew in 1883.

STONE-COLD KILLER

WHILE SOME SCIENTISTS measured Laguna del Maule's size, others were more concerned with its temperature. In the classic view, the magma stored below active volcanoes is a seething liquid mass that then rises toward the top of the crust like a glob within a lava lamp. But in 2014 Adam Kent of Oregon State University and Kari Cooper of the University of California, Davis, made a startling discovery that prompted many in the research community to consider that some volcanoes really might be cold-natured.

Kent and Cooper examined tiny crystals embedded within the volcanic rocks previously released from Oregon's volcanic Mount Hood. Before those crystals erupted, they grew in the magma chamber below, accreting layer after layer that—much like a set of tree rings—recorded the evolving chemistry of the magma, including changes in composition, pressure and temperature. The crystals from Mount Hood rocks, for example, indicated that its magma spent as much as 99 percent of its time at temperatures too cool to erupt. It was not really a liquid but a kind of mush: a network of crystals with some fluid between them. "It's kind of like peanut butter, you know, when you pull peanut butter out of the fridge and you try to spread it—it's too solid," Kent says.

That finding made scientists wonder whether the same story might hold true for other volcanoes. The answer appears to be yes. In 2017 Cooper and her colleagues performed the same analysis on crystals that had erupted from New Zealand's Taupo Volcanic Zone—a region that runs down the center of New Zealand's North Island and has seen several supereruptions. The scientists learned these crystals had also spent most of their lifetime nestled within cool, solid magma. And in late 2017 Singer and his colleagues analyzed the volcanic leftovers from the Long Valley supereruption in California and saw a similar record. Yellowstone's magma chamber also holds a cooler crystalline mush.



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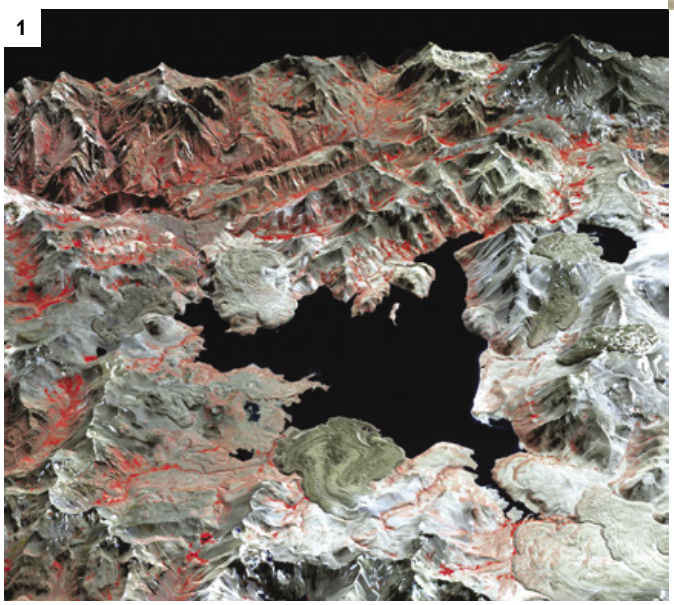

NASA/GSFC/METI/ERSDAC/JAROS AND U.S./JAPAN ASTER SCIENCE TEAM

Although Kent and Cooper have found hints that magma might reside at slightly hotter temperatures at a few old sites in North and South America, it is becoming very clear that in general supervolcanoes tend toward the cold. And the behemoths stay cold until the moment before they erupt. That means that hot magma is ephemeral, only coming into existence immediately before eruption. Cooper's work at Taupo suggests that these systems liquefy only 40 years prior to eruption. At Long Valley, the liquefaction happens in decades to a few hundred years. At Yellowstone, it also takes mere decades. Cooper says these timescales could run as short as a few years because scientists tend to publish conservative estimates.

What about Laguna del Maule? There, too, the massive magma body appears to be a crystalline mush. Singer and his colleagues argue that 95 percent of the system is composed of crystals, whereas a mere 5 percent is liquid melt. The mush is also a relatively chilly 800 degrees Celsius, more or less; lava that cascaded down the slopes of Hawaii's Kilauea this summer, in contrast, was about 1,200 degrees C, or 50 percent hotter. The dis-

VOLCANIC FEATURES around Laguna del Maule, seen in a satellite view (*1*), show vegetation (*red*) and snow-covered peaks (*white*). Geologists place sensors near the lake to detect rising ground (*2*).

coveries reinforce the notion that these cold-hearted beasts wake up in an instant. When Nathan Andersen, a geologist at the University of Oregon, analyzed the small crystals embedded within the past lava flows at Laguna del Maule, he saw that they resided in magma for only 10 to 100 years.

AWAKENING A GIANT

BUT THAT PICTURE PRESENTS a conundrum: How do these frozen systems melt and mobilize so rapidly? At Yellowstone, the last great supereruption occurred when liquid magma rose up through the earth and hit an upper, solidified reservoir, contends Christy Till, a geologist at Arizona State University. Her model is a broad outline—there were no scientists around with sensors at the time—but it appears from volcanic leftovers that the rising liquid mixed with the more solid material, melting crystals. This heated the entire chamber, and the added liquid volume built pressure until the liquid exploded onto the surface.

What is happening in Chile, however, may be very different. "There isn't a one-size-fits-all model for these volcanoes," Till says. Yellowstone sits atop a hot plume, for instance; Laguna del Maule and Long Valley do not. At those spots, one plate of planetary crust is diving underneath another, melting rock into magma as it goes. That creates a different type of eruption trigger, Andersen says, one that heats only part of the volcano reservoir and involves an explosion of bubbles.

When Andersen analyzed crystals from Laguna del Maule's past eruptions, he found that basaltic magma originating deep in the planet did not completely infiltrate the volcanic system. Such magma stalled at the base of Laguna del Maule's upper rhyolite-rich reservoir. The two types of rock never mixed. The basalt cooled down when it stalled, releasing heat into the material above it. It also gave off volatile water vapor in the form of bubbles. As the heat and the bubbles started to rise, they melted some of the surrounding crystals, creating buoyant, bubble-filled plumes that percolated upward to the top of the reservoir. At that point, they exerted so much pressure on the crust above that they burst out.

This idea worries Singer. If volatile bubbles are currently rising below Laguna del Maule, there is no way for them to escape. There are no hydrothermal features, such as Old Faithful geysers, fumaroles, hot springs or vent sites, near the mountain lake. "In my mind, that makes Laguna del Maule potentially more dangerous than other kinds of systems," Singer says. If some gases were able to leak to the surface, the growth of the reservoir might slow. "But if you've got this reservoir that's trapped down there and incubating down there, this is probably the kind of condition that can allow a system to grow very large, like Yellowstone did before its last big eruption," Singer says. "That would be a game changer. That's the kind of eruption that humans haven't seen."

Thus, although the reservoir below Laguna del Maule is barely at supervolcanic size, it could grow even bigger over the coming centuries. At the moment, Singer's fears are somewhat speculative. The eruption mechanisms are, too. It might be, for example, that rising, bubble-rich melt cannot create enough pressure by itself to generate a giant explosion and requires the help of a local earthquake. Singer's team is currently trying to identify signals associated with such additional hidden triggers.

Even if Laguna del Maule were to release a series of smaller eruptions—and the record of ash and lava on the surface indicates that it has done that in the past—the effects could still be felt across South America. Ash would halt air traffic in the area and potentially devastate agricultural production for years within Argentina (where it will likely land because of easterly wind patterns). Additionally, ash flows might breach a dam at the nearby Maule River, thus causing catastrophic flooding that could hit Talca, a city at the bottom of the valley that hosts more than 200,000 residents.

Singer's team has removed its instruments from the field, but scientists from Chile and Argentina have picked up the baton, placing new monitors that help to watch over the lake. At the moment, the region continues to steadily balloon toward the heavens—movement that appears relatively harmless. But should the lake show further signs of unrest, researchers just might be able to accurately predict the volcanic field's next eruption—now that they better understand the spark that can ignite a cold beast. SA

MORE TO EXPLORE

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FROM OUR ARCHIVES

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scientificamerican.com/magazine/sa

BRAD S. SINGER *University of Wisconsin–Madison*

MEDICINE

OUT OF THE SILENCE

After false starts, researchers are making progress toward treating deafness with gene therapy

By Dina Fine Maron

Photographs by Ethan Hill

Dina Fine Maron, formerly an associate editor at *Scientific American,* is now a wildlife trade investigative reporter at *National Geographic.*

HANNAH CORDERMAN IS TRYING TO FILL IN THE BLANKS in her world, but the blanks are growing bigger. She cannot always hear conversations, so she nods or smiles at what seem like appropriate moments, taking her cues from people around her. Picking out individual words can be hard even though doctors recently turned up the volume on her hearing aids. "There's a lot missing from conversations—bits and pieces," she says. "But I make it work."

Making it work is becoming more difficult. Corderman has an inherited condition called Usher syndrome that is slowly but inexorably robbing her of two major senses. A genetic mutation is starving cells in both her inner ear and her retina of proteins needed to detect sound and light. On top of her hearing loss, her declining vision, which forced her to give up driving at night as a teenager, has recently worsened. Now, at the age of 24, she has blind spots that make it harder to see during the day, too. No current treatment can halt or slow the disease, so Corderman lives with the knowledge that in 10 years, maybe 20 if the deterioration is slow, she could be deaf and blind.

As a child, Corderman's trouble seemed to be a straightforward hearing deficit. Then one summer in high school, as she looked up at the sky from her home in Needham, Mass., the stars seemed to blink out one by one. She told herself they were probably just covered by clouds. But the problems continued, and eventually doctors diagnosed her with Usher type 2A, a deaf-blind disorder that sets in gradually over many years. She took in the news quietly, she told me when I spoke with her. After absorbing it, she said, she decided to get on with her life. Today, seven years after her diagnosis, Corderman has finished college and works on the marketing side of her family's construction company, pushing back as much as she can against a disease that she says will not define her.

There is not much doctors can do to help. Corderman could one day get a cochlear implant, a device that bypasses the hair cells to directly stimulate the

IN BRIEF

Hearing loss is one of the most common birth defects, and genetic flaws are frequently the cause. Gene therapy, an experimental treatment with a checkered past, could be an important remedy.

Safety and effectiveness of the therapy have recently improved, and its use in people has been approved for several diseases. The advances in the treatment are now extending to deafness.

In a promising result, researchers were able to correct ear defects in deaf mice by injecting them with a gene-carrying virus, restoring the animals' hearing to unprecedented levels.

auditory nerve and give her some sense of sound. But the device is a relatively blunt fix. For eyes, retinal implants—electrical stimulators for light-detecting cells—are rarely used because they do not come close to actual vision.

Corderman is not a rigorous reader of science journals, but she is aware of several hundred young mice in a few laboratories in Boston, not far from her house. The mice were bred to have auditory disorders like her own—but these mice are getting better. Using an approach called gene therapy, biologists have been dosing them with healthy DNA to make up for bad stretches that produce faulty proteins. Last year biologist Gwenaëlle Géléoc of Boston Children's Hospital and her colleagues reported an "unprecedented recovery" in such mice after the scientists delivered a DNA infusion to the inner ear, restoring the animals' hearing to near-normal levels. Around the same time, a separate team at Harvard Medical School reported more modest hearing restoration when they used a similar genetic approach in mice with a different hereditary disorder. A third Boston-area group recently employed gene-editing methods to knock out a faulty gene in "Beethoven mice"—rodents with another form of progressive hearing decline named after the deaf composer. The advances are providing hope that for the first time, genetic hearing disorders—some of the most common birth defects in the U.S.—could be treated and even stopped at their source.

GOING VIRAL

GENE THERAPY has had a difficult and checkered past. In an infamous 1999 incident, an 18-year-old liver disease patient named Jesse Gelsinger died in an early gene therapy trial conducted by researchers at the University of Pennsylvania. A virus was used to ferry genes into his body, but the dose and type caused Gelsinger's immune system to whip itself into a fatal frenzy, attacking his own organs. The tragedy chilled public enthusiasm and funding and made many scientists cautious about going further.

Others, however, continued to quietly work with this technique, at first focusing on cells and animals, in hopes of developing therapies for complex disorders such as osteoarthritis, cancer and type 1 diabetes. As a safeguard, they lowered the doses of viruses used as delivery vehicles to keep the immune system from overreacting. They also moved away from the virus that had been used with Gelsinger, a member of a group called adenoviruses, and instead experimented with other types. One promising alternative seemed to perform particularly well in these tests: adeno-associated virus (AAV), a gene courier that appears benign to the human immune system because it does not harm our cells. Sometimes the gene-carrying viruses have been prepackaged within cells when injected, a technique that keeps them in a small target area. The field has become about "matching the right vehicle to the right disease and target and understanding dosing and where the viruses are going in the body," says researcher Cynthia E. Dunbar of the National Institutes of Health, who recently served as president of the American Society of Gene & Cell Therapy.

The improvements have worked. Recently the U.S. Food and Drug Administration issued the first wave of approvals of gene therapy for people, indicating that it may be an idea whose time has finally come. In August 2017 the FDA gave a green light to Kymriah, a virus-delivered treatment for a form of childhood leukemia. And in December of that year, the agency approved the first gene therapy for a rare inherited form of blindness. Pharmaceutical companies and venture capitalists are now pouring a lot of resources into gene therapy, Dunbar says. At the society's 2018 annual meeting, about 3,400 people showed up. Only 1,200 were in attendance five years earlier.

HANNAH CORDERMAN was born with Usher syndrome, a genetic disease that is gradually stealing her hearing and her sight.

How to Save Hearing

Some of the most common reasons for early childhood hearing loss are genetic. Inner ear hair cells are responsible for detecting sound signals and sending them to the brain, but gene mutations within those cells lead to poorly functioning anatomy. Researchers working with mice have devised a method for replacing those flawed genes with healthy versions: they put the healthy genes into a modified adeno-associated virus (AAV) and inject it into the inner ear. When the virus infects the ear hair cells, it delivers the healthy genes. If the approach (*shown here*) works in people, it could treat a major birth defect at its genetic source.

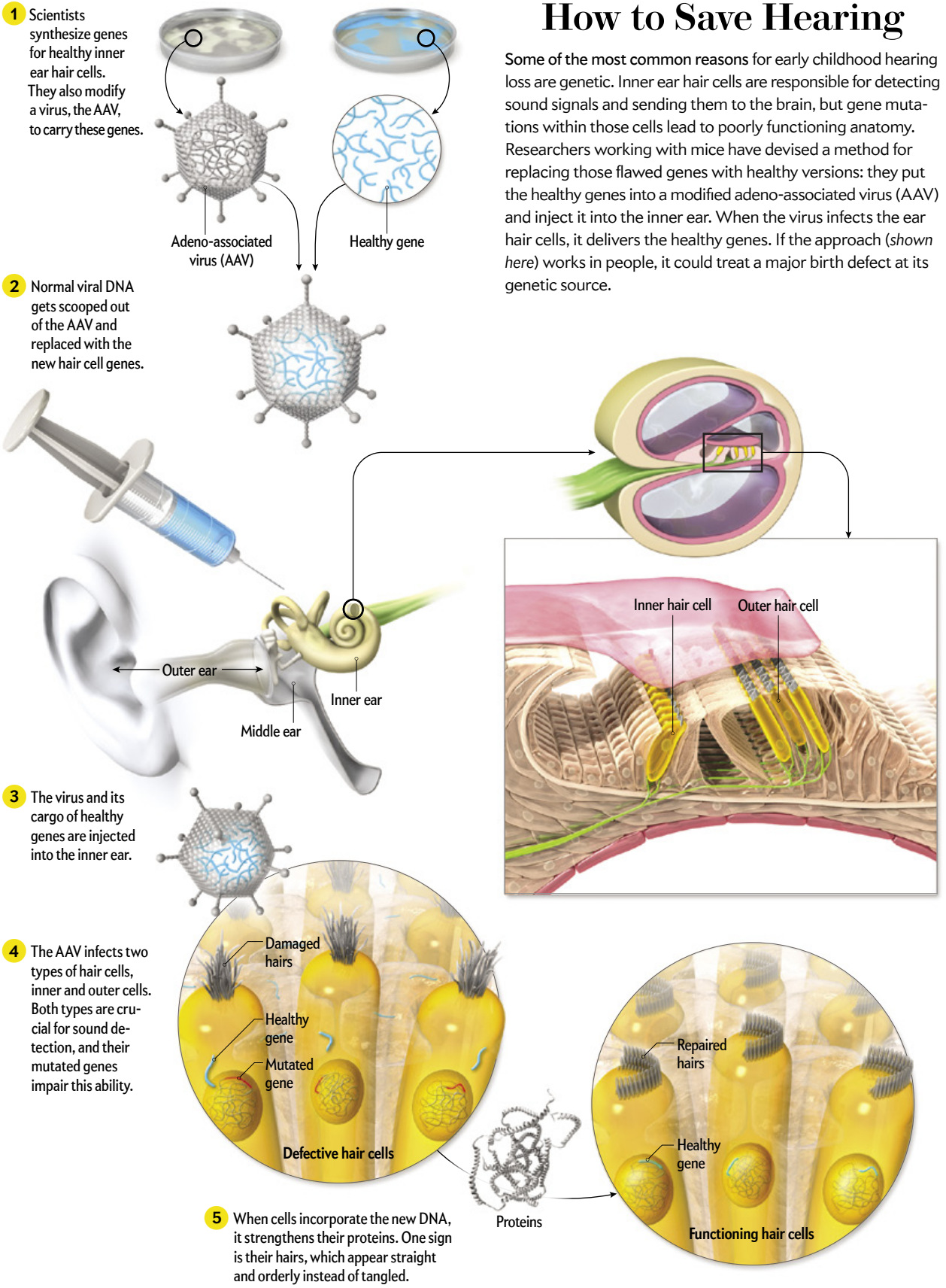

Illustration by Emily Cooper

This enthusiasm now extends to hearing loss, a disorder that is often genetic in nature. Though popularly associated with aging or accidents, hearing loss is one of the most common birth defects afflicting people; it affects as many as three of every 1,000 babies. Genetic flaws are responsible for more than half those cases, including diseases such as Usher syndrome. Usher is a particularly appealing target because each patient has mutations in a single gene, and fixing them could fix the symptoms. Certain forms of the disease, such as Corderman's, progress gradually, which provides a window after diagnosis when treatment could stop the genetically instigated damage. That damage occurs in hair cells within the inner ear—the hairs pick up sound waves from outside and transmit them to the brain. Corderman and others like her have defective genes that grow weakened hair cells. Those cells are "like a spark plug in a car" says David Corey, one of the Harvard scientists who restored sound sensation to some mice. "Without them, hearing just doesn't work."

Gene therapy for these cells is a way to treat the root cause of the disease rather than putting on a high-tech bandage such as a hearing aid. The recent "successes are very impressive and important early promising steps," says Theodore Friedmann, a pediatrician who helps to lead a consortium of gene therapy researchers at the University of California, San Diego, and was not involved in the work. Mice are not people, of course, and the technique has yet to be tried on humans. But Friedmann says such interventions do, for the first time ever, open the door to treating deafness at the genetic level.

HAIR TREATMENT

ONE MORNING LAST YEAR in a lab at Harvard, I watched Bence György lean through that door. He was actually bending over a rodent bred to have faulty hair cell genes. The mouse had been anesthetized, and György, a postdoctoral fellow who works with Corey, made a tiny incision behind the animal's ear. He pushed past paper-thin pieces of tissue as he searched for a tiny spot in the middle ear called the round window membrane, the portal to the inner ear. When György found the membrane, he inserted a fine needle and started to slowly inject a pale pink solution containing about 200 billion particles of an AAV, each carrying a corrected form of the gene responsible for the mouse's hearing loss.

Using a virus such as an AAV to ferry that precious cargo boosts the gene's chances of arriving at its destination in the inner ear because even harmless viruses are good at infecting cells. Researchers have learned that they cannot use just any AAV, however. The hallmark of a successful AAV is the ability to infect not just one but two types of hair cells. Various AAVs are reasonably good at delivering DNA into the innermost rows of hair cells, which communicate with nerve cells, but those same viruses do a poor job of getting into the outer rows of such cells, and those are the ones that amplify sound in the first place. For full restoration of sensitivity, the vehicle needs to get into both types, says Corey, who did some of the crucial research on hair cell function.

Through a mix of trial and error and some viral gene redesign, scientists hit on a few AAVs that are drawn strongly to the two inner ear targets. They altered proteins that make up the external shell of the virus, molecules that help it bind to a cellular target. Eventually this work yielded a set of shell proteins that appear to match up with molecules on both types of hair cells, allowing the virus to make its way inside. In the paper by Géléoc and her colleagues published last year, researchers reported that one of these specially modified AAVs arrived intact in rodents genetically destined to be deaf at birth and produced rows of strong, well-functioning hair cells. Other research groups reported they were able to get related AAVs into the inner ear hair cells of older rodents with ears that more closely resemble those of young children.

> One main test of restored ear function involves exposing the rodents to a sudden, startling noise to see if they jump. Many did: the once deaf mice could hear.

Getting in, however, was only part of the hearing therapy problem. The other part was identifying the mutations that led to defective hair cells. Researchers started to do this in the 1990s by identifying families with hearing and vision loss typical of Usher and comparing their genomes. These individuals had several genes that seemed to be involved with both ear and eye development, making them prime suspects. Scientists then bred mice both with and without those suspect mutations to test whether any of the genetic changes were truly responsible for symptoms. The comparison pointed a finger at a few specific alterations. Changes to a gene called *USH2A,* for example, are behind gradual disorders such as Corderman's; the nonmutated version of the gene produces healthy hair cells. Each case of the most

USING A VIRUS to ferry healthy genes into deaf mice, Gwenaëlle Géléoc and Jeffrey Holt, researchers at Boston Children's Hospital, restored a sense of hearing to the rodents.

severe and rapid-onset form of the disease, called Usher type 1, is associated with mutations in one of five different genes, such as one called *USH1C*.

In the past several years Géléoc's team put all these pieces together. In the lab, she and her husband, otolaryngologist Jeffrey Holt, and others took an AAV version with a customized shell, scooped out a bunch of its genes related to the life cycle of the virus and replaced them with intact, healthy versions of *USH1C*. They also added a DNA sequence called a promoter that turns *USH1C* on in the hair cells. The new gene acted like a booster for the cells when it was delivered. The cells still had the old, faulty DNA that made weak hair proteins, but the addition of well-functioning DNA helped them create a large batch of other healthy proteins that kept the hairs strong.

The team at Boston Children's Hospital then took the entire package and, using a surgical insertion method similar to the one I watched György use, put it inside Usher mice. Within two weeks the virus had infected at least some of the ear hair cells; by six weeks it had penetrated around 80 percent of them. More to the point, these animals reacted to sounds. One of the main tests of restored ear function involves exposing the rodents to a sudden, startling noise to see if they jump. Many did: the once deaf mice could hear.

Sound was not the only important check. Hair cells do another key job in the body: they create a sense of balance and orientation as the hairs flex within the fluid of the inner ear, sending signals about their position to the brain. Mice with hairs damaged by Usher often have difficulties with movement and figuring out where they are in a space. Instead of sniffing around a cage, these rodents cower in the corner. And although mice are natural-born swimmers—ready to thrive the first time they are placed in the water—an Usher mouse will frantically paddle in circles for a few seconds, struggling to determine which side is "up." (Scientists quickly rescue it before the animal becomes too distressed.) If the gene therapy mice at Boston Children's Hospital truly had restored hair cell function, these problems should have gone away.

When I visited Holt and Géléoc's lab right after my trip to Harvard, I saw mice that acted remarkably like, well, mice. Rodents that had gene therapy two months prior nosed around their environment; their behavior in open spaces and in the water was virtually indistinguishable from their normal counterparts. They moved so easily that I repeatedly asked Holt and his team if they were sure these were the mice with mutations. The scientists, who have a careful system for tracking their animals, assured me each time that I was looking at damaged and treated rodents.

THE SIZE OF THE PROBLEM

DESPITE THIS SUCCESS, there are still several vexing difficulties to sort out before these viruses are tried on people. One problem is that the current AAVs are too small. Although they are big enough to carry genes to correct Usher type 1C—the disorder that responded so well in mice trials—many other types involve much larger genes. Corderman's form of Usher, for instance, involves a gene that is simply too big to squeeze into the available AAV storage space. "It would be like trying to fit a size-14 body into size-4 pants," Dunbar says.

One work-around would be to slice up the large gene into several chunks that could be carried through the ear in multiple viral vehicles. Each of the gene bits would have sticky ends so that when they arrived at their destination, they could stick themselves back together like Velcro. For example, Corderman's type of Usher gene is so large that it would need to be cut into three parts. For the approach to work, all three virus carriers must get into the inner ear hair cells, and then the three stretches of DNA need to find one another within a cell and paste themselves back together. The highly specific nature of DNA sequences makes this possible—normally in the body, stretches of the genetic alphabet interact only with complementary stretches—but nonetheless difficult to pull off, Géléoc says.

Other options include using a bigger non-AAV virus, tweaked to avoid widespread immune system alarms, or avoiding viruses altogether and trying to deliver the genetic goods within nanoparticles (minuscule lab-made objects that can penetrate cells). Various researchers, including Holt and Géléoc, are also exploring a way to remove the problem gene and replace it with the right one using the gene-editing technique CRISPR/Cas9. Usher is a recessive disorder, caused by two copies of the faulty gene. If researchers could cut out one of these genes and swap in a healthy dominant one, that new gene could take over and swamp the negative effects of the remaining recessive DNA.

No one has yet achieved this feat using CRISPR, however; the method seems better suited to cutting things out than to sticking them in. For that reason, current CRISPR work in mice looks like it would be more effective for rare hearing issues caused by one faulty gene instead of two. The problem gene could simply be knocked out, allowing the remaining gene to do its job properly. The experiments on Beethoven mice used that approach. Although it worked well, other scientists using CRISPR have seen that it caused unwanted DNA changes on other, nontarget cells. For that reason, nobody thinks gene editing of this type is ready for people. Viral vehicles still seem to be the front-runners for therapy.

No matter what delivery system or other solution researchers devise, it will not help many people unless hearing loss diagnoses improve among infants, who would benefit most from early interventions. In the U.S., most newborns are screened for hearing loss, yet they are rarely diagnosed with a specific disorder or its underlying genetic cause. That is exactly what happened to Corderman, who was not diagnosed with a genetic problem until high school. That will need to change so that children can get treated properly.

Gene therapists do think they will be able to treat children—and perhaps sooner rather than later. "It's exciting that there are actual products wending their way through the system," Dunbar says. Elizabeth Olmsted-Davis, a gene therapy researcher at the Baylor College of Medicine, says she is not surprised that gene therapy for other ailments has recently become a clinical reality and that new treatments will eventually follow the same path. "The therapies on the horizon are the culmination of decades of work by talented researchers who saw the potential that these approaches hold," she says.

> Gene therapy will not help many unless hearing loss diagnoses in infants improve.

Although interest in gene therapy is clearly surging in the research community, Hannah Corderman is not waiting for the wave to reach her. With or without medical advances, she is determined to live a full life. She has booked multiple trips to watch the Northern Lights in case, one day, she can no longer see them. "I'd say my outlook on life has completely changed because it's like I only have so much time to get things done," she says. She has become an advocate for fellow patients, too. Corderman says she has realized that speaking out about the genetics problems can help push research further and "potentially inspire others to live their lives and not let this disease hold them back." Losing her hearing, she says, does not mean retreating into silence. SA

MORE TO EXPLORE

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FROM OUR ARCHIVES

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scientificamerican.com/magazine/sa

SUSTAINABILITY

SPONGE

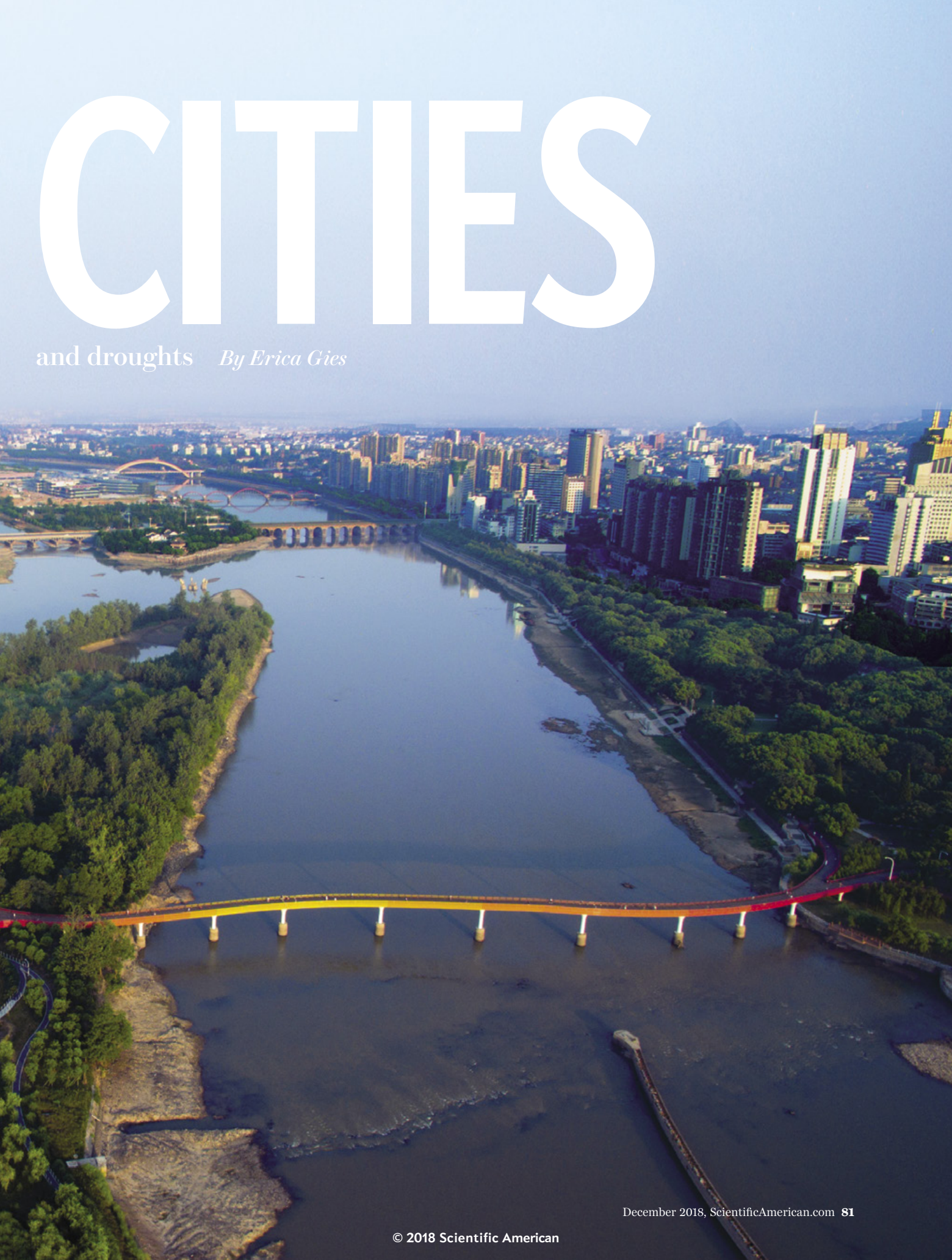
Restoring natural water flows in cities can lessen the impacts of floods

YANWEIZHOU PARK (*center*) absorbed high river water during a heavy monsoon, protecting Jinhua, China, from flooding.

CITIES

and droughts

By Erica Gies



ELEVEN INCHES OF RAIN chucked down on Beijing on July 21, 2012, flooding roads and filling underpasses. Landscape architect Yu Kongjian barely made it home from work. "I was lucky," he says. "I saw many people abandon their cars." As the deluge continued, the city descended into chaos. Beijing's largest storm in more than 60 years killed 79 people, most of them drowned in their vehicles or sucked into underground drains. Damages reached nearly $2 billion.

Erica Gies writes about science and the environment from Victoria, B.C., and San Francisco. Her work appears in *Nature*, bioGraphic, the *New York Times*, and elsewhere.

To Yu, co-founder of the internationally acclaimed landscape architecture firm Turenscape, the disaster was avoidable, a consequence of heedless development. He had warned the city government several years earlier, after he led a research team mapping the metropolis's "ecological security pattern," identifying land with high flood risk that should be left undeveloped and used to manage stormwater. "The 2012 flood gave us the lesson that ecological security patterns are a life-and-death issue," he says.

A similar story has played out across China. Sixty-two percent of its cities flooded between 2011 and 2014 alone, imposing $100 billion in economic losses, according to the Chinese Ministry of Housing and Urban-Rural Development. The floods are partly the result of stronger storms fueled by climate change. But the harm is mostly self-inflicted: intensive urbanization over the past 30 years has gobbled up wetlands, felled forests, paved over farms and grasslands, and channeled rivers in concrete straitjackets, leaving stormwater that once filtered into the ground nowhere to go but up.

Urban sprawl is exacerbating water scarcity in China, too. Buildings, streets and parking lots block rain from recharging aquifers. Instead drains and pipes funnel it away—lunacy in a place with water shortages, Yu thinks. Like other cities in China's north, Beijing is pretty dry outside of the summer monsoon season. For decades it has pumped groundwater to supply its growing population and consumption. The city is lowering the water table about a meter a year, causing the ground to sink as well.

Cities worldwide share similar problems because of development and the attempt to control water with "gray" infrastructure—concrete dams, levees, stormwater tanks, pipes and walled-in rivers whose floodplains are covered with buildings. Experts are recognizing that by breaking the natural water cycle, municipalities are raising the likelihood and severity of flooding, causing disasters from Houston to Chennai, India.

Yu is at the forefront of a global movement of urban planners, water managers, ecologists and engineers who are trying to restore natural water cycles. The work is a kind of un-engineering: giving water space to expand and contract to lessen flooding and slowing it down so it can soak into the ground, preventing shortages later. Practitioners preserve or restore floodplains and wetlands, unearth buried creeks, and create bioswales, retention ponds, sunken parks and permeable parking lots. Unlike hardscapes, green infrastructure can also clean water and re-create habitat for wildlife. And it gives urbanites access to nature, an amenity increasingly recognized as a pillar of mental health.

Local landscape design projects are popping up everywhere. But Yu and other leading practitioners are looking to manage water at a grander scale: an entire city, an entire watershed. Known as green infrastructure in Europe, low-impact development in the U.S. and sponge cities in China, these approaches mimic nature as much as possible, says Tony Wong, an engineer and chief executive of the Cooperative Research Center for Water Sensitive Cities, based in Melbourne, Australia. The goal is to create water infrastructure that "functions as a living organism," he says.

The sponge cities movement is gaining momentum. In March the United Nations released a report called *Nature-Based Solutions for Water* that advocates the approach. The U.S. Army Corps of Engineers, infamous for its muscular engineering of rivers and wetlands, now has an Engineering with Nature initiative. After centuries of dikes to enclose rivers and low-lying land, the Dutch are onboard, too. Following a near disaster in 1995, when water rose in the Rijn, Maas and Waal rivers, forcing 250,000 people to evacuate, the government created a countrywide program called Room for the River. Instead of only building bigger dams and dikes, Dutch officials increased the capacity of river deltas by asking farmers to agree to move or to let their land flood as necessary.

China, with its rapid growth and centralized government, is pursuing sponge cities on a scale difficult for most countries to even consider. The ambition is impressive. Yet Yu is finding that he still has to overcome a tendency among planners toward one-size-fits-all approaches, which could be disastrous because each location has unique hydrological systems and needs. He is also confronting a penchant in his country for stronger dams, bigger pipes and larger storage tanks, which symbolize power and progress in modern China.

MR. SPONGE CITY

ON A SPRING DAY in Beijing with a "very high" air pollution rating, I visited Yu at Turenscape's headquarters in the city's Haidian

IN BRIEF

Floods and droughts are crippling many urban areas. Concrete river channels, stormwater tanks and pipes are not keeping up.

An urban-planning approach called sponge cities can more effectively lessen floods, save water for dry spells and reduce water pollution.

Yu Kongjian is leading the way as China reengineers old cities and designs new ones to embrace rather than fight natural water flows.

PRECEDING PAGES: TURENSCAPE

KABAN LAKES in Kazan, Russia, were polluted and flood-prone. Now their redesigned banks absorb and clean urban runoff.

District. A slim, intense man in his 50s, with sharp eyes and just a bit of gray at the temples, Yu traces his passion to the agricultural commune where he grew up in Zhejiang province southwest of Shanghai. There he observed the Chinese "peasant wisdom" for managing water, practiced for thousands of years. Farmers maintained little ponds and berms to help rainfall infiltrate the ground, storing it for a dry day. The creek next to his village swelled during certain seasons, which no one saw as a threat. "If you have wise ways to deal with flooding, water can be friendly," he says.

Since starting Turenscape in 1998 with his wife and a friend, Yu has built the award-winning company into a landscape architecture empire with 600 employees. The company has more than 640 projects built or under way in 250 Chinese cities and 10 other countries, including a redesign of the Kaban Lakes system in Kazan, Russia. Yu is dean of the school of landscape architecture at Peking University and has taught periodically at Harvard University.

For years while Yu was building his firm's portfolio, many Chinese derided his farm-based ideas as backward. He says that some even called him an American spy—a nod to his doctorate from Harvard's Graduate School of Design and his opposition to those big dams. But in recent years sentiment has begun to shift. Various groups in China are building green infrastructure projects, often in partnership with Americans, Australians and Europeans. Yu's influence has been growing in parallel. He lectures regularly at the Ministry of Housing and Urban-Rural Development, and his 2003 book about his practices, *The Road to Urban Landscape: A Dialogue with the Mayors,* has been printed multiple times in China. Dignitaries such as the Mexican ambassador to China, who is hoping he can solve Mexico City's water problems, ask for his input.

The 2012 Beijing flood was a turning point. Soon afterward, a Turenscape stormwater project in Harbin won a top U.S. design prize. China Central Television broadcast a long, high-profile interview with Yu. A government minister told him afterward that Xi Jinping, who would soon become president, had seen it. About a year later the president stood before China's central urbanization conference and announced his Sponge City initiative, elevating the idea from struggling concept to national goal.

In 2015 the government initiated 16 demonstration projects, each covering at least 10 square kilometers. Today there are 30. The objectives include reducing urban flooding, retaining water for future use, cleaning up polluted water bodies and improving natural ecosystems. By 2020 each project is supposed to retain 70 to 90 percent of the site's average annual rainfall. Premier Li Keqiang said in his 2017 government work report that sponge city construction will continue to expand.

A RIVER RECONSTRUCTED

A WEEK AFTER MEETING YU, I visited one of Turenscape's latest projects, Yongxing River Park, in a Beijing exurb called Daxing. "Before" satellite pictures from three years ago show open land surrounding the river, already straightened and confined by steep concrete walls. "Now" pictures are chockablock with buildings. Showing me the park are two of Yu's employees, Geng Ran, who goes by Katie when talking to English speakers, and Zhang Mengyue, aka Sophie.

The government recognizes that development reduces rain infiltration, Zhang says, so it invited Turenscape to design a park that would enlarge the riverbed to hold more water. The project was nearly completed when I saw it in early April. About four kilometers long and perhaps two city blocks wide, the park follows the river. We stand on a large berm that divides the riverbed into two channels. The river flows on our right; on our left the channel has big dirt holes of varying depths. During the dry season, the holes will be filled with partially cleaned effluent from a sewage treatment plant. Wetland plants in the pools will further clean the water, Geng says, and filter some of it into

TURENSCAPE

aquifers. During the monsoon, the channel will be reserved for flood waters, and the effluent will be treated industrially.

"We say you can't stop the weight of the river," Geng says, "so that's why we enhance this river." Turenscape's plan involved removing concrete along the river and excavating soil to widen the bed. That dirt was then molded into the big berm. Thousands of small sedges planted in closely set rows now dot those riverbanks, holding the earth in place. They remind me of Georges Seurat's pointillism. Turenscape projects use native plants because they "are adapted to the local environment," Yu says, "and need no supplemental water."

Earlier installations are already demonstrating their efficacy. Yanweizhou Park in Jinhua, near where Yu grew up, absorbed a 100-year flood, protecting the city. Shanghai's 14-hectare (34.6-acre) Houtan Park cleans up to 2,400 cubic meters (634,000 gallons) of polluted river water daily, improving the water's quality from grade V (unsuitable for human contact) to grade II (suitable for landscape irrigation) using only biological processes.

Projects like these are most effective when they connect to other green infrastructure throughout the watershed, enabling water to flow in an approximation of its natural path. Across China, whole new cities being built from scratch show what is possible. Turenscape has completed part of the ambitious Wulijie Eco-City in Hubei province. Wulijie's design preserves the natural wetlands for catching and cleaning stormwater on-site. This approach reduced construction costs for underground drainage pipes and conserved habitat for wildlife and vegetation. Buildings have roof gardens and living walls, and pedestrian and bike paths thread through the green space, all of which should enhance quality of life for residents.

BEYOND CITIES

IT'S NOT EASY to make space for water in an environment that has already been built, however. Architects have to shoehorn tiny projects into existing infrastructure. In Houston, for example, developers often limit themselves to building bioswales in new apartment complexes. In San Francisco, workers have been jackhammering bits of sidewalk and roadway medians to make room for plantings.

Hence the appeal of derelict industrial sites ripe for dramatic reclamation. Turenscape oversaw the first phase of such a project in the 1,000-year-old city of Kazan, which surrounds three oxbow lakes on the Volga River. During the Soviet period, pollution had killed nearly all life in the lakes. Moreover, the city was prone to flooding because of the way dams were built. When waters would rise, the city's seven pumping stations could not keep up.

Turenscape's design, which is partially complete, calls for reclaiming 11 square kilometers of land for floodwater along the river and its tributaries. There the city is building linear parks, promenades and bioswales that slow, absorb and clean urban runoff before releasing it into the lakes. Walking and biking routes give people access to the riparian zone and support human-powered transportation throughout the city.

Such extensive redesigns are encouraging Yu to dream beyond sponge cities to what he calls "Sponge Land." His inspiration is to take care of the national landscape. "Water is a system," he says, bigger than cities.

Inspired in part by American landscape designer Warren Manning, who created "A National Plan" for the U.S. a century ago, Yu is working on a landscape master plan for all of China. "That is an incredible vision," says Niall Kirkwood, a professor of landscape architecture and technology at the Harvard Graduate School of Design, who has known Yu for many years. "No one thinks at that scale and with that political savviness."

1

2

Yu's office walls display maps of China that document elevation, watersheds and flood paths, as well as biodiversity, desertification, ecological security, soil erosion and cultural heritage. For his big plan, Yu can use them along with geographic information system (GIS) and satellite imagery to track China's landscape changes as urbanization spreads, as estuaries and deltas silt up, as water starts to move differently across landscapes and cityscapes. He can isolate priority areas where projects will have the biggest impact. Kirkwood says this is like applying acupuncture to the human body. Yu "has the understanding that doing a piece of work in one area will have an effect in another area," he says. Compared with most landscape architects, Kirkwood says, Yu is "thinking much more holistically."

CUSTOM SOLUTIONS NEEDED

YU'S HOUSE, a duplex of side-by-side apartments where he and his sister live, is a personal testament to his ideas. Between the two apartments is a living wall Yu built of porous limestone. Water captured from the roof dribbles down its face, from which maidenhair ferns and philodendrons sprout. The green wall cools the two homes enough that they do not need air-conditioning, he says, although he concedes that it gets a bit warm in summer.

Decks off the bedrooms are watered with roof-caught rain, stored in tanks under plant beds. Yu's deck smells great, emanating whiffs of rosemary, lemongrass and Chinese chrysanthemums. It even has a tiny creek in which goldfish swim. On the other side of the wall, his sister's deck has terraced beds replete with lettuce and chard. "We collect 52 cubic meters of stormwater [annually], and I grow 32 kilograms of vegetables," Yu says proudly.

The ideas engineered into Yu's house are widely applicable to buildings, but each sponge city design must be unique, fac-

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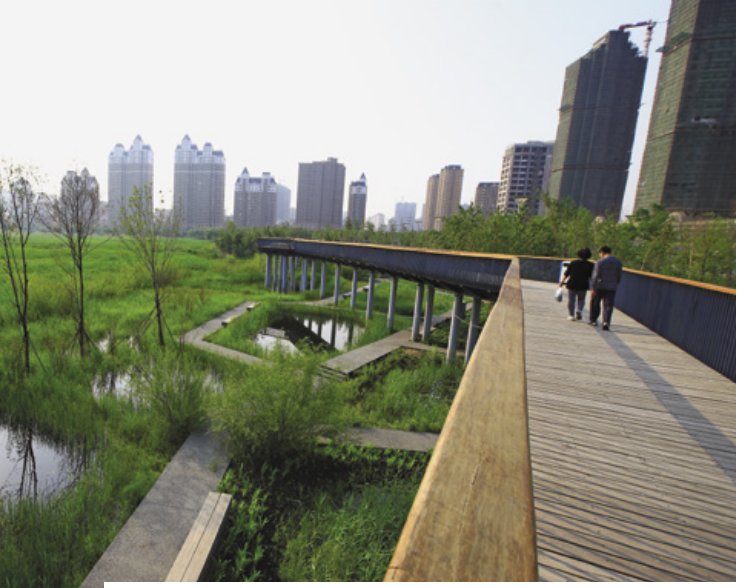

YU KONGJIAN (*1*), framed by the "living wall" inside his home, has championed China's sponge city projects, including a stormwater park in Harbin (*2*).

toring in the site's local climate, soil and hydrogeology. "Every patient needs a different solution," as Yu says. There is a danger that, in their haste, Chinese planners will ignore this fact. If they do, the broad ambition for sponge cities may falter, says Chris Zevenbergen, an expert in urban flood-risk management at the IHE Delft Institute for Water Education in the Netherlands and a visiting professor in Nanjing and Chengdu. The tendency to hurriedly pursue cookie-cutter solutions in erecting cities over the past 20 years did not allow builders time to understand imperfections in design and adjust. That is why so many cities have ongoing problems with floods, he says. Copycat implementation of sponge cities could lead to similar problems. Xi's program has strict deadlines, which may not provide time to monitor performance and adjust if necessary, Zevenbergen says.

A paper written by Chinese government research institutes last year expressed similar concerns. To provide guidance, the government has formed a committee that is composed of civil engineers, economists and landscape architects, including Yu.

The sponge city vision faces other challenges. It will take private investment to fully implement the national plan. But Yu worries that companies might find pipes or dikes—things they can charge for—more attractive than sponge cities' embrace of natural systems.

The stakes for the grand vision go beyond tempering floods and drought. Xi also wants sponge cities to deal with another big water issue China faces: pollution. Nutrients, heavy metals, pesticides and microplastics taint surface waters in China, according to Randy Dahlgren, a scientist at the University of California, Davis, who specializes in soil and water chemistry and has worked in Zhejiang province. "If they can get this water to infiltrate into the ground, a huge number of these potential contaminants will be retained within the wetlands systems, buffers, detention basins and bioswales," he says.

Wetlands cannot just be built and forgotten, however. Phosphorus, heavy metals and some nitrogen can accumulate in the plants and return to the soil when those plants die. "You really need to be harvesting those plants," Dahlgren says. They can be made into biomass fuels and incinerated, although some pollutants such as metals gather in the ash, which must be disposed of. "It does take active management of wetlands to make them an effective sink for a lot of pollutants," he says. Planners should also be cautious about "trading a surface-water pollution issue for a groundwater pollution issue," where impurities could persist for tens of years to several centuries.

If the planners get it right, though, the payoff could be huge. Sponge city techniques are already reducing pollution in places such as Philadelphia. Like many U.S. cities, its stormwater runs through sewage-treatment plants, which overflow in big storms, pushing untreated sewage into rivers. With its Green City, Clean Waters initiative, the city is reclaiming land along the banks of local creeks and rivers to absorb excessive rainfall and building parks that can flood when necessary. Philadelphia also gives incentives to landowners for creating rain gardens, green roofs, urban farms and porous pavement. These techniques allow stormwater to percolate into the ground, reducing the volume entering the sewage system. Five years in, the city had "greened" 339 hectares, enough to reduce pollution from sewer overflows by more than 5.7 million cubic meters annually.

STATE OF FLUX

NATURAL WATER-MANAGEMENT SYSTEMS are not static or predictable like gray infrastructure: nature is messy. Water rises and falls. Plants sprout, live and die. Mud is exposed. Although these spaces can be beautiful—perhaps more beautiful than, say, a dam—residents might not always like what they see. For sponge cities to spread, people will have to accept a dynamic environment.

Yu calls this shift "big feet aesthetics," a counterreference to when Chinese considered the bound, tiny feet of aristocratic women to be beautiful because they were useless, a sign that the women were too rich to work. "Now we need to find big feet attractive," he says. "We need to change our aesthetic to find useful green infrastructure beautiful."

Educators will need a change in perspective as well. Despite the national promotion of sponge cities, China's schools are still training engineers using 20th-century principles, Yu says. "We are fighting so hard to try to get people to think in an ecological way." The hubris of believing that people can control water with concrete will be increasingly exposed as more of those kinds of projects fail, unable to buffer the knock-on impacts from rapid population growth, urban sprawl and climate change. Although sponge cities will likely not protect everyone from these challenges, their advocates think their resilience can temper extremes better than the concrete alternatives. Plus the multiple benefits they bring can make the lives of humans and other species healthier and happier. SA

MORE TO EXPLORE

Letters to the Leaders of China: Kongjian Yu and the Future of the Chinese City. Edited by Terreform. Terreform, 2018.

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FROM OUR ARCHIVES

Eco-Cities of the Future. David Biello; September 2008.

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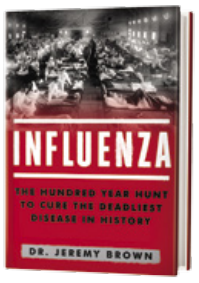
RECOMMENDED

By Andrea Gawrylewski

Influenza: The Hundred Year Hunt to Cure the Deadliest Disease in History

by Jeremy Brown. Touchstone, 2018 ($26.99)



In 1918, as the First World War was ending, "something fierce" was spreading. Troops in the battlefield camps and in their home countries, along with civilians, were falling sick with flu. The pandemic killed up to 100 million people within a year. A century later emergency room doctor Brown traces the complex history of misguided flu remedies such as bloodletting, inhalation of toxic gases, use of mercury chloride, misuse of aspirin and not very effective vaccines. Although we know a lot more about the virus today, which kills 30,000 people in the U.S. annually, we do not know enough to stop the next pandemic. Brown argues that a critical preparatory step should be to place the 1918 pandemic in our collective memory as we have for wars and battles—perhaps with a physical memorial—to honor our losses and to remind us how much there is yet to do. *—Ankur Paliwal*

Out There: A Scientific Guide to Alien Life, Antimatter, and Human Space Travel (for the Cosmically Curious)

by Michael Wall. Grand Central Publishing, 2018 ($27)

"Are we alone in the universe?" is just the first—though rarely the last—question that many people have about aliens. What might they look like—the "Greys" from alien-abduction tales, or silicon-based robotic beings, or quivering clumps of unthinking protoplasm? If we ever found them, would they befriend us, breed with us—or even see us as "breakfast"? Science writer Wall delivers marvelously witty and informed speculations to these common queries underpinning the still fruitless scientific search for alien life. Along the way, he ruminates on related ideas, such as the long-term fate of life in our solar system and the prospects for humanity someday visiting other stars or building time machines. *Out There* is a refreshingly playful romp through the most exciting aspects of space exploration. *—Lee Billings*

Anti-Science and the Assault on Democracy: Defending Reason in a Free Society

edited by Michael J. Thompson and Gregory R. Smulewicz-Zucker. Prometheus Books, 2018 ($26)

The Enlightenment saw the development of a widespread scientific worldview, centered in skepticism, objectivity and reason. The technology that, hundreds of years later, grew out of that intellectual blossoming—the Internet, smartphones, social media—now enables people to entertain their bizarre, antiscience worldviews in insulated online forums and communities, argue the essayists in this robust collection. Such thinking fosters a "broader political climate in which a resistance to science shapes public opinion and a more general hostility to scientific reason." In the book, edited by political scientists Thompson and Smulewicz-Zucker, contributors theoretical physicist Lee Smolin, science historian Michael Ruse, political scientist Diana M. Judd, and others rely on philosophy, history, the law and sound reasoning to trace the origins of antiscience thinking. What is best for the planet and humans, they say, is a reliance on the self-correcting scientific method and its demand for objectivity.

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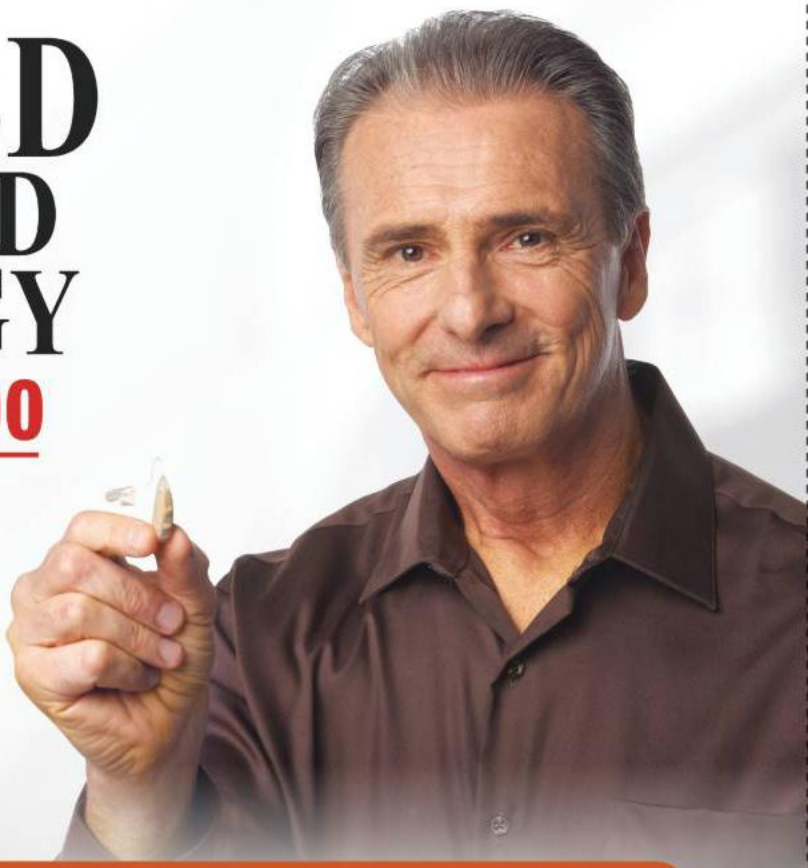

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Michael Shermer is publisher of *Skeptic* magazine (www.skeptic.com) and a Presidential Fellow at Chapman University. His new book is *Heavens on Earth: The Scientific Search for the Afterlife, Immortality, and Utopia.* Follow him on Twitter @michaelshermer

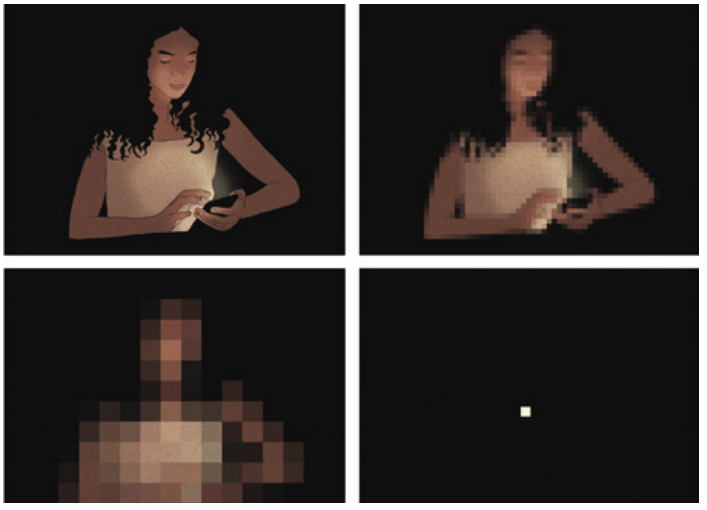
Kids These Days

A looming crisis and how to avert it

By Michael Shermer

Something is amiss among today's youth. This observation isn't the perennial "kids these days" plaint by your middle-aged correspondent. According to San Diego State University psychologist Jean Twenge, as reported in her book *iGen* (Atria, 2017), to the question "Do you have [a] psychological disorder (depression, etc.)?" the percentage of college students born in 1995 and after (the Internet Generation, or iGen) answering affirmatively in a Higher Education Research Institute study rose between 2012 and 2016. For men, the figure increased from 2.7 to 6.1 percent (a 126 percent increase) and for women from 5.8 to 14.5 percent (a 150 percent rise). The National Survey on Drug Use and Health found that between 2011 and 2016 the percentage of boys who experienced a depressive episode the prior year increased from 4.5 to 6.4 and in girls from 13 to 19.

iGeners began entering college in 2013. Between 2011 and 2016 there was a 30 percent increase in college students who said they intentionally injured themselves (for example, by cutting), and according to the Fatal Injury Reports by the Centers for Disease Control and Prevention, suicide rates increased 46 percent between 2007 and 2015 among 15- to 19-year-olds. Why are iGeners different from Millennials, Gen Xers and Baby Boomers?



Twenge attributes the malaise primarily to the widespread use of social media and electronic devices, noting a positive correlation between the use of digital media and mental health problems. Revealingly, she also reports a negative correlation between lower rates of depression and higher rates of time spent on sports and exercise, in-person social interactions, doing homework, attending religious services, and consuming print media, such as books and magazines. Two hours a day on electronic devices seems to be the cutoff, after which mental health declines, particularly for girls who spend more time on social media, where FOMO ("fear of missing out") and FOBLO ("fear of being left out") take their toll. "Girls use social media more often, giving them more opportunities to feel left out and lonely when they see their friends or classmates getting together without them," Twenge adduces. This, after noting that the percentage of girls who reported feeling left out increased from 27 to 40 between 2010 and 2015, compared with a percentage increase from 21 to 27 for boys.

In search of a deeper cause of this problem—along with that of the campus focus of the past several years involving safe spaces, microaggressions and trigger warnings—Greg Lukianoff and Jonathan Haidt argue in their book *The Coddling of the American Mind* (Penguin, 2018) that iGeners have been influenced by their overprotective "helicoptering" parents and by a broader culture that prioritizes emotional safety above all else. The authors identify three "great untruths":

1. **The Untruth of Fragility:** "What doesn't kill you makes you weaker."
2. **The Untruth of Emotional Reasoning:** "Always trust your feelings."
3. **The Untruth of Us versus Them:** "Life is a battle between good people and evil people."

Believing that conflicts will make you weaker, that emotions are a reliable guide for responding to environmental stressors instead of reason and that when things go wrong, it is the fault of evil people, not you, iGeners are now taking those insalubrious attitudes into the workplace and political sphere. "Social media has channeled partisan passions into the creation of a 'callout culture'; anyone can be publicly shamed for saying something well-intentioned that someone else interprets uncharitably," the authors explain. "New-media platforms and outlets allow citizens to retreat into self-confirmatory bubbles, where their worst fears about the evils of the other side can be confirmed and amplified by extremists and cyber trolls intent on sowing discord and division."

Solutions? "Prepare the child for the road, not the road for the child" is the first folk aphorism Lukianoff and Haidt recommend parents and educators adopt. "Your worst enemy cannot harm you as much as your own thoughts, unguarded" is a second because, as Buddha counseled, "once mastered, no one can help you as much." Finally, echoing Aleksandr Solzhenitsyn, "the line dividing good and evil cuts through the heart of every human being," so be charitable to others.

Such prescriptions may sound simplistic, but their effects are measurable in everything from personal well-being to societal harmony. If this and future generations adopt these virtues, the kids are going to be alright. SA

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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.

Parsex

One common activity on *Star Trek* was to boldly get busy

By Steve Mirsky

If you're like me, you've watched a lot of *Star Trek*. If you're even more like me, you'll read the new book *Live Long and Evolve: What* Star Trek *Can Teach Us about Evolution, Genetics, and Life on Other Worlds,* by Mohamed A. F. Noor, professor of biology at Duke University and editor in chief of the journal *Evolution*.

And being like me, you will turn immediately to Chapter 5: "Sex, Reproduction, and the Making of New Species." Because ever since you first saw Captain Kirk canoodle with a series of apparently female, apparently humanoid organisms you've been like, "I gotta check the Statutes of Alpha III to see if that's kosher."

Closely related species do get it on and can even beget offspring. A horse and a donkey can produce a mule. A lion and a tiger can produce a liger. A polar bear and a grizzly can produce a pizzly. But a human being and anything not a human being can produce a court appearance.

Still, humans bonk nonhumans regularly (by which I mean often—though I don't know about the actual ways and means) in Roddenberryland. "Given that interspecies mating is uncommon on Earth, it appears unusually common among the humanoid species depicted in the various *Star Trek* series," Noor writes. "Indeed," he continues, "attraction to members of other humanoid species does not seem noticeably weaker in any of the five series than attraction to members of one's own species."

So I called Noor and asked him what's with all the outer-spacey interspecies mating? "It's interesting the way the *Star Trek* series depicts it," he responded. "They make it seem as though different species are no different from human ethnic groups or something like that, where, oh, this person is slightly exotic and therefore attractive. And that's not what you expect if you're looking at an actually different species. If we go to the zoo and we see a chimpanzee, we're not attracted to it any more than it is attracted to us."

In fact, depending on what fictional history of the *Trek* universe you subscribe to, a human being and a Vulcan or a Klingon never had a common ancestor and are the result of amazingly high-fidelity convergent evolution. Or an exceedingly ancient species (represented by the "Humanoid Progenitor" in *The Next Generation* episode "The Chase") seeded the universe to force evolution to come up with all of us different types of bilaterally symmetrical, upright-walking intelligent space travelers. Which means *Trek* humans and the other species with which they're bumping uglies (we don't know how ugly) have no evolutionary relationship at all or that the relationship is far more distant than the one between us and chimps.

But we'll grant the *Trek* writers a certain license so that they can include romance in their story lines—and because there's only so much you can do to make human actors look like alien species you'd never meet for coffee.

(For some anatomically intriguing interspecies mating, see the best of all the *Star Trek* movies, namely *Galaxy Quest,* which is not really part of the franchise, in particular the scene in which Tony Shalhoub makes out with Missi Pyle, who starts caressing him with tentacles. To which Sam Rockwell echoes my earlier concerns when he says, "Oh, that's not right.")

If you assume a relatively close degree of genetic similarity among these humanoid species, "the interspecies mating is not so crazy," Noor noted. "Rather than humans and chimps being the analogy, it's more like humans and Neandertals." And when Noor says "humans," it's shorthand for us modern humans, *Homo sapiens sapiens*. Plenty of other human species have existed, including the one categorized by some researchers as *Homo neanderthalensis,* a fully separate species, and by others as *Homo sapiens neanderthalensis,* just another subspecies. However you slice it, we know that *saps* and *thals* mixed it up—you've got Neandertal genes in your pool.

So here's to the *Trek* universe's interspecies residents, including B'Elanna Torres (Klingon-human), Deanna Troi (Betazoid-human) and, of course, Mr. Spock (Vulcan-human). As Kirk said at one of Spock's funerals, "Of all the souls I have encountered in my travels, his was the most [Shatner pause] human." Which Spock would have found deeply insulting. SA

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Illustration by Matt Collins

DECEMBER

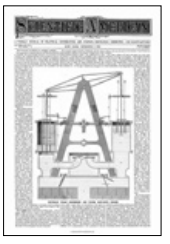
1968 Pluripotent Cells

"The best evidence for the retention of genes in fully differentiated cells comes from experiments carried out at the University of Oxford on eggs of the frog *Xenopus*. The first experiments with intestine cell nuclei were designed to show that at least some of these nuclei possess all the genes necessary for the differentiation of all cell types, and therefore that some of the transplant embryos derived from intestine nuclei could be reared into normal adult frogs. Both male and female adult frogs, fertile and normal in every respect, have in fact been obtained from transplanted intestine nuclei. Their existence therefore proves that at least some intestine cells possess as many different kinds of nuclear genes as are present in a fertilized egg. —J. B. Gurdon"

John B. Gurdon shared the 2012 Nobel Prize in medicine for this work.

1968

1918



1868

1918 The Good Ant

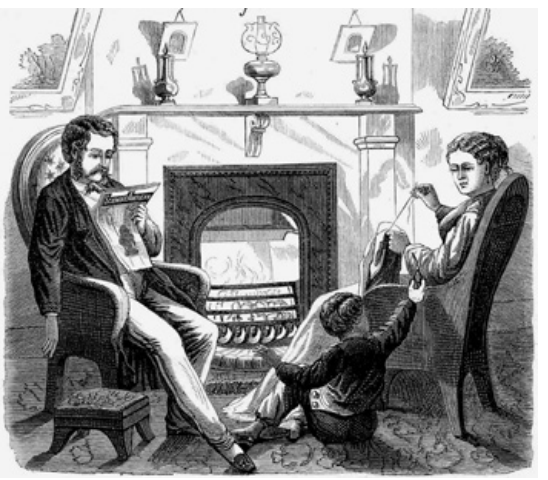
"In *Sudan Notes and Records* a plea is made on behalf of the white ant [termite], which has naturally acquired a bad reputation among European residents. The characteristic feature of the climate of the Sudan is the rapid growth of vegetation promoted by seasonal rains, followed by drought and desiccation. The white ant attacks vegetation only when it is weakened by drought or disease, and in that case the sooner it is destroyed the better. But for the white ant the whole of the fertile parts of the Sudan would, in very few years, be covered with an impenetrable layer of dead vegetation; and the only alternative method to clear it off would be by the agency of fire, the dangers of which are obvious."

Demobilization Upheaval

"The United States took four million men from industry and put them into khaki. Two million of them are coming slowly back from foreign soil, to be reabsorbed into the body politic. The other two million are to be demobilized as rapidly as possible. If it were practical to throw two million men upon the country at once, each one with only $30 in pay and a ticket to his home in his hand, chaos could result. There wouldn't be trains enough to carry them, there might not be roofs enough available to cover them, and there might not even be food enough to give them meals. Certainly, while there are two million manless jobs waiting for two million jobless men, the two could not connect overnight."

1868 Fireplace Upgrade

"Any who value home comforts understand the enjoyableness of a glowing open fire, notwithstanding the superior heating qualities of heaters and closed stoves, and many prefer the inevitable waste and additional costliness of the open grate, with its home-like pleasantness, to these more economical and less healthful appliances. If the grate or open fireplace could be made to yield the same amount of heat that the stove does, at no greater cost, everyone would prefer it. To extend these comforts is the object of the improvement in open grates shown in the engraving."



1868: A more efficient household fireplace (maybe).

Flight Risk

"The keeper of Minot's Light had retired for the night on Wednesday, when a great crash was heard, resounding through the whole substantial building. The lighthouse keeper supposed his assistant had, by accident, broken some glass vessel, but the latter, with alarm on his countenance, soon reported that the plate glass, more than a quarter of an inch in thickness, constituting one side of the great lantern at the top of the lighthouse had been smashed in, perhaps by a rifle ball. Examination was immediately begun, but the discovery on the ledge of the lighthouse of a dead shelldrake duck, with nearly every bone in its body broken, explained what would otherwise have been a very mysterious affair. He was cooked, eaten, and pronounced excellent by the lighthouse keeper and his family."

Traffic vs. Pedestrians

"In all our overcrowded cities, New York, for instance, pedestrians are forced to cross streets to get from block to block, to the peril of life and the utter despoilment of broadcloth and patent leather. Nine tenths of all the accidents from collisions occur at crossings. This city employs a large number of policemen to assist people in fording rivers of filth and prevent them from being run down by reckless drivers. Crossings should be tunneled. Bridges are required to be too high to accommodate the loaded vehicles and omnibuses. Tunnels at crossings, on the contrary, need not be deep, and they can be lighted day and night with gas, for one-fourth the expense of keeping policemen to guard the principal crossings."

SCIENTIFIC AMERICAN, VOL. XIX., NO. 23., DECEMBER 2, 1868

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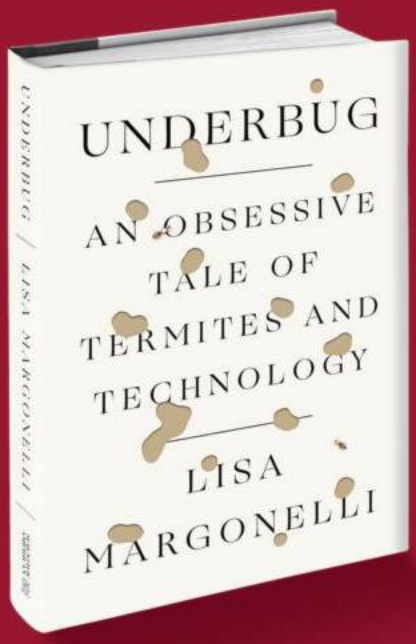

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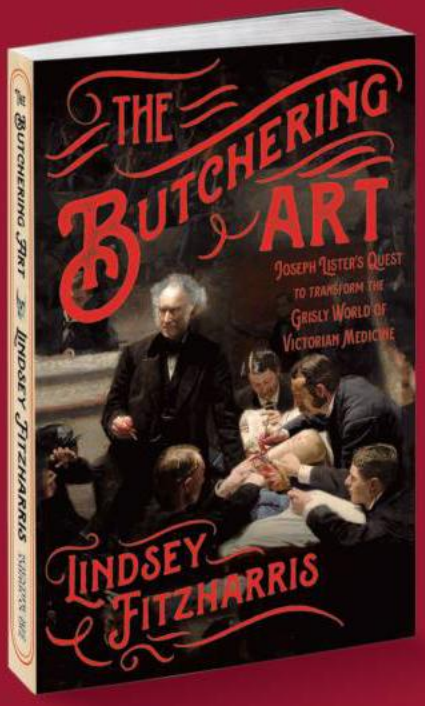

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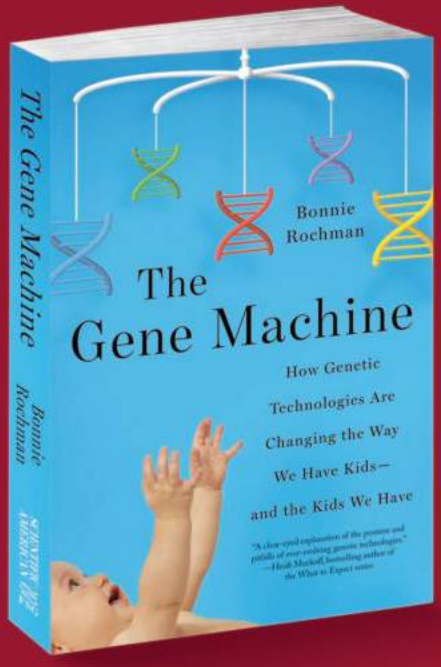

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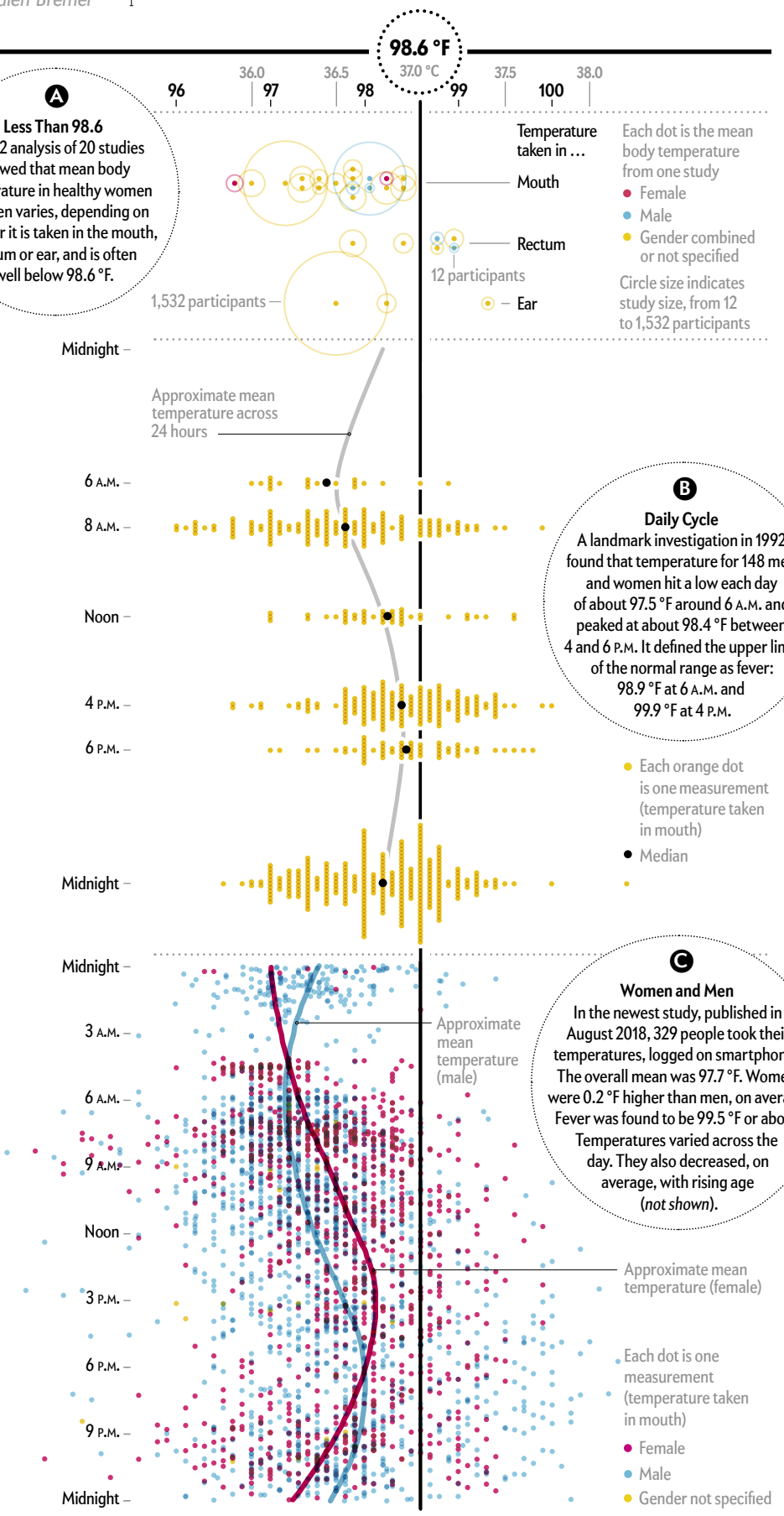
Goodbye, 98.6

Healthy body temps are surprisingly lower

Normal body temperature is 98.6 degrees Fahrenheit, right? Not so. There is no baseline for humans **A**, and even if there was, it would be closer to 97.7 °F. Temperature also varies across the day, peaking in late afternoon and bottoming out in early morning **B**. It is slightly higher for women than for men as well **C**. For two decades research has debunked the benchmark, set way back in 1868, yet it persists. One important ramification, says Jonathan S. Hausmann, a rheumatologist at Boston Children's Hospital, who led the latest study, is to redefine fever. Most doctors use 100.4 °F or higher, but if "normal" is lower, then the fever threshold should be, too. It also should vary with the daily pattern and be tailored to each individual, Hausmann says: "A child at 99.0 °F at 4 A.M. may be highly abnormal but at 4 P.M. could be within normal limits."

R.I.P.
German physician Carl Wunderlich put the mercury thermometer and temperature charts into widespread clinical use. His 1868 book set normal body temperature at 37.0 degrees Celsius, or 98.6 °F. Time to let it go.



SOURCES: "NORMAL ORAL, RECTAL, TYMPANIC AND AXILLARY BODY TEMPERATURE IN ADULT MEN AND WOMEN: A SYSTEMATIC LITERATURE REVIEW," BY MÄRTHA SUND-LEVANDER ET AL., IN *SCANDINAVIAN JOURNAL OF CARING SCIENCES*, VOL. 16, NO. 2; JUNE 2002 (A); "A CRITICAL APPRAISAL OF 98.6 °F, THE UPPER LIMIT OF THE NORMAL BODY TEMPERATURE, AND OTHER LEGACIES OF CARL REINHOLD AUGUST WUNDERLICH," BY PHILIP A. MACKOWIAK ET AL., IN *JAMA*, VOL. 268, NO. 12; SEPTEMBER 23–30, 1992 (B); "USING SMARTPHONE CROWDSOURCING TO REDEFINE NORMAL AND FEBRILE TEMPERATURES IN ADULTS: RESULTS FROM THE FEVERPRINTS STUDY," BY JONATHAN S. HAUSMANN ET AL., IN *JOURNAL OF GENERAL INTERNAL MEDICINE*. PUBLISHED ONLINE AUGUST 13, 2018 (C)

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