BLACK HOLE PARADOX
Can information escape from the abyss? PAGE 50

HACKING GPS
The shocking vulnerability of an essential system PAGE 38

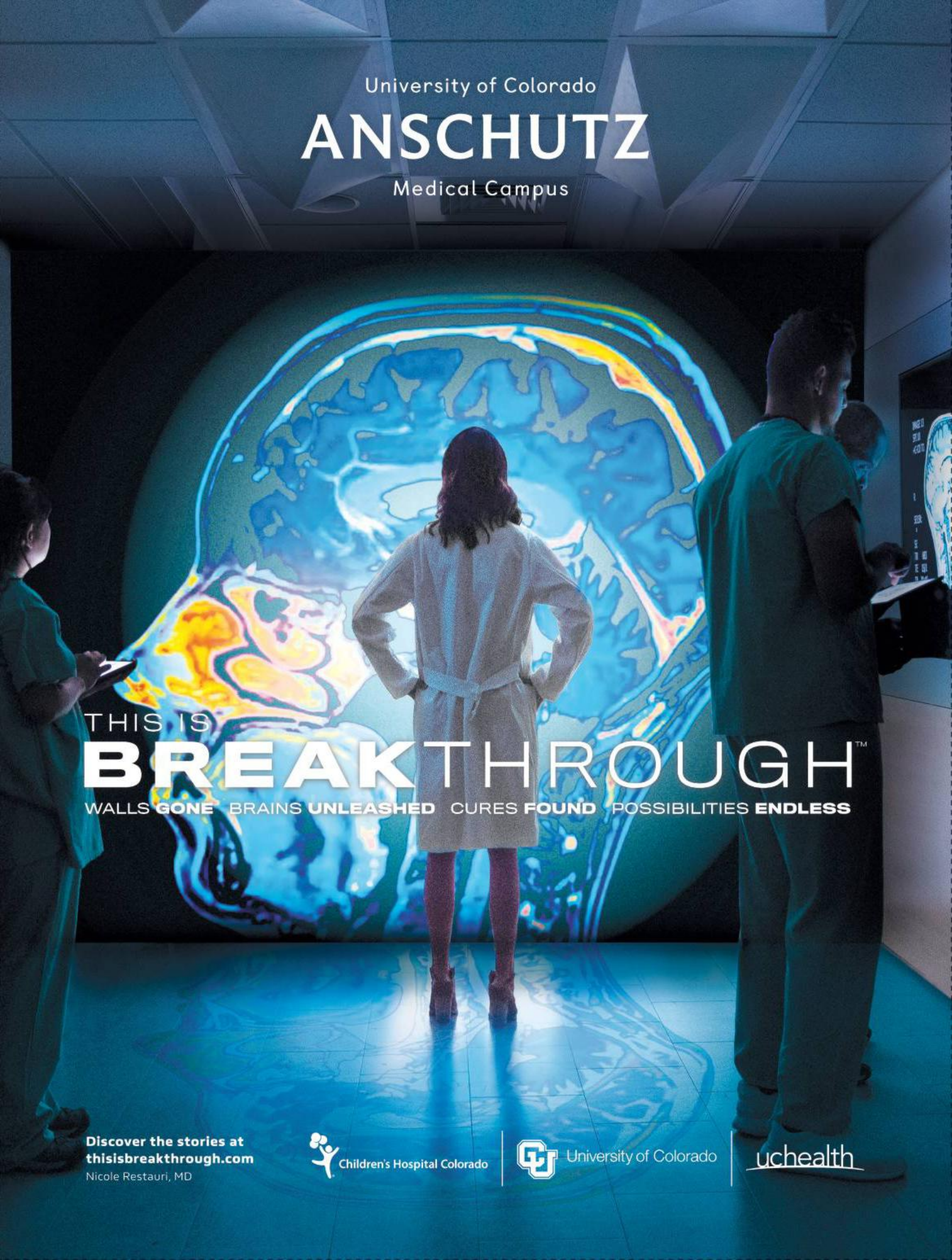
FIRE TORNADOES
Working to predict a deadly phenomenon PAGE 60

SCIENTIFIC AMERICAN

TOP TEN

EMERGING TECHNOLOGIES OF 2019

DECEMBER 2019
ScientificAmerican.com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SCIENTIFIC AMERICAN

ON THE COVER

DNA-based data storage, social robots and the next best thing to teleportation are among the potential breakthroughs profiled in our annual special report on emerging technologies, produced in collaboration with the World Economic Forum.

Illustration by Mark Ross Studio.

Photograph by Spencer Lowell

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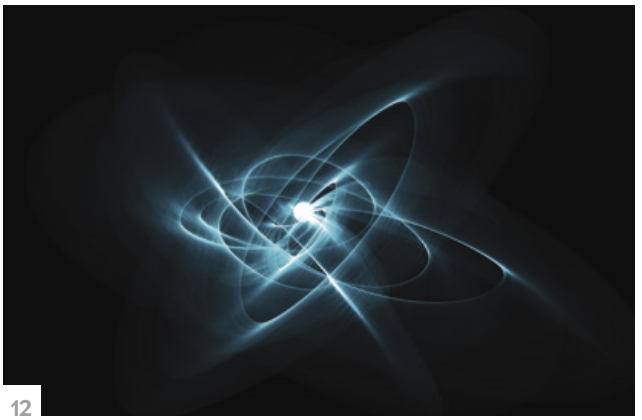

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79

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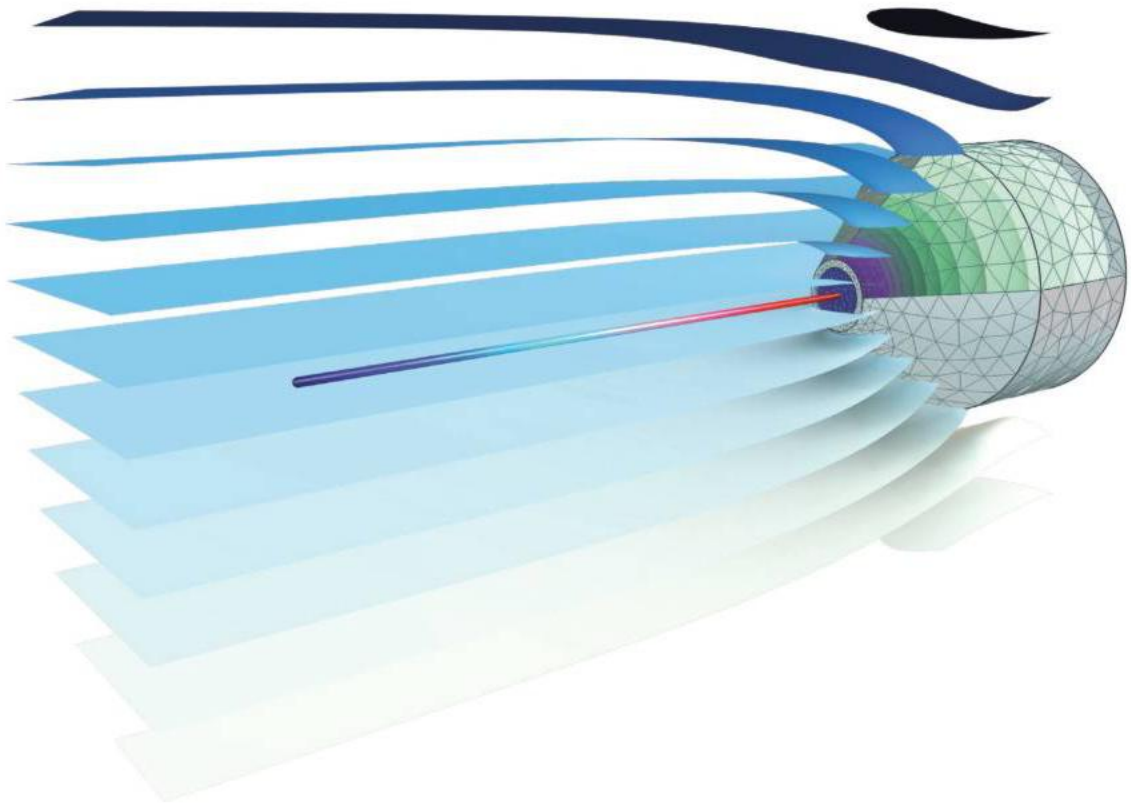
Hearing aids can't solve the cocktail party problem...yet.



Visualization of the total acoustic pressure field around and inside an elastic probe tube extension attached to a microphone case.

Many people are able to naturally solve the cocktail party problem without thinking much about it. Hearing aids are not there yet. Understanding how the human brain processes sound in loud environments can lead to advancements in hearing aid designs.

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Curtis Brainard is acting editor in chief of *Scientific American*. Follow him on Twitter @cbrainard

The Tech Horizon

In 1999 the late Douglas Adams penned a column for London's *Sunday Times* on gripes about the nascent Internet. "Another problem with the net is that it's still 'technology', and 'technology', as the computer scientist Bran Ferren memorably defined it, is 'stuff that doesn't work yet,'" he wrote. "We no longer think of chairs as technology, we just think of them as chairs."

Starting on page 26, our cover story, entitled "Top 10 Emerging Technologies of 2019," showcases diverse inventions that our editors hope one day will become as common as chairs. Like the Internet, these viable technologies could yield disruptive change with major social and economic benefits. The annual list, now in its third year in print, is produced in collaboration with the World Economic Forum. A Steering Group, co-chaired by *Scientific American* editor emerita Mariette DiChristina and IBM chief innovation officer emeritus Bernard S. Meyerson, reviews dozens of nominations drawn from the magazine's board of editors and the forum's network of experts before making final selections.

One technology that isn't on the list but that has emerged in full force is the Event Horizon Telescope (EHT), an array of radio telescopes that captured the world's first picture of a black hole—a fiery ring of starlight surrounding a dark center. Astronomers now believe these mysterious structures are common throughout the universe, but as quantum physicist Steven B. Giddings explains in "Escape from a Black Hole," on page 50, "their very existence threatens the present foundations of physics." New characterizations of black holes might resolve that conundrum, and the EHT, along with gravitational-wave detectors (another recent feat of technology), could finally help scientists test their predictions.

Alas, some game-changing technologies are so commonplace that we take them for granted, often at our peril. Take GPS, the satellite-based Global Positioning System. People use it to find their way to and from locations every day, but it is also essential to the 16 "critical infrastructure sectors" in the U.S., including energy, health care and finance. And the system is under attack. Hackers can jam or spoof GPS with shocking ease, journalist Paul Tullis warns in "GPS Down," on page 38. Moreover, whereas many countries have a ground-based backup system that is difficult to tamper with, the U.S. has never built one—something to think about if you happen to be reading this at an American airport.

There are many other reminders in the issue about the importance of technology to nearly every aspect of modern life, from lab equipment that helps emergency responders understand when and where dangerous wildfires erupt ("Fire Tornadoes," by Jason M. Forthofer, on page 60) to debates about whether or not artificial-intelligence systems could ever be truly conscious ("Proust among the Machines," by Christof Koch, on page 46).

I am also reminded, as *Scientific American* heads into its 175th year of publication, how technology underlies the history of this magazine. Our founding editors dubbed us "the advocate of industry and enterprise, and journal of mechanical and other improvements." So here's to all those Promethean scientists who, over the decades, have harnessed the elements of nature in pursuit of a better world and let us tell such wonderful stories along the way.

Illustration by Nick Higgins

Supermicro

Systems Help Capture the First Ever Images of a Black Hole

Data Processing and Storage for Black Hole Event Horizon Imaging

The first imaging of the event horizon for a black hole involved an international partnership of eight radio telescopes with major data processing at leading research institutes in the US and Germany. The contribution of the brilliant scientists was aided by the expanded computing power of today's IT infrastructure. Processing of the 4 petabytes (PB) of data generated in the project in 2017 for the original imaging utilized servers and storage systems, with many of these servers coming from Supermicro.

Learn more at www.supermicro.com/blackhole

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August 2019

"When it comes to human cancers, many theories about treatment have not panned out."

CARY PETERSON *LINCOLN, NEB.*

CANCER CONTROL

As a community oncologist, I enjoyed James DeGregori and Robert Gatenby's article "Darwin's Cancer Fix." Their approach to treating metastatic prostate cancer by managing its growth, rather than trying to kill all cancer cells, to avoid drug-resistant tumors is intriguing and deserves a large randomized phase III trial. But it is very important to remember that, biologically, cancers are extremely heterogeneous, and there are caveats to the principles the authors outline.

First, certain advanced cancers (especially testicular cancer, Hodgkin's disease and large-cell lymphoma) are curable with vigorous, optimum therapy. Substantial evidence demonstrates failure to maintain dose intensity and interruptions in the treatment schedule compromise chances for a cure. Second, long-term, typically uninterrupted hormonally based treatment for local breast cancer is crucial to preventing metastases. Studies show that for many, 10 years of treatment is superior to five. Third, one of medicine's greatest successes—pediatric acute lymphoblastic leukemia, which now has a cure rate of 80 to 90 percent—requires both optimum initial intensity and long-term, uninterrupted treatment, often for three years.

For the majority of advanced, metastatic cancers not known to be curable, optimum scheduling of therapy certainly deserves careful study. When it comes to human cancers, however, many theories about how treatment should work have not panned out.

CARY PETERSON *Lincoln, Neb.*

AD ASTRA

"The Good Kind of Crazy," by Sarah Scoles, describes research on exotic propulsion technologies for spacecraft being conducted by Heidi Fearn and James F. Woodward, both at California State University, Fullerton. I was a co-organizer of the 2016 conference in Estes Park, Colo., that is featured in the article, and I am a technical witness to much of what Scoles sets out. I have worked on exotic propulsion—in the area of gravitational physics—for more than 20 years and know this field is difficult to effectively report on as a journalist—or to collaborate on as a researcher. Many press reports are fawning and uncritical. Scoles does a very good job of presenting and balancing the differing perspectives in this field.

Woodward has been a great inspiration in the field, and Scoles is right to recognize him. But she distinguishes herself by also taking care to note results that contradict his claims. Such criticism is important, even necessary, to push the envelope. What Scoles may not have realized, however, is that such work in exotic propulsion is a search for one of the greatest discoveries in gravitational physics. A propulsion application is the goal, but its glamour makes us overlook the larger implications such a mechanism might portend for gravitational theory. And it makes us complacent.

Some of the results Scoles describes would constitute important discoveries in gravitational physics if they are confirmed. Yet it is rare for an exotic propulsion researcher to present such results to gravitational scientists at their meetings or in their journals. Integration with textbook gravitational physics is missing from some prominent areas of exotic propulsion research. There is, however, a new generation of exotic propulsion researchers who are committed to integrating these exciting propulsion possibilities within the framework of known gravitational physics, where they belong.

LANCE WILLIAMS *Konfluence Research Institute, Manitou Springs, Colo.*

POCKET TECHNOLOGY

In "The Big Slowdown" [Ventures], Wade Roush claims we live in a time when technological shifts are increasingly rare in comparison with the century prior to 1970. But as I see it, we are living in a time when technology has brought on remarkable, world-shifting change.

I am referring, of course, to the new era of electronic communication. Roush nods toward this "outlier" when he mentions the rise of smartphones, but he pauses only long enough to mention the dangers they bring, not their revolutionary impact.

When worlds change, change changes as well. We miss this process if we look for shifts in the wrong places. Roush mentions consumer robotics and space exploration as areas that have not seen dramatic successes recently. Yet that is because moving mass from one place to another is no longer the arena where the real shifts are happening. Instead it's all about our ability to communicate and gain access to information. Because we are walking around with computers in our pocket that make all this possible, we are living in a different world than three decades back.

JACK PETRANKER *Center for Creative Inquiry, Berkeley, Calif.*

STOPPING GUN VIOLENCE

In "Gun Research Needs More Firepower" [Science Agenda], the editors urge scientists to utilize funding for gun violence prevention research if an appropriations bill passes the Senate.

Some steps can be taken immediately that would have a significant impact on gun use: First, enact a very large excise tax on the manufacture and sale of all ammunition and on materials and equipment to make D.I.Y. ammunition. Second, prohibit the import of those objects. Third, elimi-

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nate all gun show events and mail-order purchase of weaponry and related materials. And fourth, eliminate shipment of weapons and related materials by common carrier across state lines.

All these steps are much cheaper than the proposed $50 million, which would just be used to study the matter ad infinitum.

JIM WRIGHT *via e-mail*

POETRY IN NUMBERS

Steve Mirsky concludes "Do the Math" [Anti Gravity], his piece about the relation between physics and mathematics, by quoting Robert Frost's poem asserting that "the Secret sits in the middle and knows." When I get to the next world, I expect to see Albert Einstein and Isaac Newton sitting in the middle of a grove of apple trees, arguing about whether the mathematics of physics is primarily geometric or analytic. If anyone knows, they should. (My wife and I agree, for once: it is geometric.)

DAVID J. MILLER *Emeritus professor of physics, University College London*

The universe doesn't just speak "to us in numbers," as Mirsky quotes from physics historian Graham Farmelo's similarly entitled book. It speaks to us in mathematics quite removed from numbers.

Further, the article cites a *New York Times* obituary describing British mathematician Michael Atiyah as having "united mathematics and physics … in a way not seen since the days of Isaac Newton." But he simply understood both. The obituary ignored such people as German mathematician David Hilbert and French mathematician Henri Poincaré, who were at home in both camps long after Newton.

SEYMOUR J. METZ *via e-mail*

CLARIFICATION

"Eye of the Flycatcher," by Jim Daley [Advances], describes a novel retinal structure that researchers found in the eye of the Acadian flycatcher. The same study had found the structure in the eye of the least flycatcher as well.

ERRATUM

"Divide or Conquer," by Mark Fischetti, should have defined a coastline's foot of slope as the maximum change in gradient rather than the maximum steepness.

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Adapt or Mitigate? Both

To cope with climate change, we need every strategy we've got

By the Editors

Not that long ago "adaptation" was considered a dirty word among climate activists. Their view was that if we could retool our lives to accommodate the consequences of climate change—rising seas, longer wildfire seasons, and a long list of other not so natural disasters—industries and governments would use that as an excuse to avoid a more important job: curbing our emissions of the heat-trapping greenhouse gases that cause these problems in the first place.

That position might have been reasonable in 1988, when climatologist James E. Hansen first focused the world's attention on the threat. Back then there was still time to cut back on emissions in a measured way. More than three decades later, however, we know mitigation didn't happen. The atmosphere is packed with more carbon dioxide and methane than ever. The most significant reduction effort to date, the much hailed 2015 Paris climate accord, has not yet put a dent in the problem. Climate change is a clearer and more present danger than it has ever been.

As a result, dismissing adaptation is no longer an option. In September a newly formed global commission led by Ban Ki-moon, Bill Gates and Kristalina Georgieva, managing director of the International Monetary Fund, released its first report about the urgent need to adapt to the effects of climate change, which are quickly accelerating. Central banks, militaries and reinsurance companies are sounding the alarm about the financial consequences of doing nothing. U.S. presidential candidates (the Democrats, anyway) talked on national television about relocating people away from flooded coastlines—a topic that was long taboo.

But adapting well takes serious money, and the mechanisms for funding it are misaligned. Many industries and governments, still staving off a systematic overhaul of energy and economic frameworks, are only taking incremental steps to deal with the effects of global warming. One result is that vulnerable communities already experiencing the impact are not receiving adaptation funding from the groups that contributed most to the problem.

Powerful tools are coming on the scene that could help increase adaptation funding and direct it to those who need it most. Researchers in the emerging field of attribution science, for example, can determine how much climate change is worsening the impact of natural events, as described in a recent paper in *Geophysical Research Letters* that found that human-caused climate change probably led to at least 19 percent more rainfall during Hurricane Harvey in 2017 than would have been expected from the storm otherwise. What if fossil-fuel companies had to pay for their role in creating the extra deluge? People working in attribution law are beginning to tackle such questions by launching lawsuits seeking to hold emitters accountable for the damage caused by climate change and the expenses of future adaptation.

The focus on mitigation has led to research and debate about the methods, technologies and economics of lowering concentrations of greenhouse gases. But innovations for adaptation tend to be far behind. Ideas for adapting to sea-level rise, for instance, are too focused on "hard" solutions such as seawalls, whereas natural features could be used more widely as protective infrastructure. More cities could be changing their zoning laws to prevent the development of frequently flooded land. Alignment of insurance programs with climate threats could help prevent exploitative practices in real estate development and mortgage lending. And families who want to relocate to safer areas should get logistical and financial support to do so, rather than being forced to rebuild in increasingly dangerous locations.

Innovative resilience plans have already been launched in some low-lying nations. Fiji's Environment and Climate Adaptation Levy, which includes a 10 percent income tax on the rich, has produced more than $117 million in funding for projects that make Fiji's built and natural environments more resilient to rising waters and heavier storms. And Tri Rismaharini, mayor of Surabaya, Indonesia, has transformed paved land into hundreds of parks and restored mangrove forests that absorb floodwaters and buffer the city from cyclone-generated storm surges. They also pull carbon out of the atmosphere and act as a natural coolant—thereby reducing the need for air-conditioning.

None of these adaptive actions—which are essential for health, safety and economic stability—diminish the need for a rapid global transition from fossil fuels to clean energy. But they do make climate risk more visible and much harder for politicians and the financial sector to ignore. SA

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Illustration by Francesco Zorzi

Qanta A. Ahmed is an academic physician at NYU Langone and a visiting fellow at the Independent Women's Forum.

Legal Child Abuse Must End

Female genital mutilation continues in the U.S.

By Qanta A. Ahmed

It was a failure to denounce a crime against humanity. In July, Ani Zonneveld, president of Muslims for Progressive Values, asked Representative Ilhan Omar of Minnesota to make a statement concerning women and girls victimized by female genital mutilation or cutting (FGM/C). Instead of educating the audience and pledging to improve legal protections against it, Omar, a Somali-American Muslim woman, pointed out that she had spoken against the practice elsewhere and excoriated Zonneveld for making the request simply because of Omar's religion—ignoring the fact that Zonneveld is herself a follower of Islam.

As a female Muslim physician, I find Omar's response inexcusable. In May 2017 Omar, then a state lawmaker, did vote for more severe penalties for FGM/C, although she expressed serious reservations. That bill died in the state senate. Omar has also cosponsored a resolution in Congress to condemn the practice. But the mutilations continue, as does the pressure to accept them as an act of cultural conformity. This political inaction leaves at-risk girls and women in America without recourse to justice. The Centers for Disease Control and Prevention notes that the number of such women—currently estimated as 513,000—has risen with increasing immigration.

The World Health Organization classifies FGM/C in four categories: clitoroidectomy, or excision of variable amounts of the clitoris and clitoral hood; excision consisting of partial or total removal of the clitoris and labia; infibulation, or excision and repositioning of the internal and/or external labia to narrow or block the vaginal opening, sometimes with suturing of the vulva, preventing penile penetration and restricting the passage of urine and menstrual blood; and all other forms of mutilation, including cauterization.

FGM/C affects more than 200 million women and girls globally, mostly in Africa, the Middle East and Asia. In eight nations the prevalence exceeds 80 percent. In Somalia, where FGM/C impacts girls between four and 11 years of age, it reaches 95 percent.

Sanitized as "female circumcision," these procedures have no positive impacts on health. FGM/C devastates women and girls permanently. Not only can menstruation and sexual intercourse become painful and traumatic, but victims also are left with permanent genital deformity and may experience loss of libido, delayed menarche, chronic pelvic infections, urinary tract infections, fistulas that can cause urinary and fecal incontinence, and sepsis, which can sometimes be lethal. Members of tribal diaspora communities in the U.S. often return to sub-Saharan Africa to brutalize their daughters over the summer vacation season, known as the cutting season.

Muslim families are finding practitioners in the U.S. who are willing to perform the procedures. In the case of Jumana Nagarwala, a Muslim woman who was the first American physician to be federally charged for performing the procedure, two girls were confirmed to have undergone FGM/C procedures in Michigan, after being transported from Minnesota. In 2006 the first conviction for FGM/C in the U.S. was made when an Ethiopian immigrant was found guilty of performing the surgery on his daughter in the state of Georgia.

Data on FGM/C in the U.S. are lacking, but an anecdotal observation from the Hennepin County Medical Center in Minneapolis estimated that type III FGM/C is seen in 99 percent of Somali women. The American Medical Association has classified it as child abuse. And Minnesota law on FGM/C renders the practice a felony but fails to hold parents accountable for aiding and abetting the crime and for the endangerment of a child, although such charges can be brought under other state laws. During the Obama administration, the U.S. criminalized the transport of minors for FGM/C. Still, in much of the U.S., legislation needs to be augmented: Only 10 states have mandatory-reporting laws specifically for FGM/C. Only 35 make FGM/C a felony for practitioners, and several of those laws fail to address the role of guardians or the possibility of cultural defenses and "vacation cutting."

The Independent Women's Forum (IWF) is petitioning for FGM/C to be included in the federal Violence Against Women Act (VAWA). The act has been reauthorized three times, and IWF rightly argues that FGM/C is violence against women (and girls) and must be part of more robust and comprehensive VAWA legislation.

Silence here is never an option. SA

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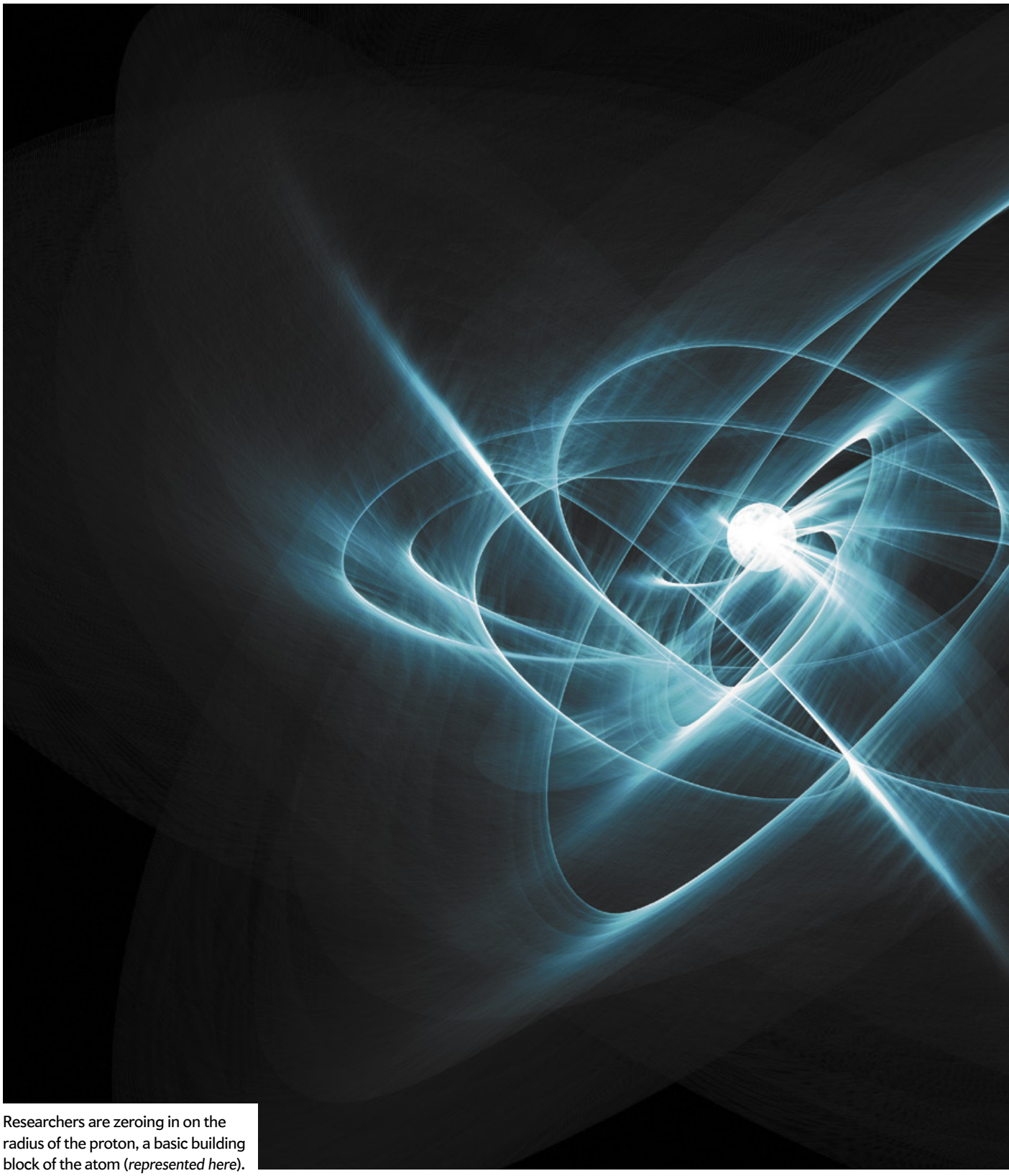
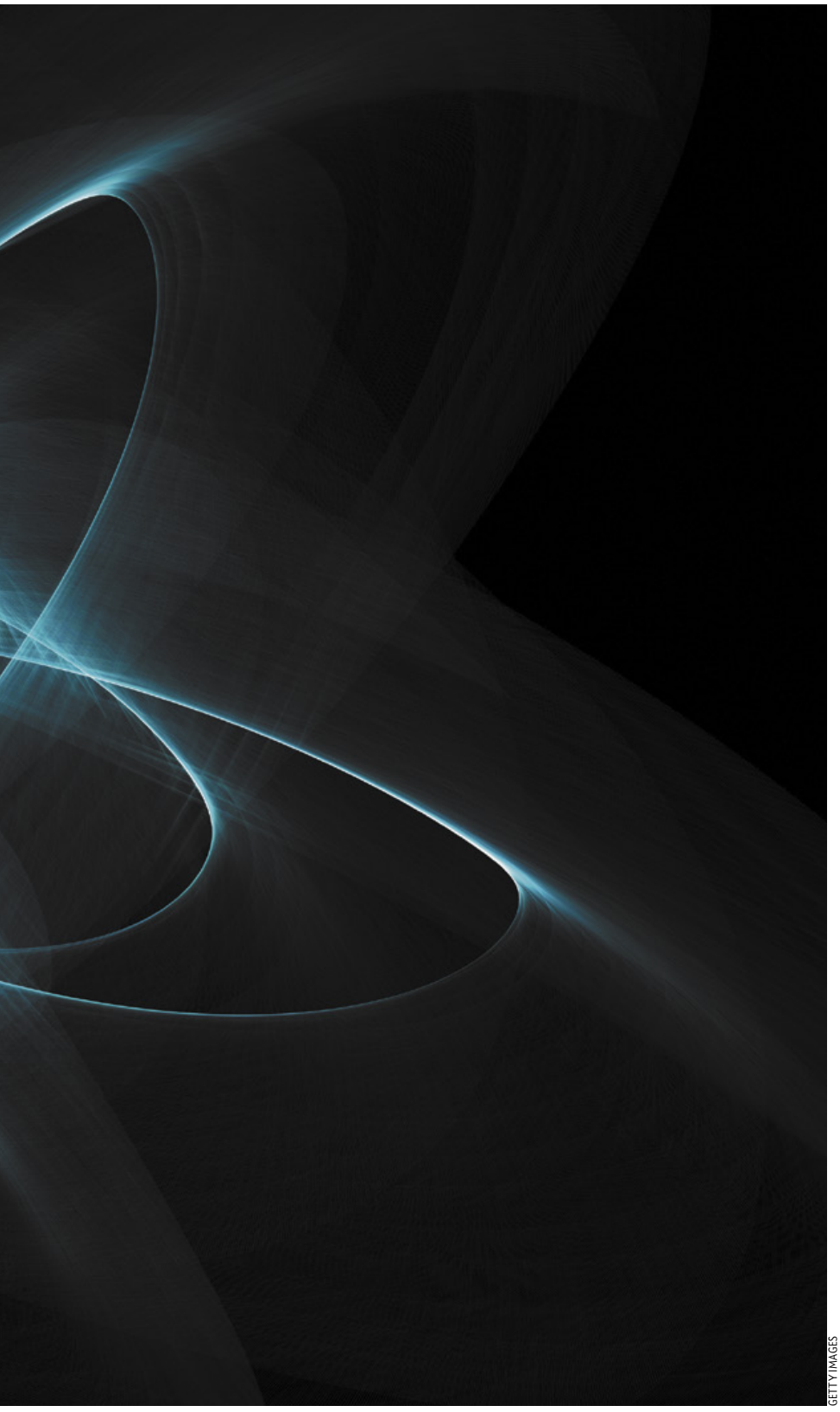


Researchers are zeroing in on the radius of the proton, a basic building block of the atom (*represented here*).



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Proton Size Puzzle

New work may solidify a critical benchmark

Scientists love precision. They can measure the distance from Earth to the moon to within a couple of centimeters and the spins of far-off pulsars to fractions of a millisecond. When peering inside a nearby atom, however, that kind of precision is harder to come by. Consider protons, the positively charged chunks of matter found in every atomic nucleus. Physicists have been trying to pin down their size for more than half a century, but it has proved fiendishly difficult—and conflicting measurements have left researchers scratching their heads. Now an ultraprecise measurement at York University in Toronto may finally have tamed the proton.

Protons are, of course, tiny—less than two trillionths of a millimeter across—so teasing out their radius requires exacting techniques. Researchers can fire a beam of electrons at a hydrogen atom, whose nucleus consists of a single proton; the angles at which the electrons bounce off the proton are determined by its size. Another strategy relies on spectroscopy, which measures the intensity of the radiation at various frequencies that an object emits. Scientists can

excite a hydrogen atom's electron so it jumps from one energy state to the next and then carefully track the frequency of the radiation needed to drive this transition. The size of the "gap" between the energy levels depends on the proton's size.

Measurements dating back to the 1950s, from work using both methods, set the proton's radius at an apparent 0.88 femtometer (a femtometer is 10^{-15} meter). In 2010 researchers led by Randolf Pohl, then at the Max Planck Institute for Quantum Optics in Garching, Germany, tried something different. They used the spectroscopic method but with special "muonic" hydrogen: instead of an electron, this atom contains a muon, a particle with about 200 times the mass of an electron. Because the muon hugs the proton more tightly than an electron would, its energy levels are more sensitive to proton size, promising more accurate results. Plus, the particular transition they studied (in which the muon jumps from its first excited state to its second) leads more directly to the proton radius than other transitions. Pohl and his team were surprised to find a lower value for the radius, pegging it at 0.84 femtometer—well outside the range of potential sizes established by earlier measurements.

Pohl's result sent the head-scratching into high gear. Was something wrong with the earlier experiments? Or is there something peculiar about how protons interact with muons, compared with their behavior around electrons? That was the most intriguing possibility: that some as yet unknown physics, which might require a tweak to the so-called Standard Model, was at play.

"When there's a discrepancy in the data, it really gets people excited," says David Newell, a physicist at the National Institute of Standards and Technology in Gaithersburg, Md., whose work has focused on pinning down the value of Planck's constant, another crucial parameter in atomic physics.

The discrepancy caught the attention of Eric Hessels, head of the York team, who a decade ago was at the workshop where Pohl first presented his results. Hessels took Pohl's findings as something of a personal challenge and worked to replicate the experiment—right down to the particular energy-level transition—using regular instead of muonic hydrogen. This jump is known as the Lamb shift (for physicist Willis Lamb, who first measured it in the 1940s). A precise measurement of the Lamb shift in regular hydrogen seemed guaranteed to reveal something of interest. If it matched the earlier, larger value, it might point the way to new physics; if it matched the lower value, it would help pin down the size of the proton, solving a decades-old puzzle.

It took Hessels eight years to find the answer. "It was a more difficult measurement than I anticipated," he says, "and more difficult than any other measurement that we've taken on in our lab." He used radio-frequency radiation to excite hydrogen atoms, noting the precise frequency at which the radiation drove the electron energy jump associated with the Lamb shift. In the end, his team determined that the proton's radius is 0.833 femtometer, plus or minus 0.010 femtometer—which agrees with Pohl's measurement. *Science* published the results in September.

In an age of "big science"—think of the Large Hadron Collider and its tunnel's 27-kilometer circumference—physicists may take some comfort in the fact that such important results can still be obtained with tabletop experiments. Hessels's setup fit in a single room on York's campus.

It is unclear why previous experiments produced a larger value for the proton's radius. Errors in experimental design are one possibility, researchers suggest. Another possibility—seemingly less likely, in light of Hessels's measurement—is that unknown physics still skews the results.

MEDICINE

Plasma Power

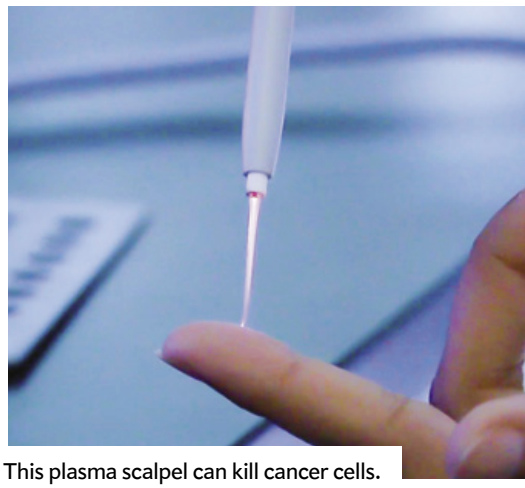
New supercharged scalpel takes on cancer

When a surgeon removes a tumor, some cancer cells may get left behind, threatening to seed another malignant growth. Researchers have just begun the first clinical trial of a new anticancer tool that they hope will kill these stubborn cells: a plasma scalpel.

The pen-size scalpel emits a small jet of helium whose charged particles glow with a vivid lilac hue. An electrode at the scalpel's tip splits some of the helium atoms into a plasma soup of positive ions and electrons.

Unlike in the sun's blazing plasma, the scalpel's ions are relatively slow-moving—so the jet feels like a cool breeze to the touch. But its fast electrons are packed with energy and can convert atmospheric oxygen and nitrogen into reactive forms, including superoxide, nitric oxide and atomic oxygen. These substances can interrupt key metabolic processes and hamper cell reproduction, and researchers have found that cancer cells are much more vulnerable to such effects than healthy cells are. The scalpel can be used on a tumor site for just a few minutes during surgery, says Jerome Canady, a surgeon in Washington, D.C., and part of the team that developed the tool. "We just spray that area with plasma to kill any microscopic tumors," he says.

Cold plasma is already used to treat infections and sterilize wounds, and more energetic plasma can neatly cut or cauterize tissue. Turning it against cancer has long been a goal, and the new trial is a major milestone, says Mounir Laroussi, who studies the biological effects of cold plasma at Old Dominion University. "I think this is huge," he says.



This plasma scalpel can kill cancer cells.

In the past few years doctors have used plasma scalpels on three cancer patients on a "compassionate use" basis, after all other

The York finding's precision and closeness to the 2010 figure suggest a consensus forming around the lower value for the proton radius. "There are now a number of measurements, and they're starting to line up with the muonic-hydrogen measurement," Hessels says. "So the controversy is starting to diminish."

Diminish but not disappear: As good as Hessels's result is—it is one of the best spectroscopic measurements achieved with normal hydrogen—Pohl's measurement is more precise because of the greater sensitivity of the muonic-hydrogen method. This finding means there is room for even more sensitive experiments, researchers say.

Meanwhile there are other secrets the proton has yet to give up. For starters, we know protons and neutrons both consist of three quarks bound by the strong nuclear force—but the exact nature of that binding is poorly understood, says Nilanga Liyanage, a physicist at the University of Virginia.

"Protons are the stuff we're made of," says Liyanage, who has tackled the proton radius puzzle through electron-scattering experiments at the Jefferson Lab in Virginia. And "99.9 percent of our mass—of ourselves, of everything in the universe—comes from protons and neutrons." The proton radius is a critical benchmark quantity, he adds: "It's a very important particle, and we need to understand it." —*Dan Falk*

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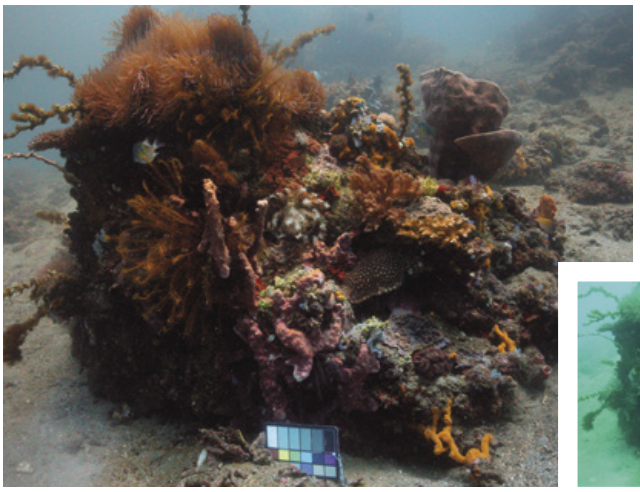
treatment options had failed. The plasma successfully killed residual cancer cells in these people, Canady says, but a full clinical trial will provide vital data about safety and longer-term effects. As *Scientific American* went to press, Canady and his colleagues were due to perform the first surgery of their trial in late October 2019. They aim to use the plasma scalpel on 20 patients with late-stage solid cancers, including those affecting the pancreas, ovary or breast.

Laroussi says it took more than a decade of laboratory work on cell cultures and animals to prepare the plasma scalpel for the clinic. The process involved identifying the chemicals it generates, measuring their penetration into tissue and understanding how the disruption of cancer cells works. "You also have to stay below a certain dose—otherwise you kill both cancer cells and healthy cells," he says. Laroussi hopes the trial will show that the device can be fine-tuned to take out its cancerous quarry without causing unwanted damage. —*Mark Peplow*



Large coral formation in Lembeh Strait in Indonesia before (*inset*) and after processing with the Sea-thru algorithm.

OPTICS

Ocean Vision

A new algorithm takes the water out of underwater photographs

Coral reefs are among nature's most complex and colorful living formations. But as any underwater photographer knows, pictures of them taken without artificial lights often come out bland and blue. Even shallow water selectively absorbs and scatters light at different wavelengths, making certain features hard to see and washing out colors—especially reds and yellows. This effect makes it difficult for coral scientists to use computer vision and machine-learning algorithms to identify, count and classify species in underwater images; they have to rely on time-consuming human evaluation instead.

But a new algorithm called Sea-thru, developed by engineer and oceanographer Derya Akkaynak, removes the visual distortion caused by water from an image. The effects could be far-reaching for biologists who need to see true colors underneath the surface. Akkaynak and engineer Tali Treibitz, her postdoctoral adviser at the University of Haifa in Israel, detailed the process in a paper presented in June at the IEEE Conference on Computer Vision and Pattern Recognition.

Sea-thru's image analysis factors in the physics of light absorption and scattering in the atmosphere, compared with that in the ocean, where the particles that light interacts with are much larger. Then the program effectively reverses image distortion from water pixel by pixel, restoring lost colors.

One caveat is that the process requires distance information to work. Akkaynak takes numerous photographs of the same scene from various angles, which Sea-thru uses to estimate the distance between the camera and objects in the scene—and, in turn, the water's light-attenuating impact. Luckily, many scientists already capture distance information in image data sets by using a process called photogrammetry, and Akkaynak says the program will readily work on those photographs.

"There are a lot of challenges associated with working underwater that put us well behind what researchers can do above water and on land," says Nicole Pedersen, a researcher on the 100 Island Challenge, a project at the University of California, San Diego, in which scientists take up to 7,000 pictures per 100 square meters to assemble 3-D models of reefs. Progress has been hindered by a lack of computer tools for processing these images, Pedersen says, adding that Sea-thru is a step in the right direction.

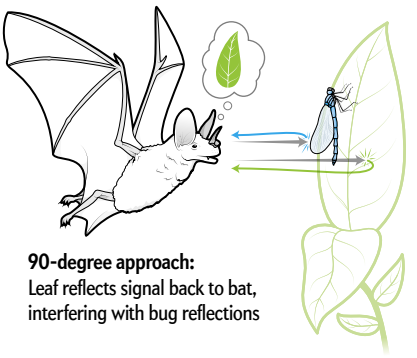
The algorithm differs from applications such as Photoshop, with which users can artificially enhance underwater images by uniformly pumping up reds or yellows. "What I like about this approach is that it's really about obtaining true colors," says Pim Bongaerts, a coral biologist at the California Academy of Sciences. "Getting true color could really help us get a lot more worth out of our current data sets." —*Erik Olsen*

DERYA AKKAYNAK

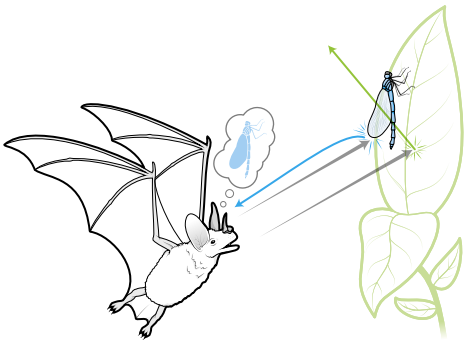
ANIMAL BEHAVIOR

Sound Judgment

Strategic angles help bats hunt stationary bugs on leaves



90-degree approach: Leaf reflects signal back to bat, interfering with bug reflections



60-degree approach: Leaf reflects signal away from bat, revealing bug reflections

Bats are known for using high-frequency acoustic signals to deftly snatch flying insects from the air at night, even amid dense forests. But more than 40 percent of insectivorous bat species hunt by plucking prey resting on leaves or other surfaces. Because the sound waves bats emit reflect off vegetation at all angles, the returning jumble of echoes should render a leaf-bound insect virtually imperceptible—so scientists have long suspected that bats use clues from vision, smells or prey-generated sounds to help find a motionless meal.

Now, however, biologists Inga Geipel of the Smithsonian Tropical Research Institute, Ralph Simon of Free University Amsterdam and their colleagues have shown how some bats detect a still and silent insect on a leaf using echolocation alone. By approaching the target along a specific trajectory, the common big-eared bat *Micronycteris microtis* treats the leaf as an acoustic mirror to reflect unwanted echoes away from its angle of attack. This makes the insect's signal stand out, according to a study published in August in *Current Biology*.

"To the bat's ears, echoes from the prey are enhanced, while those coming from the leaves are effectively reduced," says John Ratcliffe, an animal biologist from the University of Toronto, who was not involved in the new work.

The researchers lined a room with microphones and monitored how sound waves generated by a synthetic batlike sonar reflected off a leaf. They found that the waves bounced off the leaf itself in a direction away from the source. But when an insect was placed on the leaf, pulses coming in at angles around 60 degrees from vertical reflected back to the sonar's source. Next the researchers filmed four wild bats nabbing dragonflies perched on leaves. "The bats approached exactly from the expected angles," Simon explains. Outside of that range of angles, the target became much harder to detect.

This is not the first time scientists have observed bats bouncing waves off a surface in this way; individuals feeding at lakes and ponds use a similar process to help make floating prey stand out. But that tactic relies on the water's large, smooth surface—and bats do not have to maneuver as delicately to approach from the correct angle. "It's exciting to learn that the same process can be exploited in a very different environment," says neuroscientist Michaela Warnecke of the University of Wisconsin–Madison, who has investigated echolocation but was not involved in the study.

Whether *M. microtis*'s hunting strategy is unique among bat species remains to be seen, Ratcliffe says. But this work helps to reveal the bat's acoustic world, which could lead to new applications, including improved bat-inspired sonar systems, according to the study's researchers.

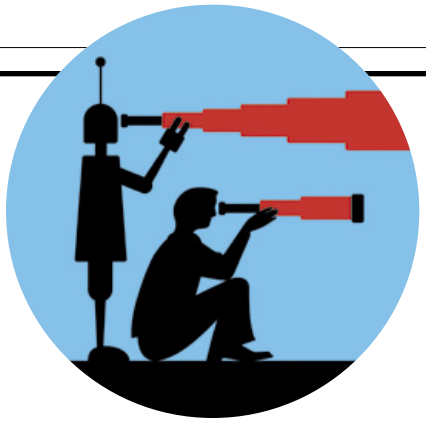
—*Rachel Berkowitz*

Illustration by Brown Bird Design

ARTIFICIAL INTELLIGENCE

Automating History

Computers can tell what will matter (slightly) better than humans can



As 2019 draws to a close, prepare for endless roundups of the year's most important news stories. But few of those stories may be remembered by 2039: new research shows the difficulty of predicting which events will make the history books.

Philosopher Arthur Danto argued in 1965 that even the most informed person, an "ideal chronicler," cannot judge a recent event's ultimate significance because it depends on chain reactions that have not happened yet. Duncan Watts, a computational social scientist at the University of Pennsylvania, had long wanted to test Danto's idea. He got his chance when Columbia University historian Matthew Connelly suggested analyzing a set of two million declassified State Department cables sent between 1973 and 1979, along with a compendium of the 0.1 percent of them that turned out to be the most historically important (compiled by historians decades after their transmission).

Connelly, Watts and their colleagues first scored each cable's "perceived contemporaneous importance" (PCI), based on metadata such as how urgent or secret it had been rated. This score corresponded only weakly with inclusion in the later compendium, they reported in September in *Nature Human Behaviour:* the highest-scoring cables were only four percentage points more likely to be included than the lowest-scoring ones. The most common prediction errors were false positives—cables that got high scores but later proved unimportant. "I do think there's a kind of narcissism of the present," Connelly says. "I've been struck by how many times sports fans say, 'That's one for the history books.'"

Next, Watts says, to approximate an ideal chronicler, the scientists decided to "build the beefiest, fanciest machine-learning model we could and throw everything into it—all the metadata, all the text." The resulting AI algorithm significantly outperformed humans' contemporaneous judgment. In one statistical measure of its ability to pick out cables later deemed significant, where 1 denotes no incorrect inclusions or exclusions, it scored 0.14, whereas the PCI scored 0.05. Although the algorithm's performance was far from perfect, the researchers suggest that such an "artificial archivist" could help to narrow the field of events to highlight for posterity. When tuned for this purpose, their model weeded out 96 percent of the cables while retaining 80 percent of those that wound up in the compendium.

Emily Erikson, a sociologist at Yale University, who was not involved in the new research, says that despite its use of imperfect data—compendium inclusion was up to the subjective judgment of a few historians, for example—the study offers a practical tool and addresses Danto's hypothesis. "To see a machine-learning empirical test of this conceptual puzzle is really exciting," she says, "and just kind of fun to think through."

—Matthew Hutson

ECOLOGY

Biome Boost

Sewage-treatment changes helped wildlife in an English river

Rivers act as Earth's arteries and veins, providing sustenance and sweeping away waste to keep terrestrial habitats in shape. By that measure, England is unhealthy: a startling 86 percent of its rivers do not meet water-quality standards, posing a risk to wildlife and human health.

A new study offers hope. Invertebrate biodiversity in one Thames River tributary has increased in the past 30 years, thanks to an adjustment in wastewater treatment, scientists at the U.K.'s Center for Ecology & Hydrology have found. "It's starting to reach levels one might expect to find in a river without any wastewater," says environmental scientist Andrew Johnson, lead author on the analysis, which appeared in August in *Environmental Toxicology & Chemistry.*

Invertebrates such as crustaceans, insects and worms are key players in aquatic ecosystems. They shape their environment by digging into riverbeds and filtering water, and they are both predators and prey. These animals also respond quickly to environmental changes, indicating an ecosystem's health.

The researchers analyzed data collected by the U.K. Environment Agency between 1977 and 2017 for a 12-kilometer stretch of the River Ray downstream from a large wastewater treatment plant in the southwestern town of Swindon. They found a steady increase in the variety and numbers of invertebrates since June 1991.

That timing coincides with the 1991 European Union Urban Wastewater Directive, which pushed treatment plants to switch from filtration to an activated sludge process that uses microbes to break down contaminants. This dramatically cut the organic matter and toxic ammonia going into rivers—and so invertebrate biodiversity slowly improved, the team concluded. "You could liken it to being given a diet of cheeseburgers for 20 years and then switching to a healthy diet," Johnson says. "Recovery is not instant."

John Sumpter, an ecotoxicologist at Brunel University London, says this increase most likely boosted diversity among larger creatures, too, and that these results probably apply in other places. Still, published studies showing such improvements are rare. "A big problem is that very few countries have the long-term data sets to conduct the analyses required," he says.

The new work suggests that "urban rivers in the U.K. are recovering from the gross pollution problems of the industrial era," says Steve Ormerod, an ecologist at Cardiff University in Wales. But full restoration will require more work and tougher regulations, he adds, noting the growing problem of agricultural pollution: "The basic story of British rivers is one of urban improvement but rural decline."

Yet Johnson thinks the River Ray results show a possible path forward. "And maybe," he says, "wildlife is more robust than we'd thought."

—Prachi Patel

Illustrations by Thomas Fuchs

IN THE NEWS

Quick Hits

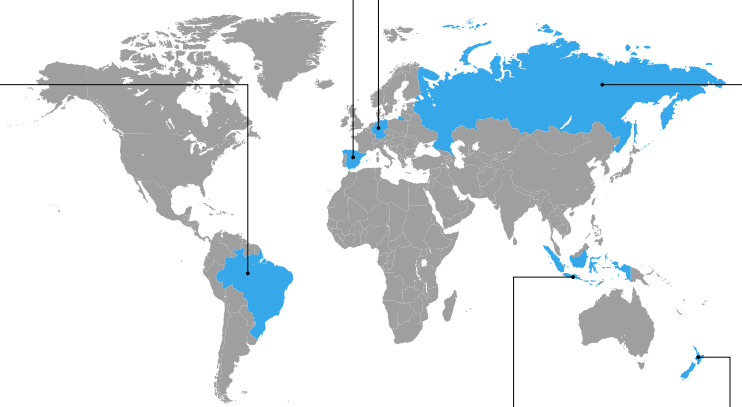
By Sarah Lewin Frasier

SPAIN

Summer's powerful drought revealed a more than 4,000-year-old oval of at least 100 standing stones called the Dolmen of Guadalperal, which had been submerged since 1963 in an engineered reservoir.

GERMANY

An underwater environmental-monitoring station 48 feet below the surface of Eckernförde Bay disappeared in August. Researchers found only a frayed cable at the site of the more than 1,750-pound observatory, and the search continued with additional dives and ship-based sonar.



BRAZIL

A newfound species of electric eel in Brazil, *Electrophorus voltai*, produces the strongest shock scientists have ever measured from a living animal. It can let loose 860 volts; a Taser delivers about 1,200.

RUSSIA

Scientists identified a small group of Nordmann's greenshanks, among the most endangered shorebirds, in a bog in Russia's far eastern region. They helmed the first in-depth study of the bird since 1976 and are the first ever to capture a photograph of an adult on a nest.

NEW ZEALAND

Researchers found that humpback whales traveling near Raoul Island, 700 miles off New Zealand's coast, learn songs from members of other breeding grounds.

INDONESIA

Climate models have more firmly connected a record-setting cold European summer in 1816 to the previous year's eruption of Indonesia's Mount Tambora, which injected sulfur dioxide into the atmosphere and caused widespread surface cooling.

For more details, visit www.ScientificAmerican.com/dec2019/advances

MATERIALS SCIENCE

Silky Tissue

Wild silkworms generate proteins ready for 3-D bioprinting

Wild silkworm species *Antheraea assamensis*

INDIAN INSTITUTE OF TECHNOLOGY GUWAHATI

Many research groups are testing "ink" made from silk proteins to print human tissues, implants and perhaps even organs. The process is a less costly alternative to conventional 3-D printing with collagen, a key protein in the body's natural scaffolding. Researchers in Assam, a state in India, are investigating using local silkworm species for the task—they recently submitted a patent for bioinks using a combination of proteins extracted from local species *Antheraea assamensis* and *Samia ricini,* as well as the commonly used *Bombyx mori.* The scientists have woven them into synthetic structures ranging from blood vessels to liver lobes; in a paper published in September in *ACS Applied Materials & Interfaces,* they described mimicking the cartilage of an entire ear.

Silk is a natural polymer, a substance with long, repeating molecular chains. It is mechanically strong and completely biodegradable, well suited for applications in tissue engineering. To use it, researchers draw liquid silk from the silkworm's glands or dissolve silk fibers in solvents. They carefully mix the gelatinous liquid with a patient's stem cells, then build structures layer by layer with a 3-D printer. After implantation, the cells grow and replace the silken scaffold, which eventually degenerates into amino acids.

Extracting and purifying collagen from animal remains, a common medical source, is complex and expensive. "Compared with collagen, silks have an immense advantage in terms of supply and processing. Local sourcing is also a clear plus in their use in India," says David Kaplan, who heads the department of biomedical engineering at Tufts University and is not involved in the new research. Silk from domesticated silkworms has been used widely in bioprinting, but Biman B. Mandal's laboratory at the Indian Institute of Technology Guwahati in Assam is among the first to incorporate wild silks.

These silks are ideal candidates for bioinks because they can be combined to build strong and resilient scaffolds, says Mandal, the lab's principal investigator. "This is important, for example, when making bone tissue," he adds.

Researchers commonly use chemicals to cross-link silk polymer chains, which helps to maintain a 3-D structure, but Mandal's group found a blend of silks and gelatin that works without many of those chemicals. Also, the wild silk has spots that cells naturally attach to, he says: "For other silks, they have to be decorated with chemicals that promote adherence. This can be complicated, expensive and potentially toxic." Kaplan agrees, adding that these binding spots allow cells to adhere rapidly to the silk matrix.

Mandal and his collaborators have already created prototype structures, including bone and soft tissues such as those of the heart and liver. Reconstructing a human knee meniscus and the complex tissue at the ends of a bone will be next. —*Harini Barath*

TECH

Fusing Ceramics

A new laser technique could pave the way for tougher electronics

Ceramics are hard and durable; they resist scratches better than glass and stand up to high heat better than most metals. They could protect electronic devices from challenging conditions found in space or in the human body—but their very toughness makes them hard to manipulate. Joining two ceramic slabs with an airtight seal requires heating them to about 2,000 degrees Celsius, which would typically destroy embedded electronics. Now, however, researchers have developed a welding technique that spot heats the ceramics with lasers, as described in August in *Science.*

Lasers have already fused glass: pulsing a specially tuned beam about a trillion times a second can melt a targeted spot. But unlike glass, a ceramic scatters this light instead of absorbing it. "When you think of a ceramic, you think of a coffee cup or a bowl," says principal investigator Javier E. Garay, a mechanical and aerospace engineer at the University of California, San Diego. Such items are opaque because they contain tiny light-scattering pores, Garay explains. Adjusting the manufacturing process to reduce the pores' size and number, an idea pioneered by ceramic scientist Robert Coble 60 years ago, can make the material translucent or transparent.

Working with a transparent version of a common ceramic and a laser technique similar to the one used for glass, the researchers successfully welded cylindrical containers. The resulting seam was tight enough to hold a vacuum with little air leakage, qualifying it for use in harsh environments such as space. Because these ceramics do not react with living tissue, they could also encase electronic devices implanted in the human body.

"It's a major engineering achievement," says Himanshu Jain, a materials scientist at Lehigh University, who was not involved in the new study. Although previous research has used lasers to melt ceramics, he notes, this is the first time a laser has welded ceramic pieces together. "The hardest part is to get the proof of principle," he says. "Now, to go into detail and understand the science behind it, why it works and how it works—all those things are yet to be done." —*Sophie Bushwick*

Macrobrachium rosenbergii

BIOLOGY

Single-Sex Snail Fighters

"Superfemale" prawns could help take on a deadly disease

Scientists are mobilizing an all-female army to help stymie schistosomiasis, a sometimes deadly parasitic disease that affects millions of people every year.

Macrobrachium rosenbergii prawns "are voracious predators of parasite-carrying snails" that spread the illness, says Amir Sagi, a biologist at Ben-Gurion University of the Negev in Israel and principal investigator of a new study on the subject. "The possibility of nonreproducing monosex [prawn] populations, which will not become invasive, opens the path for their use as biocontrol agents."

Using crustaceans to control *Schistosoma*-carrying snails is not a novel concept, but developing a sizable population that is all one sex and therefore cannot reproduce—and potentially ruin an ecosystem—has proved challenging.

Like humans, prawns pass on specific chromosomes that determine their offspring's sex. But unlike humans, female prawns usually have one male and one female chromosome, whereas males have two identical male chromosomes. Laboratory-bred "superfemales," each with two female chromosomes, can yield only female offspring—making them extremely useful in building a nonbreeding population.

Current methods to produce superfemales are inefficient. By implanting cells from a male's androgenic gland, Sagi and his colleagues sparked the transformation of superfemales physically into males, the first instance of male *M. rosenbergii* that completely lack male chromosomes. These prawns can then easily contribute their female chromosomes to new generations of superfemales. The process was detailed in August in *Scientific Reports*.

All-female prawn populations are particularly useful, scientists say. "Female prawns are more docile and less cannibalistic" than males, says Susanne Sokolow, a disease ecologist and veterinarian at Stanford University, who has worked with Sagi on related research. "They grow more evenly, potentially providing a more consistent product for harvest"—meaning local communities could use them for food, as well as snail control.

The snails that carry the schistosomiasis parasite live in southern and sub-Saharan Africa, parts of Southeast Asia, South America, the Middle East and some Caribbean islands. Within hours of touching snail-inhabited water, an infected person can suffer symptoms, including fever, cough, abdominal pain and diarrhea. The disease can also become chronic and lead to liver and kidney failure, bladder cancer and ectopic pregnancies. The World Health Organization reports that 220.8 million people required preventive treatment for schistosomiasis in 2017.

Deploying all-female prawns in addition to traditional disease treatment is an interesting strategy, but rigorous testing is needed, cautions David Rollinson, director of the Global Schistosomiasis Alliance, who was not involved in the study.

Rollinson says establishing the habitats in which the prawns could survive and determining how often more must be added should be top concerns. Sokolow adds that environmental ministries must coordinate on which types of monosex population they introduce. "Otherwise," she says, "the environmental benefits to prevent local invasive establishment would be hard, if not impossible, to maintain." —*Jillian Kramer*

PONGSAK POLBUPHA *Alamy*

Shifting Tactics on Alzheimer's

After a string of drug failures, it's time to look beyond targeting amyloid

By Claudia Wallis

For more than 25 years one idea has dominated scientific thinking about Alzheimer's disease: the amyloid cascade hypothesis. It holds that the disorder, which afflicts about one in 10 Americans age 65 or older, is caused by a buildup in the brain of abnormal amyloid-beta protein, which eventually destroys neurons and synapses, producing the tragic symptoms of dementia. There's plenty of evidence for this. First, the presence of sticky clumps or "plaques" containing amyloid is a classic hallmark of the disease (along with tangles of a protein called tau). It was what Alois Alzheimer saw in the autopsied brain of patient zero in 1906. Second, families with inherited defects in amyloid precursor protein (APP) or in genes encoding proteins that process APP are plagued by early-onset Alzheimer's. Third, mice genetically engineered to churn out excess amyloid tend to develop memory problems and do better when the amyloid pileup is stopped.

This evidence and more has led grant makers and drug companies to pour billions of dollars into amyloid-targeting therapies. More than a dozen have been tested, and one by one they have flopped. One of the biggest heartbreaks came last March, when a promising antibody to amyloid, called aducanumab, performed no better than placebo in patients with very early Alzheimer's.

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*.

Meanwhile researchers pursuing nonamyloid approaches were often left out in the cold, struggling to get grants and to have their work published. Science journalist Sharon Begley spent more than a year reporting on the lost opportunities in an article for the Web site Stat entitled "The Maddening Saga of How an Alzheimer's 'Cabal' Thwarted Progress toward a Cure for Decades." Begley notes that the amyloid crowd was "neither organized nor nefarious," but its outsized influence stifled other avenues of investigation.

And there are so many avenues! Genetic and other evidence points to inflammation and immune dysregulation as big contributors to the disease—and likely targets for therapy. The same goes for vascular issues. Other suspected pathways include changes in how the brain handles lipids, glucose, protein folding, communication with gut microbes and a possible role for viruses. How and if this dizzying array of pathways might intersect is unknown. "I don't think there's an obvious linear way to put these pathogenesis stories together where A causes B and B causes C," says Sam Gandy, director of the Center for Cognitive Health at the Icahn School of Medicine at Mount Sinai.

In choosing targets for intervention, "we can't pick one system," says Mary Sano, director of Alzheimer's disease research at Mount Sinai. "We have to try as many shots on goal as possible."

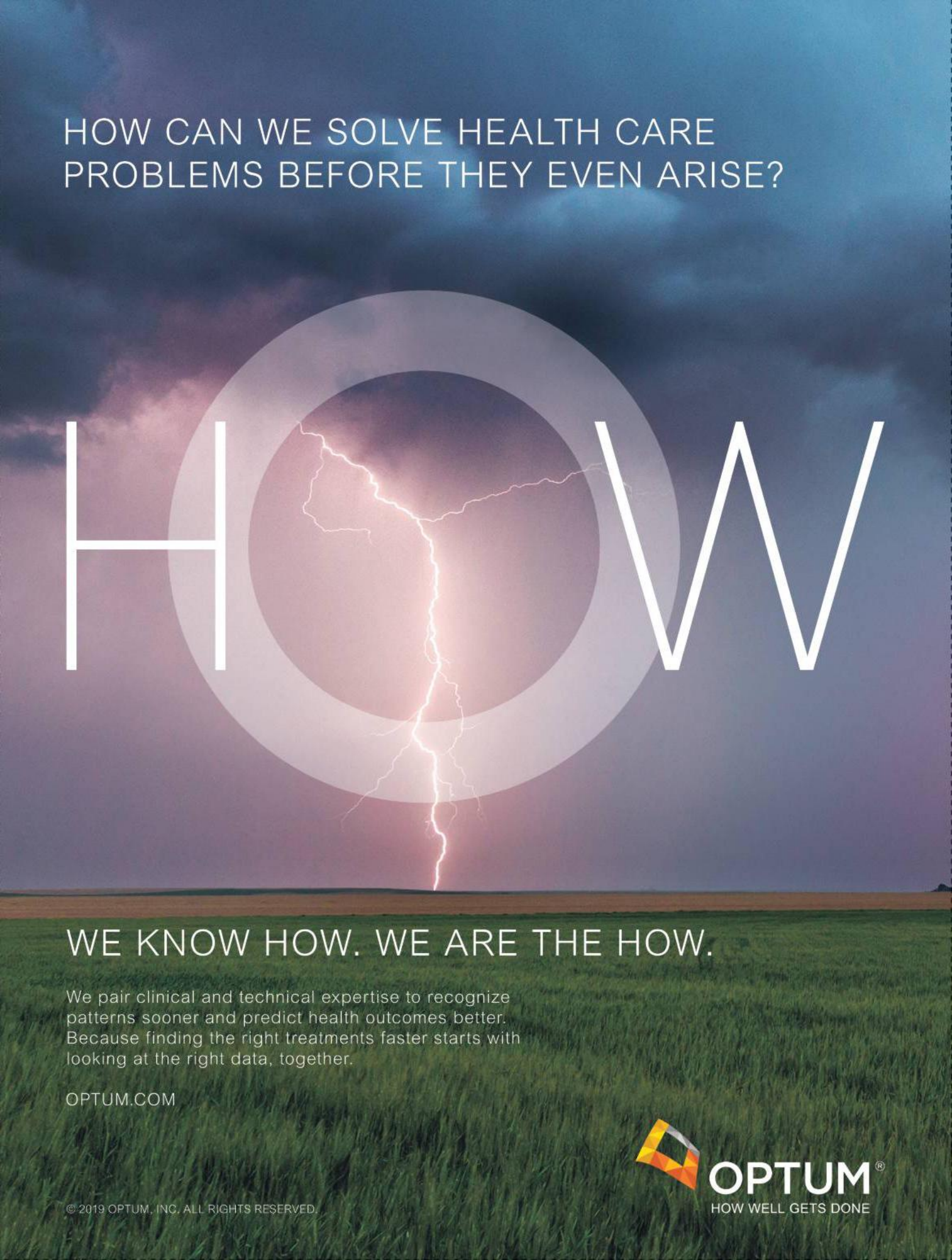
Gandy and his colleagues are pursuing several. In an intriguing 2018 paper, they showed that certain types of herpes simplex virus are overrepresented in Alzheimer's-affected brains and might influence dementia-related human genes. "We are still grappling with how to understand it," Gandy says. He is also testing a molecule called BCI-838 that promotes the growth of synapses in the hippocampus and improves brain function in rodent models of Alzheimer's. Synapse preservation is probably the key end point in beating back dementia.

Currently 96 different agents are in clinical trials aimed at altering the course of Alzheimer's, according to a 2019 analysis. Sixty percent target pathways other than amyloid. "Right now this diversity is the most important imperative," says Richard Hodes, director of the National Institute on Aging (NIA)—the top public funder of Alzheimer's research. In October the NIA announced a new $73-million effort to speed and diversify drug discovery.

Still, the NIA is not giving up on antiamyloid drugs. Hodes believes they may prove useful in staving off dementia in people at high risk for early-onset Alzheimer's, such as those with inherited mutations or Down syndrome. Blocking amyloid may be less crucial or insufficient for those with the more common version of the disease. Such people typically have vascular lesions in the brain in addition to plaques and tangles, and they may have other age-related changes that have little to do with amyloid. Some may have look-alike forms of dementia, including two newly proposed types known as LATE and SNAP. Ultimately, thwarting what we broadly call Alzheimer's is likely to require more careful diagnosis and, Sano says, "a more personalized approach."

In the meantime, there are a few things we all can do that might help preserve our brains: Manage blood pressure. Try cognitive training. Get serious about regular exercise. And, Hodes would add, please volunteer for clinical trials. SA

Illustration by Celia Krampien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Learning to Love Plastic

In some ways, it can actually be *good* for the environment

By Wade Roush

"Biodegradable" plastic doesn't do what you think it does. Your paper or metal straw takes only a tiny sip at the problem of plastic pollution. And your supposedly eco-conscious cloth grocery bag is more damaging to the environment than conventional plastic bags—unless you reuse it literally thousands of times. In other words, many of our ideas about plastic and the environment are confused. And that may be getting in the way of the fight against global warming.

Take the ruckus over single-use plastic bags and straws, which the conservative British magazine *The Spectator* predictably but correctly pegged as a "moral panic." The hullabaloo has spurred restaurateurs to roll out cups and utensils made from biodegradable materials such as polylactic acid (PLA), a polyester derived from starchy plants, including corn and sugarcane. The popular myth is that you can safely toss such items onto the forest floor or into the ocean, and microbes will break them down into raw materials that will magically be reborn as daisies or seahorses.

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

Not so much. In America and Europe, the technical standards for biodegradability are mostly about industrial composting. Put a plastic bag or bottle into a composting vessel, throw in some microorganisms and turn up the temperature to between 50 and 60 degrees Celsius (122 and 140 degrees Fahrenheit). If 90 percent of the material is released as carbon dioxide within 180 days, then you get to call the item "biodegradable" or "compostable."

In other words, a biodegradable material is one deliberately designed to *dump its carbon into the atmosphere* at the end of its life cycle. Even worse, if biodegradable plastic ends up in an oxygen-deprived landfill rather than a composting facility, anaerobic decomposition will turn it into methane, a gas that warms the planet from 34 to 86 times as much as carbon dioxide. And if you dump biodegradables into the ocean, they break up into tiny bits that choke marine animals long before they degrade appreciably.

Globally, we produce an eye-popping amount of plastic—some 380 million tons a year, virtually all of it from fossil-fuel feedstocks. So it's understandable why consumers would cling to the comforting 1980s-era idea that plastic can be engineered to disappear back into the environment. But the reality is that 60 percent of all the plastic ever produced is accumulating in landfills or as litter.

And from a climate scientist's point of view, that may actually be a good thing. Of course, it's a crime that so much plastic waste gets into terrestrial and aquatic ecosystems. But we won't outgrow our need for plastic anytime soon: for one thing, it substitutes for heavier materials in cars and planes, which saves fuel. On top of that—and this is my main point—plastic can function as an artificial carbon sink. If we're going to extract carbon from the ground at all, far better that it ends up in a soda bottle that will last 400 years than in the combustion chamber of your car.

If we want to save Earth, we should stop obsessing over biodegradability and invest instead in plastics that are *bio-based*. Plants use photosynthesis to convert water and CO_2 from the atmosphere into sugars, starch and cellulose, all of which can be processed to make plastics. PLA is one of those, but it's designed to be composted, which makes it carbon-neutral at best. The most exciting work in this area focuses on nonbiodegradable plastics such as polyethylene terephthalate (PET), which Coca-Cola uses in its PlantBottle. The current version, introduced in 2009, uses PET that is 30 percent plant-based. Both Coca-Cola and Pepsi have announced bottles made from 100 percent plant-derived PET, although neither has a market-ready version yet.

The United Nations Intergovernmental Panel on Climate Change points out that to limit global warming to 1.5 degrees C above preindustrial levels, we may need to remove tens to hundreds of gigatons of CO_2 from the atmosphere, ideally by 2050. If the world fully converted to nonbiodegradable bioplastics starting in 2020, the carbon sequestered over the next 30 years could amount to more than 10 gigatons—which would be a good start. When it comes to plastic, it's time to think more flexibly. SA

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Illustration by Jay Bendt

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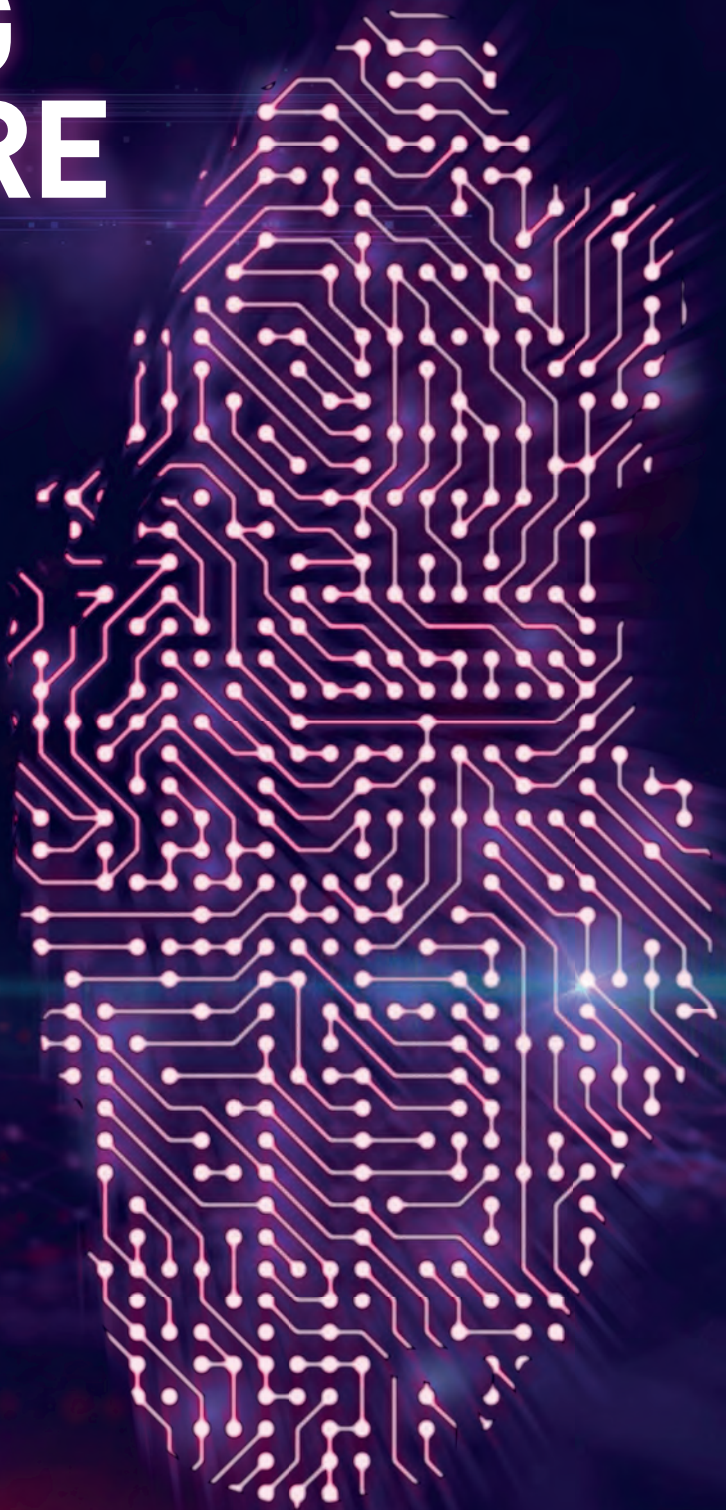

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Innovation Is for Life

Encouraging an innovation mindset and seeing ideas through to fruition is central to the Qatar Science & Technology Park. Because of that, in Qatar, the attitude of can-do and will-do is growing.

Innovation at QSTP is helping to keep people safe.

For some people making innovation happen is a way of life.

QSTP's environment fosters impact in the tech world.

Virtually every week, we're told about the necessity of innovation and how it's the solution to all our problems and challenges. Even then, because we are now so used to technology, it's debatable how often we actually think about how innovation happens, and the real impact it has on our everyday lives.

For some people, however, making innovation happen is a way of life. These are the people who recognize that a need exists, that it isn't being addressed and that they can be the solution — the change they want to see happen. In Qatar, that mindset of can-do and will-do is growing.

One of the key reasons for its growth is the support that the Qatar Science & Technology Park (QSTP) provides to local tech startups that spotted a gap in the market, whether it's through facilities, connection to international innovation ecosystems, funding or the availability of seasoned experts who can help keep an idea on the road to reality. It's this support that has allowed innovations like Stellic, which started life as a student project, to reach the point where it's being used in 15 universities across Qatar, Mexico and the United States.

Three students at Carnegie Mellon University in Qatar (CMU-Q) — one of the branch campuses of top international universities based at the Qatar Foundation, where QSTP is also housed — realized during their course that they, and students everywhere, would benefit from a one-stop shop for academic planning, data analytics and career navigation. Essentially, they wanted to help students graduate on time.

Out of this emerged Stellic, a fully integrated portal that became a tech business at QSTP, where the incubation space, financial backing and access to expertise and mentorship that the team received are cited as critical factors in its international success. "Without QSTP and Qatar Foundation," says founder and CEO Sabih Bin Wasi, "there's a strong possibility Stellic would not exist today."

The door to impact in the tech world that QSTP opens has also been walked through by Meddy. Qatar has a wealth of medical practitioners but it used to be difficult for people to find the right one for them.

So, a team of four CMU-Q graduates saw an opportunity to develop an online platform, Meddy, to help people make informed decisions about where to seek healthcare, based on knowledge and user reviews rather than guesswork. Meddy currently provides information on over 2,000 doctors from 250 private clinics, including clinic hours, medical credentials, languages spoken and insurance guidance. It's made people's lives easier.

As has Bonocle, albeit in a different way. The digital age has risked leaving millions of visually-impaired people feeling left behind in education, at work and during social activities. A team of Qatar-based innovators wanted to change this.

That's why they created a revolutionary, pocket-sized gadget that enables the visually impaired to read their emails, texts and social media feeds on phones and tablets. The size of a computer mouse, Bonocle works by transmitting digital content, via Bluetooth, to a receiver, which then converts it into braille.

QSTP PROVIDES SUPPORT TO THOSE LOCAL TECH STARTUPS THAT SPOTTED A GAP IN THE MARKET

Devised by three engineers and incubated at QSTP, the device is designed so that it cannot only be used to read content in real time, but also to store books in a braille library, meaning that they can be called up and read at leisure. As Ramy Abdulzaher, one of the team behind the device, explains: "Bonocle is much more portable and follows a design concept that integrates the visually-impaired community into society, rather than segregating them into an outlier group."

Innovation at QSTP is also helping to keep people safe. Subol, a Qatari technology startup, has created the Samam LP gas detector for homes and commercial properties, having conducted research that suggested that around 35% of homes in Qatar have suffered from gas-leakage incidents caused by human error.

A smart sensor, Samam is designed to detect these leaks and, via Bluetooth, enable the user to close the regulator valve with an app on their phone. "Because it falls under the Internet of Things, it means users can control their gas system from outside their homes, setting their minds at rest by giving them prompt notification of any problems through a secure, reliable network," says Saleh Safran, Subol's CEO.

"It also has benefits for campers who are using gas, as some of its functions can still be used without WiFi connectivity."

All these innovators, and the solutions they have developed, illustrate exactly how, every day and in many ways, innovation is improving people's lives — and all it took was the drive and courage to act on an idea. ■

TURNING CARBON LIABILITIES INTO ASSETS

What if you could take the world's most pressing challenge and turn it into an opportunity? That's the kind of inventive thinking happening right now in Qatar.

Researchers have now developed a method to remove carbon dioxide (CO_2) from the process of energy production and turn it into carbon nanotubes (CNTs) — essentially a rolled sheet of graphene, sometimes called the "miracle material." CNTs are being planned for use in a bewildering array of applications, from photovoltaics and batteries storing renewable energy to — one day perhaps — a space elevator.

Qatar is one of the world's top producers of natural gas — and unfortunately, the CO_2 that comes with processing it into usable products. But a novel process developed by Texas A&M University at Qatar could help Qatar process its natural gas while reducing it's carbon footprint. In Qatar, this could quite possibly give birth to an entirely new industry of producing high-quality industrial materials that feed a range of vital industries.

Developed in Qatar, the CARGEN reactor technology was conceived and designed by Nimir O. Elbashir and his research team at Texas A&M's Qatar campus in collaboration with Mahmoud M. El-Halwagi and his co-worker Debalina Sengupta from the Artie McFerrin Department of Chemical Engineering at Texas A&M's main campus in College Station, Texas (USA). This technology is believed to be the first of its kind that processes natural gas and captured CO_2 to produce both syngas — a valuable precursor to numerous hydrocarbon feedstocks that drive Qatar's economy — and high-quality solid CNTs. Unlike conventional processes, this method doesn't release more CO_2 into the atmosphere.

Elbashir's research focuses on converting natural gas into valuable hydrocarbon products, including ultraclean fuels or useful chemicals, in a process called gas-to-liquid conversion, or GTL. A major drawback of GTL processing is that it produces a lot of CO_2, which increases Qatar's carbon footprint and has led to the tiny country being named the world's leading producer of CO_2 per capita.

Under the umbrella of the Texas A&M University Engineering Experiment Station (TEES) Gas and Fuels Research Center (GFRC) headquartered at the Qatar Foundation, Elbashir and researchers at both campuses have focused on how to reduce CO_2 emissions and reduce Qatar's carbon footprint. Elbashir directs the GFRC, one of the largest TEES research centers and a major initiative, bringing together 32 multidisciplinary scientists and professors from Texas A&M's campuses in Texas and Qatar, all working in the same area but from different angles to speed up technology development in natural-gas processing.

CARGEN WAS DEVELOPED TO ADVANCE THE DRY REFORMING OF NATURAL GAS

The CARGEN — or CARbon-GENerator — technology was developed to advance the dry reforming of natural gas, which is especially attractive as it converts methane and CO_2 (both greenhouse gases) through a reactor to produce syngas, which is a mixture of carbon monoxide and hydrogen that is then processed to make liquid hydrocarbons and ultraclean fuels. This process, however, requires a lot of heat to drive the chemical reactions. This heat — the necessary reactions happen at more than 1,000° Celsius — usually comes from burning fuels, which emits even more CO_2.

Elbashir's team has designed the novel CARGEN reactor, a second reactor added to the reforming process, along with a catalyst to drive the chemical reactions to produce expensive CNTs and syngas from CO_2 and methane. These high-quality CNTs can be used in several industries in Qatar, including

Image: ©Moofushi - stock.adobe.com

Researchers have focused on how to reduce CO_2 emissions and reduce Qatar's carbon footprint.

steel and cement, while the syngas can be turned into ultra-clean fuels and value-added products. The process can be driven by either electric or solar power, eliminating the need to burn fuel and thereby resulting in much lower CO_2 emissions than conventional technologies.

"We are making Qatar CO_2 emissions into two products that are important to the economy and will broaden the role of hydrocarbons in Qatar's manufacturing facilities," Elbashir said. "CNTs are very expensive and extremely versatile, and can be used to manufacture products such as computers and other high-quality materials. And at the same time, we are also producing syngas, which can then be used to make the chemicals Qatar's processing industries rely on."

The CARGEN reactor is a result of a nearly US$5 million Exceptional Proposal grant from the Qatar National Research Fund's National Priorities Research Program, said Ph.D. student Mohamed Sufiyan Challiwala, who has been a significant contributor to the project. Challiwala started working on the project as a master's student in chemical engineering at Texas A&M at Qatar before pursuing his Ph.D. through the main campus and beginning his doctoral research in Qatar.

Challiwala said, "CARGEN provides a new perspective on the implementation of natural gas–reforming technology. Rather than considering carbon or 'coke' formation as a process challenge, CARGEN treats it as an opportunity to convert at least 65% of CO_2 per pass with 50% lower energy requirements. Most importantly, it produces CNTs and fibers that are considered to be next-generation materials with tremendous applications. Because of its uniqueness, this process is now patented with the support of Qatar Foundation."

Hanif Choudhury, a research scientist in Elbashir's group, said, "The CARGEN concept of CNT generation has been validated at the micro-, milli- and gram scales, with the quality of the carbon nanotubes controlled and preserved at every scale."

The next step is partnering with industry collaborators to scale up the technology even further.

"This is a major achievement in the way people will look at CO_2 utilization in the future," Elbashir said. "It's a homegrown technology developed in Qatar based on the interest of Qatar to utilize and sequester CO_2 and reduce the country's carbon footprint. We are producing material out of it, not just liquid fuel that will be burned to produce something else or power a car, for example, which then puts CO_2 back into the atmosphere. If we can scale up this technology, it will be a turning point for everyone worried about CO_2."

4 SURPRISING USES FOR CARBON NANOTUBES

Carbon nanotubes (CNTs) are hollow cylinders made of graphite carbon atoms at nanoscale (10^{-9} meters), which is much smaller than the width of a human hair. Discovered more than 50 years ago, CNTs could revolutionize the way that we make — well, everything. So how could CNTs be used?

SUPER-POWER COMPUTING

Researchers have found ways to "unzip" CNTs into atom-thick sheets of graphene. Like silicon, graphene is a semi-conductor. With their nanoscale size, CNTs can pack much more computing power in one. They could even be used as "quantum wires" able to switch a single electron.

SOLAR POWER

Researchers have been exploring ways to use this material to significantly increase the efficiency of photovoltaic cells. In addition, a team at the Massachusetts Institute of Technology pioneered a way to use CNTs to store 10,000 times more energy with solar thermal systems than with previous methods.

MOLECULAR SYRINGES AND CANCER TREATMENT

Biotechnology researchers have been finding ways to exploit CNTs to inject drugs or genes into individual cells. In one study, CNTs were injected into kidney tumors in mice and then a near-infrared laser was aimed at the cancer cells, making the CNTs vibrate. With the highest "dose" of CNTs and 30 seconds of laser light, the tumors disappeared in 80% of the mice.

SPACE ELEVATOR

Because CNTs are both strong and lightweight, researchers have explored ways to create extremely tough and flexible materials from them. Some experts imagine that 62,000-mile-long cables made of CNTs stretching out of the atmosphere and connected to a geosynchronous "captured" asteroid could be used to lift people and supplies from the Earth's surface and into orbit for far less expense and risk than using traditional rockets.

An LNG carrier costs at least $400 million, and it has to dock at a port that is equipped to take liquefied gas.

WORKING TOWARDS CLEANER FUEL

Being one of the world's leading producers of natural gas and exporters of liquified natural gas, Qatar is looking at ways to turn natural gas into higher value products, such as clean diesel fuel and lubricants. The peninsular country is also investing in efforts to make the process of extracting and harvesting natural gas more efficient with less impacts on the environment.

Consider it a case of unintended consequences. In the 1990s, governments across Europe were looking at easy ways to reduce greenhouse-gas emissions to meet their Kyoto Protocol targets. One solution was to convert their country's fleets of cars and trucks from gasoline to diesel fuel. In so doing they could reduce carbon dioxide (CO_2) by 15% for every mile driven. Nobody thought about the particulate and nitrogen dioxide (NO_2) pollution this would cause in the central cities. Diesel engines discharge 22 times more fine particulates than gasoline engines and these can cause pulmonary problems particularly in young children. Asthma attacks are now the number one cause of emergency room admissions for children in London.

Halfway across the globe a solution to this problem was taking shape, though no one knew it at the time. Scientists at the Qatar Science and Technology Park (QSTP), part of Qatar Foundation, began looking at ways to turn natural gas into higher value products, such as clean diesel fuel and lubricants.

As one of the world's leading producers of natural gas and exporters of liquified natural gas (LNG), Qatar has attracted many of the industry's key players. Researchers in the private sector and academia have also come to Qatar, working to make the process of extracting and harvesting natural gas more efficient and lessen impacts on the environment.

The process of investing in further research and natural gas production is tied to the economic cycle and the price of oil and gas.

"The key to investing in GTL [gas-to-liquid] technology is to build the plant when the price of oil is going up," says Nimir Elbashir, author of *Natural Gas Processing from Midstream to Downstream* (Wiley, 2019) and director of Texas A&M's Engineering Experiment Station's Gas & Fuels Research Center based in Qatar and Texas. "Qatar, Uzbekistan, Kazakhstan and Nigeria are geographically perfect for GTL production because the feedstock is right there and effectively free."

Before LNG was first exported from Qatar in 1996, an LNG terminal had to be built that would have cost, in today's money, over US$10 billion. An LNG carrier costs at least $400 million, and it has to dock at a port that is equipped to take the liquified gas. An LNG import terminal costs about $500 million to construct. All of the capital-intense parts of the puzzle have to be in place before

Without the critical research undertaken at QSTP, neither GTL plants would have seen completion at such a rapid pace.

natural gas can be shipped internationally. That's why Royal Dutch Shell and its partner, Qatar Petroleum (QP), began looking at constructing a GTL plant in 2004. Shipping refined GTL diesel and lubricants to markets in Asia and Europe is a lot less capital intensive than transporting LNG.

Although the incentive to produce clean GTL diesel wasn't initially environmentally driven, the timing of the completion of both major projects happened to coincide with the peak of the clean-air crisis in European cities. Clean GTL diesel emits 70% less NO_2, is sulphur-free and has virtually no particulate discharge.

Given the recent controversy about inaccurate emissions testing of diesel engines by Volkswagen and other manufacturers, public opinion about diesel has shifted in Europe. Nevertheless, retiring the diesel fleet will take at least a decade and particulate pollution in some Europe has led cities like Paris and London to ban traffic during critical periods of high pollution. One solution may be to switch to GTL diesel, which is why Pearl GTL is running at near capacity.

PEARL GTL AND ORYX GTL PLANTS PRODUCE ABOUT 140,000 BARRELS AND 34,000 BARRELS PER DAY RESPECTIVELY

Becoming the biggest GTL-producing country in the world required billions in investment but, more important, the research and innovation to make it possible. Royal Dutch Shell did have previous experience in GTL production in Malaysia, but the plant it opened in Bintulu, Malaysia, in 1993 is less than a tenth of the size of the Pearl GTL plant in Qatar and didn't require the full recycling of the water required to cool the production facility. Sasol's Oryx GTL plant was the company's first foray in the GTL production. Without the critical research undertaken at QSTP, neither venture would have seen completion at such a rapid pace. Royal Dutch Shell has more than 3,500 patents across all stages of the GTL process, including over 1,400 that were specific to Pearl GTL.

During the projected lifetime of the Pearl GTL plant, Royal Dutch Shell estimates it will have produced the equivalent of over one billion barrels of oil. On a cost basis, the plant can operate profitably as long as the price of Brent Crude is above $40 a barrel. Royal Dutch Shell invested $20 billion to construct the plant. The costs were recovered after six years of operation, and Pearl GTL is a major profit center for the company today. It produces the equivalent of 140,000 barrels of oil a day. Sasol's Oryx GTL plant produces 34,000 barrels per day

Even with the best research and development in the world, the economics of GTL production have to be right before profitability can be assured. That requires a sufficient disparity between the price of crude oil and natural gas.

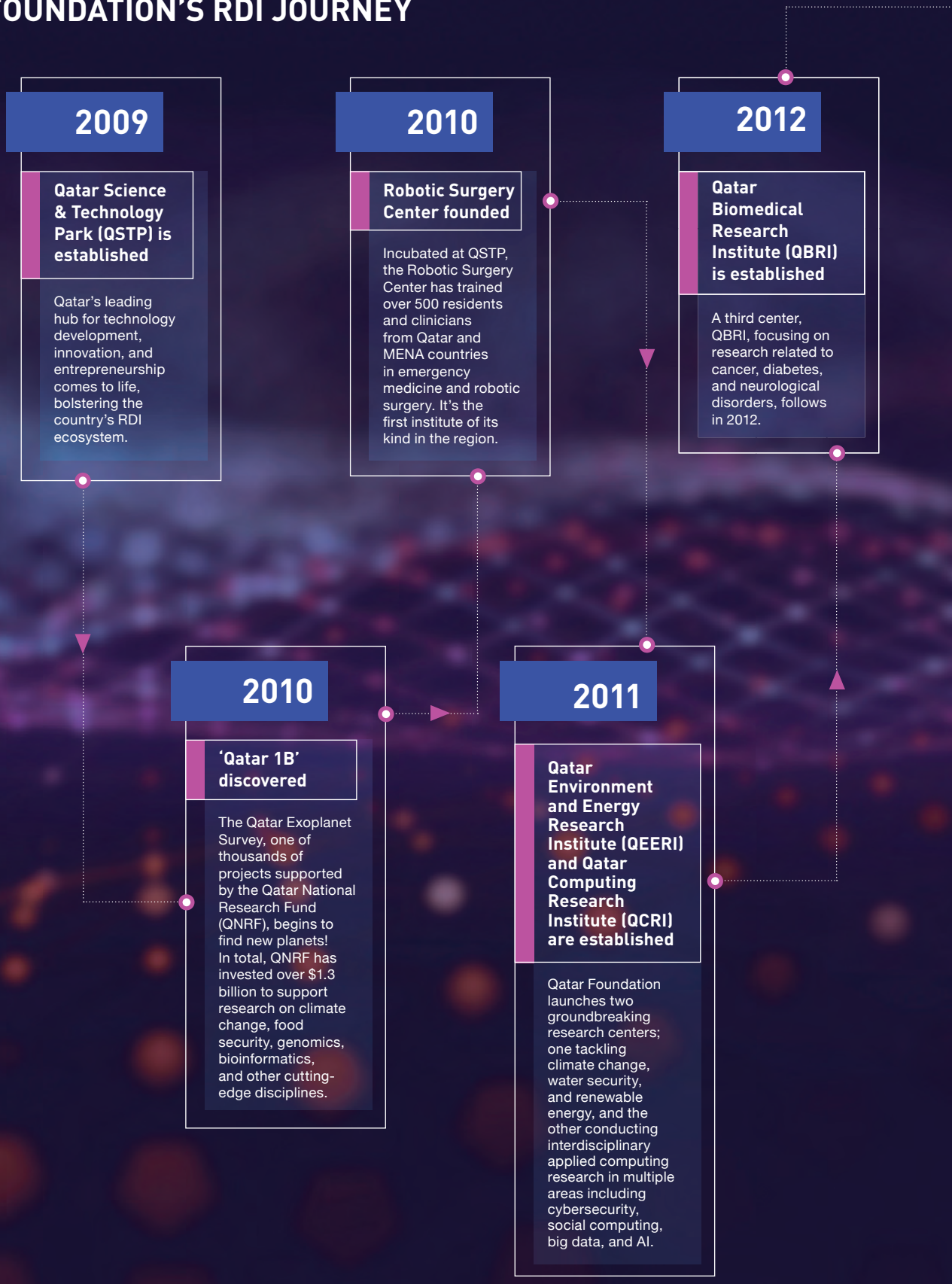
"In the U.S., it would make economic sense when the price of [West Texas Intermediate oil] is nearing $100 a barrel," adds Elbashir. "Shell recovered its $20 billion investment in the Pearl GTL plant in Qatar in just six years, and it is now one of its most profitable ventures in the world."

"In order for the process to be less expensive than processing petroleum-based refining for transportation fuels, the natural gas feedstock has to be essentially free — as in the case of Qatar, with a large stranded gas field," says David Ramberg, who authored the paper "The economic viability of gas-to-liquids technology and the crude oil-natural gas price relationship" (Energy Economics, 2019) while pursuing his doctorate at MIT. "This is one reason we don't see many other GTL plants operating in the world, and none that are as large as the Pearl complex."

The UN-backed Principles of Responsible Investing (PRI), representing investors with $86 trillion of assets under management, now estimates that demand for crude oil will peak in 2026 to 2028. Increasingly, large institutional investors — like Oljefondet, the $1 trillion sovereign wealth fund of Norway — have divested themselves of any investments linked to oil exploration, not out of environmental concerns but based upon research showing that the internal combustion engine will eventually be replaced by electric- or hydrogen-powered vehicles. They still have energy holdings in companies that are also developing renewable and less-polluting fuels.

Earlier this year, the UK parliament introduced the Air Pollution Bill, which would require the government to adopt tighter limits on air quality based on World Health Organization recommendations. Parliamentary committees heard testimony that the pollution in the UK's major cities cuts short the lives of 36,000 people a year, costs the economy £20 billion annually in healthcare and impacts on businesses and, if left unchecked, would cause 2.4 million new cases of disease in the next 16 years. Until electric vehicles begin to make up the majority cars and trucks on the road, the world will need cleaner solutions. And researchers in Qatar are working to make GTL diesel a viable alternative. ■

FROM IDEA TO IMPACT — QATAR FOUNDATION'S RDI JOURNEY



2013

Artificial Intelligence for Digital Response (AIDR) launched

Created in partnership with the UN at QCRI, the AIDR program helps direct assistance to those hardest-hit by disasters, using machine learning algorithms to scan social media data.

2016

Carbon-Negative Concrete developed at QSTP

The QSTP-based Gulf Organization for Research & Development has taken outputs from water desalination processes and turned it into an alternative to normal concrete that isn't just carbon neutral–it's carbon negative!

2017

Arab Innovation Academy established

The first Arab Innovation Academy is held at QSTP, which partners with the European Innovation Academy to run the largest entrepreneurship boot camp in the Middle East and North Africa region–challenging and supporting participants to create a new startup in just 10 days.

2017

Qatar Genome Research Consortium is initiated

The Qatar Genome Research consortium is launched with more than 130 local and international researchers to collaborate on precision medicine research. To date, the Qatar Genome Project has processed over 10,000 whole genome sequences, positioning Qatar as a leader in precision medicine globally.

2018

First Qatari separation of conjoined baby twins

Sidra Medicine–a pioneering women's and children's hospital and research center, in Doha–performs the first successful surgical procedure in Qatar to separate conjoined twins, signifying a powerful milestone in bringing world-leading medical techniques to the region.

2019

Technology Venture Fund is set up

A new $50 million fund is launched by QSTP to help startups in the region scale their business innovations through Series A and Series B funding.

TAKING INNOVATION TO THE EXTREME

10 days. One challenge. Through the Arab Innovation Academy — organized by Qatar Science & Technology Park and the European Innovation Academy — a wave of exciting new startups, and a new global tech-entrepreneurship network, is emerging.

Innovation cannot only inspire and transform; it can unite. And its ability to bring together people from different countries and diverse backgrounds, but with a collective eye on helping to shape the future, has shone through the Arab Innovation Academy (AIA) — a groundbreaking showcase of the extent of pan-Arab tech-innovation talent.

Organized by the Qatar Science & Technology Park (QSTP) — part of Qatar Foundation Research, Development and Innovation — in collaboration with the European Innovation Academy (EIA), AIA is the largest entrepreneurship boot-camp of its kind in the region. With its third edition now on the horizon — it will be held in January 2020, the program has so far challenged more than 300 aspiring tech entrepreneurs from universities across the Arab world not just to turn their idea into a viable startup, but to do it in just 10 days, and in teams whose members had never worked together before.

Using a unique, accelerated mode of experiential learning that provides authentic insight into what it takes to launch a new tech venture, the program places teams into a high-octane innovation environment: a real marketplace, with genuine customer feedback and the challenges that innovators around the world face every day. And it's also showing that, when it comes to innovation, there are no boundaries — in both a creative and a geographical sense.

"The first two editions of the Arab Innovation Academy have proved to be outstanding successes, as demonstrated by the high level of participation from 30 countries from across the region," says Yosouf Abdulrahman Saleh, Executive Director, QSTP.

"The upcoming edition of the program will provide a new batch of budding entrepreneurs with the opportunity to gain invaluable insights and guidance from leading Silicon Valley mentors and experts from the world's top corporations, who will help the aspiring participants launch their startups and market their tech products in Qatar and beyond."

The first and second editions of the two-week startup boot-camp featured 127 and 196 entrepreneurs, respectively, from Qatar and abroad, across a total of 34 teams. And one of the trends that emerged in the 2019 edition was greater participation in the program from young Arab women.

Meanwhile, the program has also broadened its reach beyond the Middle East and North Africa (MENA) region. In 2019, the future "techpreneurs" who took part included innovators from Russia and India, with whom Qatar has shared its two most recent Years of Culture. In 2020, this approach — blending the exchange of tech ideas with the exchange of cultural stories and experiences — will continue, as AIA welcomes participants from France.

Several participants have gone on to launch successful startups after completing the program, which aims to equip participants with the necessary skills and knowledge to pursue technology development and make a positive impact in the world through innovation.

The AIA's greatest impact is the different mindset it has instilled in its participants — a mindset of creative collaboration, built on diversity and the opportunity to speak freely about issues. "Before the AIA, I had many ideas that needed support and guidance, but they had not found the light of the day," says Lebanese student Dina Al Hajjar, an alumna of AIA 2018.

"And when I arrived at Qatar Foundation to take part in the program, I felt like I was in the right place — a place where innovation is born and where supporting talented young people is a priority."

By making the idea of "innovation" so accessible, AIA has demystified the aura around it, allowing participants to realize that there is no secret to the success of companies like Google or Uber. There are simply processes that, if followed in the right way, mean that these innovators can succeed as well.

"The key is to embrace the notion that knowledge is

Several participants have gone to launch successful startups.

AIA is the largest entrepreneurship boot-camp of its kind in the region.

THE AIA IS JUST ONE OF THE PATHWAYS OF SUPPORT THAT QSTP OFFERS TO TECH ENTREPRENEURS

organic and innate to us all," says Shaikha AlSubaey, who participated in the 2019 edition of AIA, and was named joint third-place winner.

On the final day of the AIA, a Grand Pitching Session sees participants live-pitch the startup ideas they had developed from scratch over the previous two weeks to an international audience of investors and experts.

As the organization behind the world's largest "extreme entrepreneurship" programs — organized every summer in France, Italy and Portugal — the EIA, a non-profit educational institution, allows aspiring tech entrepreneurs from around the world to access the support and mentorship necessary to launch a new startup in rapid time.

"Innovation distinguishes between leaders and followers," says Alar Kolk, president of EIA. "If you want to succeed, you should follow new paths. Innovation is not achieved by imitating the success of others; it's achieved by those who choose to risk failure in order to create something completely new.

"With the most innovative technology, including artificial intelligence and robotics, we are teaching entrepreneurship to students and young professionals as we truly believe that a new star will rise from Arab countries to disrupt economies and businesses in the future. We are providing the tools and cultivating a mindset of innovation among young people to challenge the world's biggest problems — problems that affect one billion lives every day. Here and now is the right moment and place to create our new future."

Looking ahead to the third edition of AIA, Saleh says, "At QSTP, the initiatives we have taken and the projects we are engaged in revolve around our commitment to the process of research, development and innovation. With leading programs like AIA, we encourage our talented youth to take the next step and propel their ideas to the stage of practical implementation.

AIA's greatest impact is the mindset it has instilled in its participants.

"We aim to develop an innovative mindset among our talented youth to nurture an unprecedented and competitive environment in the MENA region. More importantly, we believe that investment in our region's talent pool is the key to achieving long-term economic sustainability and prosperity."

The AIA is just one of the pathways of support that QSTP offers to tech entrepreneurs — both established and aspiring — across the MENA region and beyond. Its Innovation Mindset program, which targets university students, teaches them new skills and expertise in the field of innovation, entrepreneurship and product development. And it also includes Student Innovation Trips, where participants visit Silicon Valley and can enroll in the European Innovation Academy Summer Program. Meanwhile, its Summer Internship Program allows students to learn about how to develop a tech product.

In terms of accelerating innovation, QSTP's XLR8 program works with people who have a tech-based service or product idea, and are looking for mentorship, training and coaching, with the MENA Dojo — run in partnership with 500 startups — is open to tech startups that have previously raised funding from other investors, and are now preparing to scale up.

Once a startup has been established, the Research to Startup program at QSTP supports its entrance into the marketplace through enterprise creation. These promising tech startups have the choice of becoming part of QSTP's Incubation Center — a technology-focused incubation program that helps nascent tech ventures to grow by offering the facilities and support that remove many of the basic barriers facing many budding tech entrepreneurs, as well as access to a network of mentors, funding programs, training and prototyping facilities.

As capital is critical for startups and small to medium enterprises, QSTP offers two funding streams. Through the Product Development Fund, selected companies have access to funding of up to QAR 1.2 million; while the Tech Venture Fund allows tech founders and entrepreneurs to source seed-stage capital when they first embark on their entrepreneurial journey.

Put it all together, and it represents an complete ecosystem for innovation, research and tech entrepreneurship — within Qatar and beyond. ■

Images: ©Leo C.Bautista

QATAR WOMEN IN STEM

Arab women are thriving in science and math education but like women elsewhere, they lag when it comes to careers in these fields. As recent research shows, bridging this gap matters not just for women, but for the future of us all.

Here's a strange paradox: In the Middle East, where many countries face stark gender inequality, women earn more science and math degrees per capita than their counterparts in the United States and Europe. In fact, up to 57% of all STEM (science, technology, engineering and math) graduates in Arab countries are women, according to UNESCO.

Compare this with the United States, where women account for no more than 35% of all undergraduate degrees in STEM, or even the European Union, where there are roughly twice as many male graduates in STEM studies as there are female graduates.

On the other hand, take Qatar, a small country with a population of just 2.8 million. The country's first university, Qatar University, opened its doors only in 1973, with separate faculties for men and women. By 2012, there were almost twice as many female students enrolled in the university as there were males.

Bolstered by the country's fervor for higher education, more women are attending Qatar's private universities — and more are pursuing traditionally male-dominated career paths, including engineering and science. The Qatar Foundation's 3,000-acre Education City campus is home to eleven K-12 schools and nine leading universities — including branches of Georgetown, Cornell and Texas A&M. It also stands alongside a science and technology park, runs global innovation forums, and includes a modern art museum, start-up incubators and more.

Many of these Qatari campuses are already proving as big of a draw for women as their parent institutions. At Texas A&M University in Qatar, women account for 46% of the total student body; at Texas A&M's main U.S. campus, women account for 48% of the enrollment. "For people who have never been to the Middle East, they may well think women here are somehow oppressed, covered up and kept at a different level," said Lama Al-Oreibi, reservoir engineer at Royal Dutch Shell

and former student at Texas A&M University in Qatar. "But engineering and science are professions that are looked upon highly in this part of the world. I was encouraged by my family to pursue this path."

In contrast to stubborn stereotypes elsewhere, added Mashael Al-Sabah, a cybersecurity scientist at Qatar Computing Research Institute inside Education City, Qatari people don't generally perceive men to be better than women at science and math.

This sentiment was echoed by Rana Dajani, a Jordanian molecular biologist and associate professor at Hashemite University, who is currently writing a paper about this subject, slated for publication later this year. "[Middle Eastern] women's attraction to STEM studies is something that runs much deeper than the region's modern history," she said. "A theme in Islamic culture is that you are respected for your mind. Therefore, if you go into science, this is something respectful, because it celebrates your mind — and this was the same for boys and girls."

For Veronica Bermudez, senior research director for energy at Education City's Qatar Environment and Energy Research Institute, the real issue comes after university, when highly educated women enter the job force — or rather, don't. In fact, although Qatar's female labor-force participation ranks higher than the world average, the proportion of Qatari women in the work force still lags slightly behind that in developed countries. "In the renewable energy sector, for example, the growth expectations in terms of jobs are going to triple in the next 10 or 20 years," said Bermudez. "We really need to engage more females in STEM to be able to address that challenge."

Despite regional differences in female participation in STEM education, getting more women into science and math jobs remains a challenge across the world. High female participation in STEM education doesn't necessarily translate into employment. Across Organization for Economic Cooperation and Development (OECD) countries, 71% of male graduates in STEM subjects work as professionals in STEM fields, compared with only 43% of female graduates.

GETTING MORE WOMEN INTO SCIENCE AND MATH JOBS REMAINS A CHALLENGE ACROSS THE WORLD

For Arab women in particular, a number of barriers block them from finding employment in their respective STEM fields. UNESCO's "Science Report: Towards 2030" points to everything from low awareness about what a career in STEM entails to a lack of female role models and a family bias against working in mixed-gender environments. A dearth of suitable positions can hold women back, too. "We simply don't have a market like Silicon Valley," said Sana Odeh, clinical professor of computer science at New York University in Abu Dhabi, who's working on a study on Middle Eastern women's participation in STEM. "There aren't thousands of jobs that are opened up by these large companies."

Then, of course, there are the more universal issues, which for Dajani are every bit as important. "The workplace as we know it today was created around 100 or 150 years ago by men, for men," she said.

Anna Paolini, director of UNESCO's regional office in Doha, agreed: "We see willingness and interest from women to continue working, but once they get married many don't go back to work, and that's a loss for the system and for countries as small as Qatar."

This "loss" that Paolini pointed to takes a toll on the bottom line, too. A growing body of evidence shows that more diverse organizations enjoy greater creativity, stronger governance, better problem-solving skills and increased profitability. What's more, an International Monetary Fund report from this year states that the growth gains from adding more women to the labor force are larger than previously thought — closing the gender gap could increase GDP by an average of 35% for much of the developing world.

And nowhere is diversity so valuable as in scientific study itself, according to Andrei Cimpian, associate professor of psychology at New York University, who has conducted studies on gender stereotypes in STEM. "The reality of what scientists do is that they work in teams," he said. "They work for socially important goals that help humanity."

However, for Bermudez, the costs of a lack of diversity in STEM could be even greater than that. "Men and women see things from a different point of view, and if we keep this male dominance in STEM, we are skipping 50% of human resources around the world," she said. "With a diverse group, you have more opportunities to find the right way to solve problems."

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Qatar Science and Technology Park is a home for collaboration.

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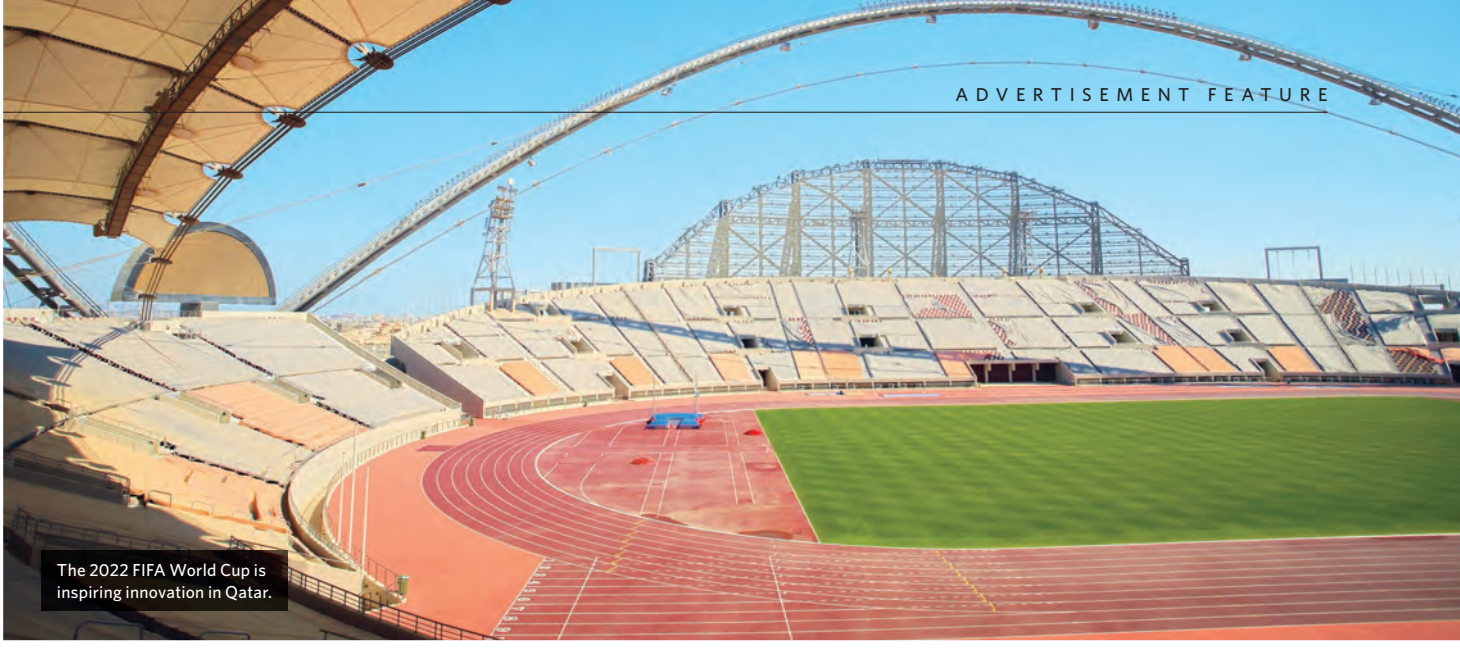

The 2022 FIFA World Cup is inspiring innovation in Qatar.

WORLD CUP INNOVATION

"Whenever you are asked if you can do a job, tell 'em, 'Certainly I can!' Then get busy and find out how to do it."

Theodore Roosevelt may not have had Qatar or soccer in mind when he said those words. But his can-do spirit is alive, well and getting ready for the world's premier sporting event.

When Qatar was named host of the 2022 FIFA World Cup, it signed up to a series of ambitious pledges that the tournament would be the most sustainable — and the most-connected — in history. Making those promises a reality has proven to be a significant spur to innovation in the small host country. Those innovations look not only to make the tournament a better experience for fans and the environment, but to benefit people in Qatar and beyond for years to come.

In 2009, the Gulf Organization for Research and Development (GORD), based at the Qatar Science and Technology Park, developed the green building Global Sustainability Assessment System (GSAS) standards that guided the design and build process for the eight FIFA stadiums. Adopted by the organizing committee and approved by FIFA after review by an independent expert panel, the GSAS standards have been effective in guiding stadium construction to outcomes. As a result, the stadiums will see an energy savings of 45% compared to being designed to meet standards set by the American Society of Heating, Refrigerating and Air-Conditioning Engineers, and they will use 44% less water compared to ones designed to International Plumbing Code standards.

Plus, the plans have won over some skeptics. "Purely in environmental terms," a *Guardian* online columnist wrote in September, "the blueprint of the first such showpiece staged in the Middle East not only looks miles ahead of the curve but a decent template for major 21st-century high-density sporting events."

Fans arriving in 2022 will be kept comfortable in other innovative ways, as well. The Qatar Mobility Innovations Center (QMIC) has used its Internet-of-Things platform to connect a series of sensors around Qatar's capital city that will make it easier for fans to plan the best route using real-time information about traffic, taxis, the new Metro system and even venue entrances and exits. Visitors

FANS ARRIVING IN 2022 WILL BE KEPT COMFORTABLE IN INNOVATIVE WAYS

will be able to download a custom smartphone app made by QMIC, also based at the Qatar Science and Technology Park, that will use this real time information to make their journey to stadiums much less stressful. The system was tested in May 2019 when fans travelling to the Amir Cup Final football match at the Zaha Hadid-designed Al Janoub Stadium were able to use an earlier version of the application, whether travelling by car or by the newly-opened Metro Red Line.

Connectivity innovations under development even extend to wearable electronics. Amine Bermak, a professor at Hamad Bin Khalifa University at the Qatar Foundation, is printing low-power sensors directly on fabric. The sensors will measure heartbeat, respiration and hydration in a snug-fitting shirt using an approach that connects each shirt via Bluetooth to others around it and ultimately to a base station. Currently in a pilot phase with wearables worn by construction workers and the cost of the low-power sensor at less than $20 per unit, Bermak envisions applications where the vital-signs data are used in real time for a variety of scenarios from athletes to hospital patients.

Qatar is making the most of its opportunity to innovate prompted by the World Cup. But the legacy of this culture of invention promises to endure long after the last soccer fan has left the final match in Lusail Stadium. ■

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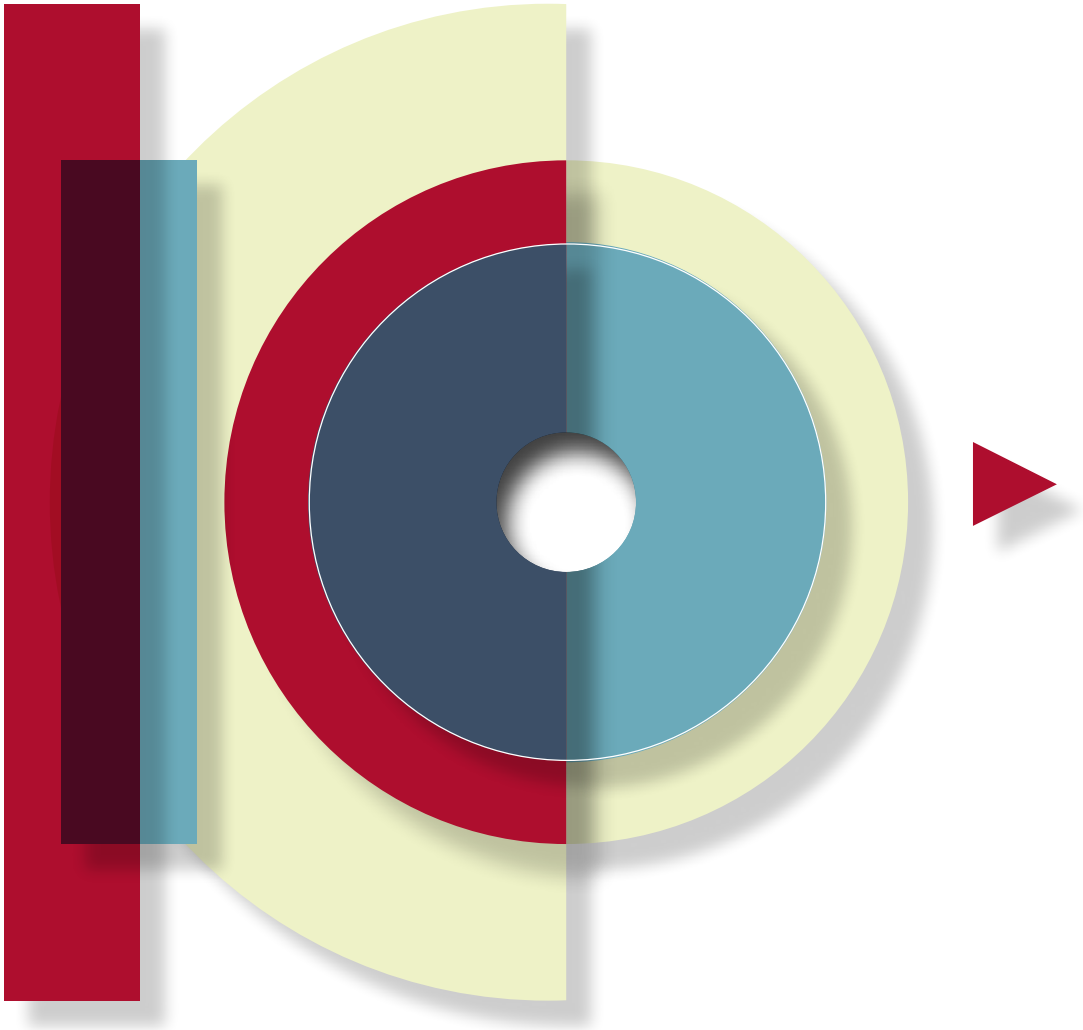

SPECIAL REPORT

TOP 10 EMERGING TECHNOLOGIES OF 2019

WORLD-CHANGING TECHNOLOGIES THAT ARE POISED TO RATTLE THE STATUS QUO

Illustrations by Vanessa Branchi

One day soon
an emerging technology highlighted in this report

will allow you to virtually teleport to a distant site and actually feel the handshakes and hugs of fellow cyber travelers. Also close to becoming commonplace: humanoid (and animaloid) robots designed to socialize with people; a system for pinpointing the source of a food-poisoning outbreak in just seconds; minuscule lenses that will pave the way for diminutive cameras and other devices; strong, biodegradable plastics that can be fashioned from otherwise useless plant wastes; DNA-based data-storage systems that will reliably stow ginormous amounts of information; and more.

Together with the World Economic Forum, *Scientific American* convened an international Steering Group of leading technology experts and engaged in an intense process to identify this year's "Top 10 Emerging Technologies." After soliciting nominations from additional experts around the globe, the Steering Group evaluated dozens of proposals according to a number of criteria: Do the suggested technologies have the potential to provide major benefits to societies and economies? Could they alter established ways of doing things? Are they still in early stages of development but attracting a lot of interest from research labs, companies or investors? Are they likely to make significant inroads in the next several years? The group sought more information where needed and honed the list in four virtual meetings.

We hope you enjoy the result, and we welcome your responses.

—Mariette DiChristina and Bernard S. Meyerson

1

ENVIRONMENT

BIOPLASTICS FOR A CIRCULAR ECONOMY

ADVANCED SOLVENTS AND ENZYMES ARE TRANSFORMING WOODY WASTES INTO BETTER BIODEGRADABLE PLASTICS

By Javier Garcia Martinez

Our civilization is built on plastics. In 2014 alone, industry generated 311 million metric tons, an amount expected to triple by 2050, according to the World Economic Forum. Yet less than 15 percent of it gets recycled. Much of the rest is incinerated, sits in landfills or is abandoned in the environment—where, being resistant to microbial digestion, it can persist for hundreds of years. Plastic debris accumulating in the ocean causes all kinds of problems, from killing wildlife when mistakenly ingested to releasing toxic compounds. It can even enter our bodies via contaminated fish.

Biodegradable plastics can ease these problems, contributing to the goal of a "circular" plastic economy in which plastics derive from and are converted back to biomass. Like standard plastics derived from petrochemicals, biodegradable versions consist of polymers (long-chain molecules) that can be molded while in their fluid state into a variety of forms. The options currently available—mostly made from corn, sugarcane, or waste fats and oils—generally lack the mechanical strength and visual characteristics of the standard kinds, however. Recent breakthroughs in producing plastics from cellulose or lignin (the dry matter in plants) promise to overcome those drawbacks. In an added boon for the environment, cellulose and lignin can be obtained from nonfood plants, such as giant reed, grown on marginal land not suitable for food crops or from waste wood and agricultural by-products that would otherwise serve no function.

Cellulose, the most abundant organic polymer on earth, is a major component of plant cell walls; lignin fills the spaces in those walls, providing strength and rigidity. To make plastics from those substances, manufacturers

must first break them into their building blocks, or monomers. Investigators have recently found ways to do so for both substances. The lignin work is particularly important because lignin's monomers are composed of aromatic rings—the chemical structures that give some standard plastics their mechanical strength and other desirable features. Lignin does not dissolve in most solvents, but investigators have shown that certain environmentally friendly ionic liquids (which are composed largely of ions) can selectively separate it from wood and woody plants. Genetically engineered enzymes similar to those in fungi and bacteria can then break the dissolved lignin into its components.

Companies are building on these findings. For example, Chrysalix Technologies, a spin-off from Imperial College London, has developed a process that uses low-cost ionic liquids to separate cellulose and lignin from starting materials. A Finnish biotechnology company, MetGen Oy, produces a number of genetically engineered enzymes that cleave lignins of different origins into components needed for a wide range of applications. And Mobius (formerly Grow Bioplastics) is developing lignin-based plastic pellets for use in biodegradable flower pots, agricultural mulches and other products.

Many hurdles must be overcome before the new plastics can be widely used. One is cost. Another is minimizing the amount of land and water used to produce them—even if the lignin comes only from waste, water is needed to convert it into plastic. As with any major challenge, the solutions will require a combination of measures, from regulations to voluntary changes in the ways society uses and disposes of plastics. Still, the emerging methods for producing biodegradable plastic offer a perfect example of how greener solvents and more effective biocatalysts can contribute to generating a circular economy in a major industry.

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2

ENGINEERING

SOCIAL ROBOTS

DROID FRIENDS AND ASSISTANTS ARE PENETRATING DEEPER INTO OUR LIVES

By Corinna E. Lathan and Geoffrey Ling

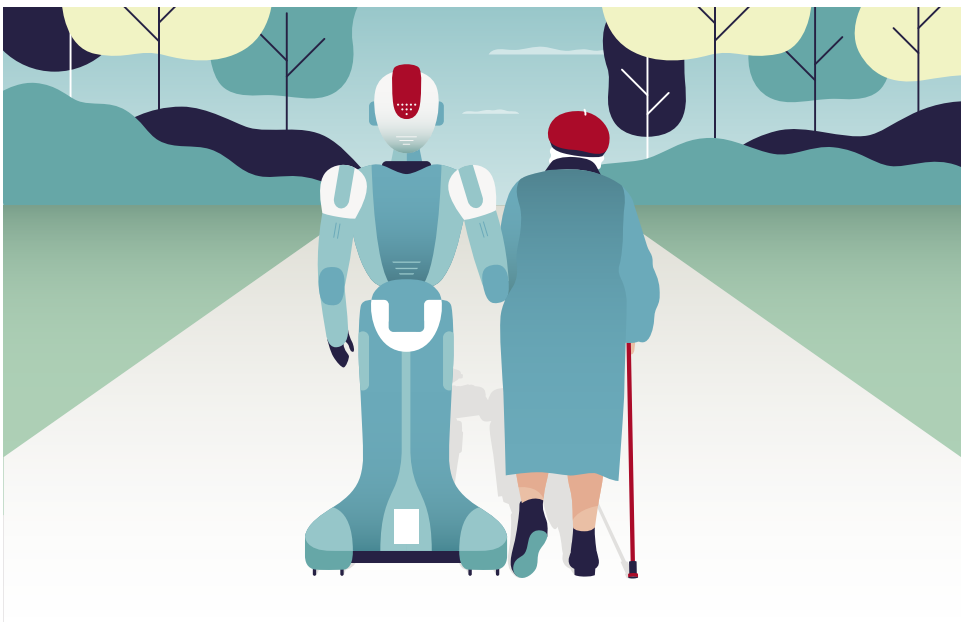
In industry and medicine, robots routinely build, break down and inspect things; they also assist in surgery and dispense prescription drugs in pharmacies. Neither they nor "social" robots—which are designed to engage with people and to elicit an emotional connection—behave like *The Jetsons'* maid, Rosie, or other beloved droids of fiction. Even so, expect social robots to become more sophisticated and prevalent in the next few years. The field seems to have reached a tipping point, with bots having greater interactive capabilities and performing more useful tasks than ever before.

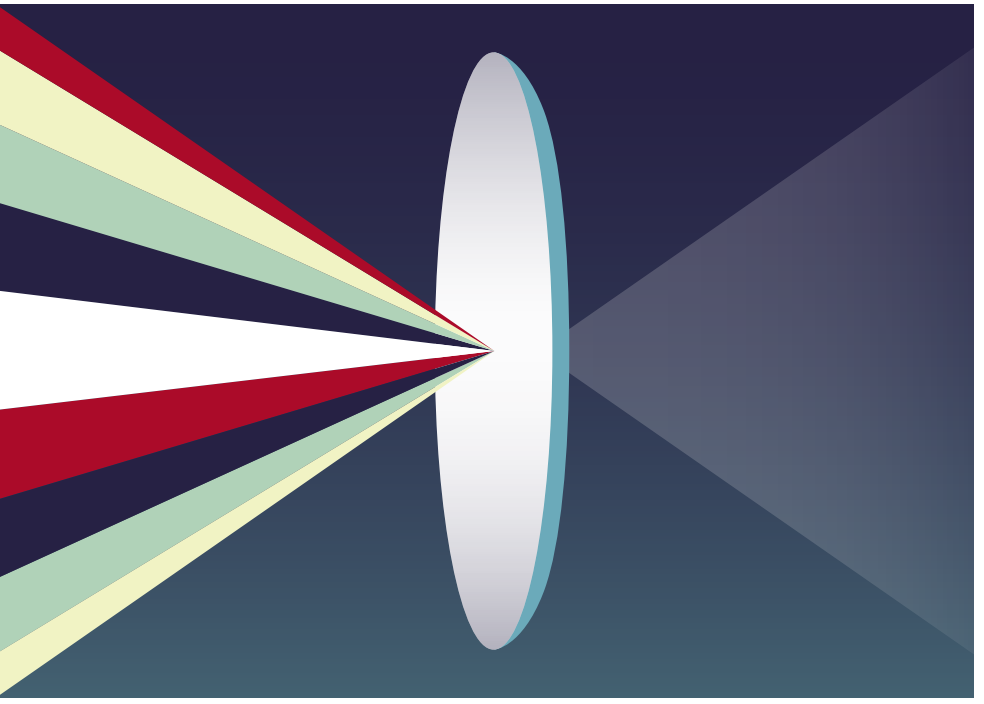
Like most robots, social robots use artificial intelligence to decide how to act on information received through cameras and other sensors. The ability to respond in ways that seem lifelike has been informed by research into such issues as how perceptions form, what constitutes social and emotional intelligence, and how people can deduce others' thoughts and feelings. Advances in AI have enabled designers to translate such psychological and neuroscientific insights into algorithms that allow robots to recognize voices, faces and emotions; interpret speech and gestures; respond appropriately to complex verbal and nonverbal cues; make eye contact; speak conversationally; and adapt to people's needs by learning from feedback, rewards and criticisms.

In consequence, social robots are filling an ever expanding variety of roles. A 47-inch humanoid called Pepper (from SoftBank Robotics), for instance, recognizes faces and basic human emotions and engages in conversations via a touch screen in its "chest." About 15,000 Peppers worldwide perform such services as hotel check-ins, airport customer service, shopping assistance and fast-food checkout. Temi (from Temi USA) and Loomo (Segway Robotics) are the next generation of personal assistants—like Amazon Echo and Google Home but mobile, providing a new level of functionality. Loomo, for instance, not only is a companion but also can transform on command into a scooter for transport.

Social robots have particular appeal for assisting the world's growing elderly population. The PARO Therapeutic Robot (developed by Japan's National Institute of Advanced Industrial Science and Technology), which looks like a cuddly seal, is meant to stimulate and reduce stress for those with Alzheimer's disease and other patients in care facilities: it responds to its name by moving its head, and it cries for petting. Mabu (Catalia Health) engages patients, particularly the elderly, as a wellness aide, reminding them to take walks and medication and to call family members. Social robots are also gaining traction with consumers as toys. Early attempts to incorporate social behavior in toys, such as Hasbro's Baby Alive and Sony's AIBO robotic dog, had limited success. But both are resurging, and the most recent version of AIBO has sophisticated voice and gesture recognition, can be taught tricks and develops new behaviors based on previous interactions.

Worldwide sales of consumer robots reached an estimated $5.6 billion in 2018, and the market is expected to grow to $19 billion by the end of 2025, with more than 65 million robots sold a year. This trend may seem surprising given that multiple well-funded consumer robot companies, such as Jibo and Anki, have failed. But a wave of robots is lining up to take the place of defunct robots, including BUDDY (Blue Frog Robotics), a big-eyed mobile device that plays games in addition to acting as a personal assistant and providing home automation and security.





3

ENGINEERING

TINY LENSES FOR MINIATURE DEVICES

THIN, FLAT METALENSES COULD REPLACE BULKY GLASS FOR MANIPULATING LIGHT

By Alberto Moscatelli

As phones, computers and other electronics have grown ever smaller, their optical components have stubbornly refused to shrink. Notably, it is hard to make tiny lenses with traditional glass-cutting and glass-curving techniques, and the elements in a glass lens often need to be stacked to focus light properly. Engineers have recently figured out much of the physics behind much smaller, lighter alternatives known as metalenses. These lenses could allow for greater miniaturization of microscopes and other laboratory tools, as well as of consumer products, such as cameras, virtual-reality headsets and optical sensors for the Internet of Things. And they could enhance the functionality of optical fibers.

A metalens consists of a flat surface, thinner than a micron, that is covered with an array of nanoscale objects, such as jutting pillars or drilled holes. As incident light hits these elements, many of its properties change—including its polarization, intensity, phase and direction of propagation. Researchers can precisely position the nanoscale objects to ensure that the light that exits the metalens has selected characteristics. What is more, metalenses are so thin that several can sit atop one another without a significant increase in size. Researchers have demonstrated optical devices such as spectrometers and polarimeters made from stacks of these flat surfaces.

In a major breakthrough last year, researchers solved a problem called chromatic aberration. As white light passes through a typical lens, rays of its varied wavelengths get deflected at different angles and thus focus at different distances from the lens; to fix this effect, engineers today need to layer lenses in a finicky alignment. Now a single metalens can focus all the wavelengths of white light onto the same spot. Beyond creating this "achromatic" metalens, scientists have developed metalenses that correct other aberrations, such as coma and astigmatism, which cause image distortions and blurring.

In addition to reducing size, metalenses should ultimately lower the cost of optical components because the diminutive lenses can be manufactured with the same equipment already used in the semiconductor industry. This feature raises the alluring prospect of fabricating, say, a tiny light sensor's optical and electronic components side by side.

For now, however, expenses are still high because it is difficult to precisely place nanoscale elements on a centimeter-scale chip. Other limitations also need addressing. So far metalenses do not transmit light as efficiently as traditional lenses do—an important capability for such applications as full-color imaging. In addition, they are too small to capture a large quantity of light, which means that, at least for now, they are not suited to snapping high-quality photographs.

Nevertheless, in the next few years the tiny lenses will probably make their way into smaller, easier-to-manufacture sensors, diagnostic tools such as endoscopic imaging devices, and optical fibers. Those potential applications are appealing enough to have attracted research support from government agencies and such companies as Samsung and Google. At least one start-up, Metalenz, expects to bring metalenses to market within the next few years.

MEDICAL & BIOTECH

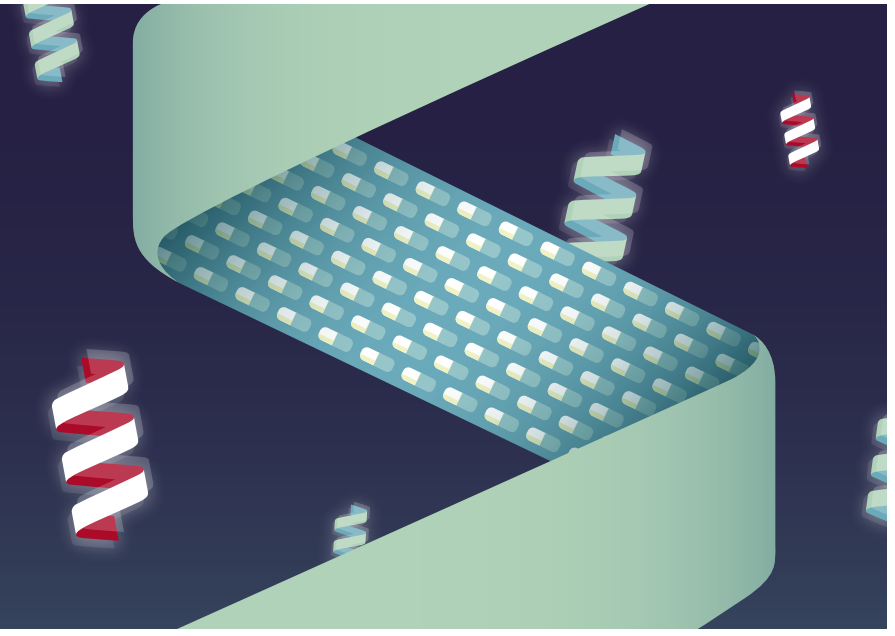
DISORDERED PROTEINS AS DRUG TARGETS

NEW POSSIBILITIES FOR TREATING CANCER AND OTHER ILLS

By Elizabeth O'Day

Decades ago scientists identified a particular class of proteins driving illnesses from cancer to neurodegenerative disease. These "intrinsically disordered proteins" (IDPs) looked different from the proteins with rigid structures that were more familiar in cells. IDPs were shape-shifters, appearing as ensembles of components that constantly changed configurations. This loose structure turns out to allow the IDPs to bring together a wide variety of molecules at critical moments, such as during a cell's response to stress. Less flexible proteins tend to have a more limited number of binding partners. When IDPs do not function properly, disease can ensue.

Yet medical researchers have not been able to create treatments to eliminate or regulate malfunctioning IDPs. Indeed, many have been called undruggable. That is because most medicines now in use require stable structures to target, and IDPs do not stay put long enough.



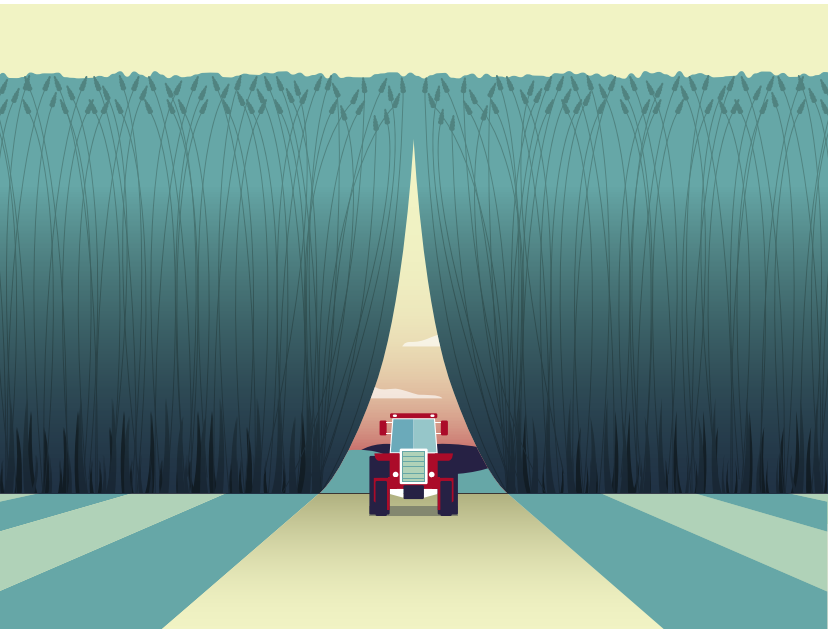
Well-known disordered proteins that can contribute to cancer—including c-Myc, p53 and K-RAS—have proved too elusive. But this picture is starting to change.

Scientists are using rigorous combinations of biophysics, computational power and a better understanding of the way that IDPs function to identify compounds that inhibit these proteins, and some have emerged as bona fide drug candidates. In 2017 researchers in France and Spain demonstrated it is possible to aim at and hit the changeable "fuzzy" interface of an IDP. They showed that an FDA-approved drug called trifluoperazine (which is used to treat psychotic disorders and anxiety) bound to and inhibited NUPR1, a disordered protein involved in a form of pancreatic cancer. Large-scale screening tests to evaluate thousands of drug candidates for therapeutic potential have revealed several that inhibit c-Myc, and some are moving toward clinical development. Additional molecules have been identified that work on IDPs such as beta-amyloid, implicated in diseases such as Alzheimer's.

This list will continue to grow, especially as the role that IDPs play in crucial cell parts known as membraneless organelles becomes clearer. Often called droplets or condensates, these organelles bring vital cellular molecules—such as proteins and RNA—close together at specific times, while keeping others apart. Proximity allows certain reactions to occur more easily; separation prevents various reactions. Scientists have designed powerful new molecular manipulation tools, which go by the names Corelets and CasDrop, that allow researchers to control how these droplets form. Using these tools and others, researchers have learned that IDPs may help control droplet assembly, function and disassembly.

This discovery is important because during droplet formation and breakdown, IDPs interact with various binding partners and sometimes hold new shapes for a few moments as they do so. It may be easier to find drugs that find and bind to those shapes than it is to find compounds that can hit IDPs in their other guises. Researchers across the globe are pioneering efforts to uncover these droplet-related mechanics.

Industry is also betting on the therapeutic potential of IDPs. Biotechnology company IDP Pharma is developing a type of protein inhibitor to treat multiple myeloma and small-cell lung cancer. Graffinity Pharmaceuticals, now part of NovAliX, has identified small molecules to target the disordered protein tau, which is involved in Alzheimer's pathology. Cantabio Pharmaceuticals is on the hunt for small molecules to stabilize IDPs involved in neurodegeneration. And a new company called Dewpoint Therapeutics is exploring the idea that droplets and their disordered components, because of the way they bring molecules together for enhanced reactions, could be used as drug targets. It is increasingly likely that in the next three to five years these once "undruggable" proteins will end up in the crosshairs of pharmaceutical development.



5

ENVIRONMENT

SMARTER FERTILIZERS CAN REDUCE ENVIRONMENTAL CONTAMINATION

NEW FORMULATIONS DELIVER NOURISHMENT ON DEMAND

By Jeff Carbeck

To feed the world's growing population, farmers need to increase crop yields. Applying more fertilizer could help. But standard versions work inefficiently and often harm the environment. Fortunately, products that are more ecologically sound—controlled-release fertilizers—are available and becoming increasingly smart.

Farmers typically fertilize crops in two ways. They spray fields with ammonia, urea or other substances that generate the nutrient nitrogen when they react with water. And they apply granules of potash or other minerals to produce phosphorus, also in reaction to water. But relatively little of those nutrients makes its way into the plants. Instead much of the nitrogen goes into the atmosphere in greenhouse gases, and phosphorus ends up in watersheds, frequently triggering excessive growth of algae and other organisms. Controlled-release formulations, in contrast, can ensure that significantly higher levels of nutrients reach the crops, leading to higher yields with less fertilizer.

A class known as slow-release fertilizers has been sold for some time. These formulations typically consist of tiny capsules filled with substances that contain nitrogen, phosphorus and other desired nutrients. The outer shell slows both the rate at which water can access the inner contents to liberate the nutrients and the rate at which the end products escape from the capsule. As a result, nutrients are meted out gradually, instead of in a wasteful, rapid burst that cannot be absorbed efficiently. Newer formulations include substances that slow nutrient delivery still further, by retarding the conversion of starting materials, such as urea, to nutrients.

Recently fertilizers that more fully fit the description "controlled release" have been developed—made possible by sophisticated materials and manufacturing techniques that can tune the shells so that they alter nutrient-release rates in desired ways as the soil's temperature, acidity or moisture changes. By combining different types of tuned capsules, manufacturers can make fertilizers that have profiles tailored to the needs of specific crops or growing conditions. Companies such as Haifa Group and ICL Specialty Fertilizers are among those offering more precise control. Haifa, for instance, ties the rate of nutrient release solely to temperature; as temperatures rise, the rates of crop growth and of nutrient emission increase together.

Although controlled-release technologies make fertilizers more efficient, they do not eliminate all drawbacks of fertilizer use. The products still include ammonia, urea and potash, for example; producing these substances is energy-intensive, which means that their manufacture can contribute to greenhouse gas production and climate change. This effect could be mitigated, however, by using environmentally friendlier sources of nitrogen and incorporating microorganisms that improve the efficiency of nitrogen and phosphorus uptake by plants. There is no evidence that the materials composing the shells hurt the environment, but this risk must be monitored whenever any new substances are introduced in high volumes.

Controlled-release fertilizers are part of a sustainable approach to agriculture known as precision farming. This approach improves crop yield and minimizes excessive nutrient release by combining data analytics, artificial intelligence and various sensor systems to determine exactly how much fertilizer and water plants need at any given time and by deploying autonomous vehicles to deliver nutrients in prescribed amounts and locations. Installing precision systems is costly, though, so only large-scale operations tend to have them. In comparison, advanced controlled-release fertilizers are relatively inexpensive and could be a front-line technology that would help farmers to sustainably increase crop production.

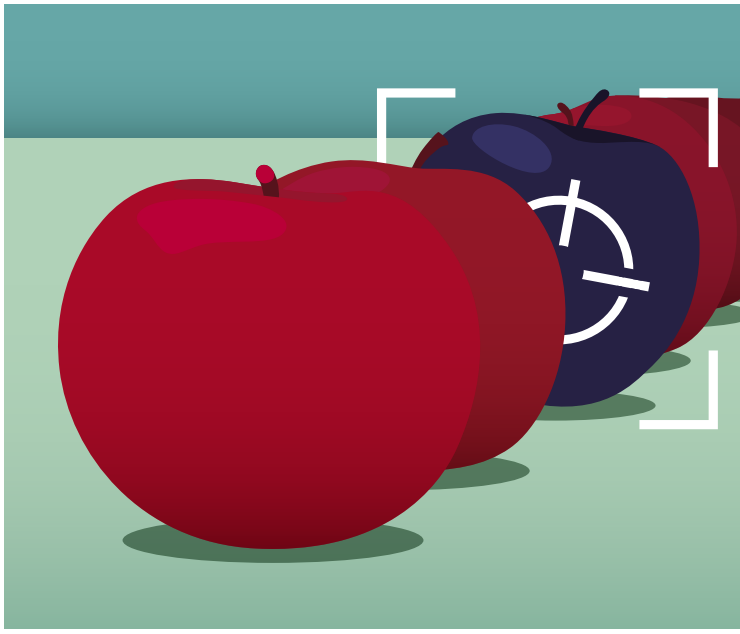
6

COMPUTING

COLLABORATIVE TELEPRESENCE

PARTICIPANTS IN VIRTUAL GATHERINGS WILL FEEL LIKE THEY ARE PHYSICALLY TOGETHER

By Corinna E. Lathan and Andrew Maynard



Imagine a group of people in different parts of the world smoothly interacting as if they were physically together, down to being able to feel one another's touch. The components that will enable such "collaborative telepresence" could transform how we work and play together, rendering physical location irrelevant.

Just as video-calling apps such as Skype and FaceTime have made what was once the domain of business widely accessible to consumers, and massive multiplayer online games have radically altered how people interact on the Internet, collaborative telepresence could transform how people interact virtually in business and beyond. Medical providers, for instance, will be able to work remotely with patients as if they were in the same room. And friends and families will be able to enjoy shared experiences, such as being together in a cozy room or touring a new city, even though they are not actually in the same place.

Progress in several realms has made this prospect feasible. Augmented-reality (AR) and virtual-reality (VR) technologies are already becoming capable and affordable enough for widespread adoption. Telecom companies are rolling out 5G networks fast enough to handle masses of data from advanced sensor arrays without lag times. Innovators are perfecting technologies that enable people to physically interact with remote environments, including haptic sensors that make it possible to feel what their robotic avatars touch. The full sensory immersion envisioned for collaborative telepresence will require lag times substantially smaller than those acceptable for video calls—and they may sometimes tax even 5G networks—but predictive AI algorithms could eliminate a user's perception of time gaps.

Although collaborative telepresence is still very much emerging, all the pieces are in place for it to become transformative within three to five years. For instance, Microsoft and other companies are already investing in technologies that are expected to underpin a multibillion-dollar industry by 2025. And the XPRIZE Foundation has launched the $10-million ANA Avatar XPRIZE competition (sponsored by All Nippon Airways) to kick-start technologies that will "transport a human's sense, actions, and presence to a remote location in real time, leading to a more connected world." As the parts are knitted together, expect to see changes in daily life and work that are as dramatic as those sparked by the widespread adoption of smartphones.

7

PUBLIC HEALTH

ADVANCED FOOD TRACKING AND PACKAGING

A COMBINATION OF TWO TECHNOLOGIES COULD VASTLY IMPROVE FOOD SAFETY

By Rona Chandrawati and Bernard S. Meyerson

About 600 million people suffer food poisoning every year, according to the World Health Organization, and 420,000 die. When an outbreak occurs, investigators can spend days or weeks tracking its source. Meanwhile more people can sicken, and massive amounts of uncontaminated food may be discarded along with the tainted items. Finding the source can be slow work because food travels a complex path from farm to table, and the records of those journeys are kept in local systems that often do not communicate with one another.

Together a pair of technologies could reduce both food poisoning and food waste. The first, an innovative application of blockchain technology (better known for

managing virtual currency), is beginning to solve the traceability problem. Enhanced food packaging, meanwhile, is providing new ways to determine whether foods have been stored at proper temperatures and whether they might have begun to spoil.

Blockchain is a decentralized accounting system in which entries are recorded in sequence in multiple identical "ledgers" stored on computers in multiple locations. This redundancy makes tampering with any one ledger futile, creating a highly trusted record of transactions. A blockchain-based cloud platform developed for the food industry—IBM Food Trust—is already employed by major food sellers. (One of us—Meyerson—is affiliated with IBM.)

By integrating growers, distributors and retailers on a common blockchain, Food Trust creates a trusted record of a given food's path through the end-to-end supply chain. In a test using the technology, Walmart traced the origin of a "contaminated" item in seconds; with the standard mix of written and digital records, this would have taken days. With this capability, retailers and restaurants can remove a contaminated item from circulation virtually immediately and destroy only stock that came from the same source (say, a particular grower of romaine lettuce) instead of wasting entire national stocks of the item. Many food-business giants—Walmart, Carrefour, Sam's Club, Albertsons Companies, Smithfield Foods, BeefChain, Wakefern Food (ShopRite's parent) and Topco Associates (a group purchasing organization)—have joined the IBM Food Trust. Other organizations have also introduced blockchain technology for enhancing traceability.

To prevent food poisoning in the first place, research laboratories and companies are developing small sensors that can monitor the quality and safety of food in pallets, cases or individually wrapped products. For instance, Timestrip UK and Vitsab International have independently created sensor tags that change color if a product has been exposed to above-recommended temperatures, and Insignia Technologies sells a sensor that slowly changes color after a package has been opened and indicates when the time has come to toss the food. (The color changes more quickly if the product is not stored at the proper temperature.) Sensors that reveal the gaseous by-products of spoilage are also being developed. Beyond preventing sickness, such sensors can reduce waste by showing that a food is safe to eat.

Cost remains a roadblock to the ubiquitous use of sensors. Still, the food industry's need to ensure food safety and limit waste is propelling this technology and blockchain forward.

8

ENERGY

SAFER NUCLEAR REACTORS

RESILIENT FUELS AND INNOVATIVE REACTORS COULD ENABLE A RESURGENCE OF NUCLEAR POWER

By Mark Fischetti

Controlling carbon in the atmosphere will require a mix of energy technologies—potentially including nuclear reactors, which emit no carbon but are seen as risky because of a few major accidents. That risk could be greatly reduced.

Commercial reactors have used the same fuel for decades: small pellets of uranium dioxide stacked inside long cylindrical rods made of a zirconium alloy. Zirconium allows the neutrons generated from fission in the pellets to readily pass among the many rods submerged in water inside a reactor core, supporting a self-sustaining, heat-producing nuclear reaction.

Trouble is, if the zirconium overheats, it can react with water and produce hydrogen, which can explode. That scenario fed two of the world's worst reactor accidents: the 1979 potential explosion and partial meltdown at Three Mile Island in the U.S. and the 2011 explosions and radiation release at Fukushima Daiichi in Japan. (The 1986 Chernobyl accident was caused by faulty reactor design and operation.)

Manufacturers such as Westinghouse Electric Company and Framatome are hastening development of so-called accident-tolerant fuels that are less likely to overheat—and if they do, they will produce very little or no hydrogen. In some of the variations, the zirconium cladding is coated to minimize reactions. In others, zirconium and even the uranium dioxide are replaced with different materials. The new configurations could be slipped into existing reactors with little modification, so they could be phased in during the 2020s. Thorough in-core testing, which has begun, would have to prove successful, and regulators would have to be satisfied. In a bonus, the new fuels could help plants run more efficiently, making nuclear power more cost-competitive—a significant motivation for manufacturers and electric utilities because natural gas, solar and wind energy are less expensive.

Although nuclear power has stalled in the U.S. and is being phased out in Germany and elsewhere, Russia and China are building aggressively. These markets could be lucrative for the manufacturers of these new fuels.

Russia is also deploying other safety measures; recent installations at home and abroad by the state-run company Rosatom have newer "passive" safety systems that can squelch overheating even if electrical power at the plant is lost and coolant cannot be actively circulated. Westinghouse and other companies have incorporated passive safety features into their updated designs as well.

Manufacturers are experimenting with "fourth generation" models that use liquid sodium or molten salt instead of water to transfer heat from fission, removing the possibility of dangerous hydrogen production. China reportedly intends to connect a demonstration helium-cooled reactor to its grid this year.

In the U.S., lack of political commitment to a permanent, deep geologic repository for spent nuclear fuel has long put a brake on expanding the industry. Sentiment may be changing. Surprisingly, more than a dozen U.S. legislators recently proposed measures to restart licensing for the Yucca Mountain nuclear waste repository in Nevada, touted since 1987 as the country's leading storage site. Meanwhile Senator Lisa Murkowski of Alaska is advocating for very small, modular reactors being developed at Idaho National Laboratory. (Rosatom is making small reactors, too.) And a group of Western states has entered a tentative deal with NuScale Power in Oregon for a dozen of its modular reactors. Improved fuels and growth in small reactors could be a big part of a nuclear power rebirth.

MEDICAL & BIOTECH

DNA DATA STORAGE

LIFE'S INFORMATION-STORAGE SYSTEM IS BEING ADAPTED TO HANDLE MASSIVE AMOUNTS OF INFORMATION

By Sang Yup Lee

Every minute in 2018, Google conducted 3.88 million searches, and people watched 4.33 million videos on YouTube, sent 159,362,760 e-mails, tweeted 473,000 times and posted 49,000 photos on Instagram, according to software company Domo. By 2020 an estimated 1.7 megabytes of data will be created per second per person globally, which translates to about 418 zettabytes in a single year (418 billion one-terabyte hard drives' worth of information), assuming a world population of 7.8 billion. The magnetic or optical data-storage systems that currently hold this volume of 0s and 1s typically cannot last for more than a century, if that. Further, running data centers takes huge amounts of energy. In short, we are about to have a serious data-storage problem that will only become more severe over time.

An alternative to hard drives is progressing: DNA-based data storage. DNA—which consists of long chains of the nucleotides A, T, C and G—is life's information-storage material. Data can be stored in the sequence of these letters, turning DNA into a new form of information technology. It is already routinely sequenced (read), synthesized (written to) and accurately copied with ease. DNA is also incredibly stable, as has been demonstrated by the complete genome sequencing of a fossil horse that lived more than 500,000 years ago. And storing it does not require much energy.

But it is the storage capacity that shines. DNA can accurately stow massive amounts of data at a density far exceeding that of electronic devices. The simple bacterium *Escherichia coli*, for instance, has a storage density of about 10^{19} bits per cubic centimeter, according to calculations published in 2016 in *Nature Materials* by George Church of Harvard University and his colleagues. At that density, all the world's current storage needs for a year could be well met by a cube of DNA measuring about one meter on a side.

The prospect of DNA data storage is not merely theoretical. In 2017, for instance, Church's group at Harvard adopted CRISPR DNA-editing technology to record images of a human hand into the genome of *E. coli,* which were read out with higher than 90 percent accuracy. And researchers at the University of Washington and Microsoft Research have developed a fully automated system for writing, storing and reading data encoded in DNA. A number of companies, including Microsoft and Twist Bioscience, are working to advance DNA-storage technology.

Meanwhile DNA is already being used to manage data in a different way, by researchers who grapple with making sense of tremendous volumes of data. Recent advancements in next-generation sequencing techniques allow for billions of DNA sequences to be read easily and simultaneously. With this ability, investigators can employ bar coding—use of DNA sequences as molecular identification "tags"—to keep track of experimental results. DNA bar coding is now being used to dramatically accelerate the pace of research in fields such as chemical engineering, materials science and nanotechnology. At the Georgia Institute of Technology, for example, James E. Dahlman's laboratory is rapidly identifying safer gene therapies; others are figuring out how to combat drug resistance and prevent cancer metastasis.

Among the challenges to making DNA data storage commonplace are the costs and speed of reading and writing DNA, which need to drop even further if the approach is to compete with electronic storage. Even if DNA does not become a ubiquitous storage material, it will almost certainly be used for generating information at entirely new scales and preserving certain types of data over the long term.

10

ENERGY

UTILITY-SCALE STORAGE OF RENEWABLE ENERGY

A ROADBLOCK TO SUSTAINABLE ENERGY SOLUTIONS IS COMING UNSTUCK

By Andrea Thompson

The way the world gets its electricity is undergoing a rapid transition, driven by both the increased urgency of decarbonizing energy systems and the plummeting costs of wind and solar technology. In the past decade electricity generated by renewables in the U.S. has doubled, primarily from wind and solar installations, according to the Energy Information Administration. In January 2019 the EIA forecast that wind, solar and other nonhydroelectric renewables would be the fastest-growing slice of the electricity portfolio for the next two years. But the intermittent nature of those sources means that electric utilities need a way to keep energy in their back pocket for when the sun is not shining and the winds are calm. That need is increasing interest in energy-storage technology—in particular, lithium-ion batteries, which are finally poised to be more than just a bit player in the grid.

For decades pumped-storage hydropower, a simple process that features reservoirs at different elevations, has been the dominant large-scale energy-storage method in the U.S. To store energy, water is pumped into the higher reservoir; when that energy is needed, the water is released into the lower reservoir, flowing through a turbine along the way. Pumped-storage hydropower currently accounts for 95 percent of U.S. utility-scale energy storage, according to the Department of Energy. But as efficiency and reliability have improved, and manufacturing costs have tumbled, lithium-ion batteries have surged. They account for more than 80 percent of the U.S.'s utility-scale battery-storage power capacity, which jumped from just a few megawatts a decade ago to 866 megawatts by February 2019, the EIA says. A March 2019 analysis by Bloomberg New Energy Finance reports that the cost of electricity from such batteries has dropped by 76 percent since 2012, making them close to competitive with the plants, typically powered by natural gas, that are switched on during times of high electricity demand. To date, whereas batteries have largely been used to make brief, quick adjustments to maintain power levels, utilities in several states, including Florida and California, are adding lithium-ion batteries that will be able to last for two to four hours. Earlier energy research firm Wood Mackenzie estimated that the market for energy storage would double from 2018 to 2019 and triple from 2019 to 2020.

Lithium-ion batteries will likely be the dominant technology for the next five to 10 years, according to experts, and continuing improvements will result in batteries that can store four to eight hours of energy—long enough, for example, to shift solar-generated power to the evening peak in demand.

But getting to the point where renewables and energy storage can handle the baseline load of electricity generation will take energy storage at longer timescales, which will mean moving beyond lithium-ion batteries. Potential candidates range from other high-tech options, such as flow batteries, which pump liquid electrolytes, and hydrogen fuel cells, to simpler concepts, such as pumped-storage hydropower and what is called gravity storage. Pumped-storage hydropower is cheap once it is installed, but it is expensive to build and can be used only in certain terrain. Similarly simple is the concept of gravity storage, which purports to use spare electricity to raise a heavy block that can later be lowered to drive a turbine to generate electricity. Although a few companies are working on demonstrations and have attracted investments, the idea has yet to take off. Other options are still under development to make them sufficiently reliable, efficient and cost-competitive with lithium-ion batteries. There were only three large-scale flow-battery storage systems deployed in the U.S. by the end of 2017, according to the EIA, and utility-scale hydrogen systems remain in demonstration stages. The U.S. government is funding some work in this arena, particularly through the Advanced Research Projects Agency–Energy (ARPA-E), but much of the investment in those technologies—and in energy storage in general—is happening in China and South Korea, which have also ramped up storage research.

It is uncertain whether and how much the costs of energy storage will continue to decline. Yet the accumulating pledges by governments—including at the state and local level in the U.S.—to achieve carbon-free electricity production will provide a continued push to bring more and more storage online.

MORE TO EXPLORE

The Top 10 Emerging Technologies of 2018. *Scientific American* and World Economic Forum, December 2018.

FROM OUR ARCHIVES

The Orderly Chaos of Proteins. A. Keith Dunker and Richard W. Kriwacki; April 2011.

Building a Weather-Smart Grid. Peter Fairley; July 2018.

Reactor Redo. Rod McCullum; May 2019.

All the World's Data Could Fit in an Egg. James E. Dahlman; June 2019.

scientificamerican.com/magazine/sa

SECURITY

GPS DOWN

Hacking the system we all rely on is not difficult, and the U.S. has no defense in place

By Paul Tullis

Illustration by Harry Campbell

IN BRIEF

Suspected hackers have jammed GPS signals that guide airliners. Electric grids, the stock market and other systems also rely on GPS to time operations.

Bad actors can jam or spoof GPS signals without complicated or expensive technology and without the need for deep training.

Many countries have a ground-based backup system based on eLoran technology that is difficult to jam or spoof, but the U.S. has never built one.

Paul Tullis is a journalist in Amsterdam who writes about the intersections of science, technology and business. He wrote our article about how rising numbers of tourists are ruining the Galápagos Islands.

ON AUGUST 5, 2016, CATHAY PACIFIC FLIGHT 905 FROM HONG KONG was heading for an on-time arrival at Manila's Ninoy Aquino International Airport when something unexpected occurred. The pilots radioed air traffic controllers and said they had lost GPS (Global Positioning System) guidance for the final eight nautical miles to "runway right-24."

Surprised, the controllers told the pilots to land the widebody Boeing 777-300 using just their own eyes. The crew members pulled it off, but they were anxious the whole way in. Fortunately, skies were mostly clear that day.

The incident was not isolated. In July and August of that year, the International Civil Aviation Organization received more than 50 reports of GPS interference at the Manila airport alone. In some cases, pilots had to immediately speed up the plane and loop around the airport to try landing again. That kind of scramble can cause a crew to lose control of an aircraft. In a safety advisory issued this past April, the organization wrote that aviation is now dependent on uninterrupted access to satellite positioning, navigation and timing services and that vulnerabilities and threats to these systems are increasing.

In incidents involving at least four major airports in recent years, approaching pilots have suddenly lost GPS guidance. In June a passenger aircraft landing in Idaho nearly crashed into a mountain, according to NASA's Aviation Safety Reporting System. Only the intervention of an alert air traffic controller averted catastrophe. Security analysts and aerospace engineers who have studied the events say the likely cause in at least some instances is malicious interference. In the best-case scenario, GPS jamming will cause significant delays as pilots are forced to reroute a flight's last miles, costing airlines and passengers, says Martin Lauth, a former air traffic controller, who now is an associate professor of air traffic management at Florida's Embry-Riddle Aeronautical University. Crippled GPS could shut down an airport. If someone hacked GPS and instrument landing systems at the major airports in the greater New York City area, there would be no easy place to send arriving planes. Incoming transoceanic flights in particular would start to run out of fuel.

Although we think of GPS as a handy tool for finding our way to restaurants and meetups, the satellite constellation's timing function is now a component of every one of the 16 infrastructure sectors deemed "critical" by the Department of Homeland Security (DHS). Cell-phone networks, financial markets, the electric grid, emergency services, and more all rely on the timing for basic operation. Yet GPS is vulnerable. Because of the great distance the radio waves must travel—more than 12,000 miles between satellites and receivers on Earth—the signals are weak and easily overridden, or "jammed," as apparently happened in Manila. They are also easy to "spoof": a slightly stronger signal from a software-defined radio—a broadcast that can be created by software on a laptop—can deliver a false message or replay an authentic message infused with false information, causing the receiver to believe it is somewhere, or some*when,* it is not.

In critical infrastructure, an error of a few microseconds can cause cascading failures that can throw off an entire network. Todd Humphreys, an associate professor of aerospace engineering at the University of Texas at Austin, as well as Dana Goward, a member of the U.S. National Space-Based Positioning, Navigation and Timing Advisory Board (a federal committee), and a former executive at a major defense contractor, each told SCIENTIFIC AMERICAN they now worry that a foreign adversary or terrorist group could coordinate multiple jamming and spoofing attacks against GPS receivers and severely degrade the functionality of the electric grid, cell-phone networks, stock markets, hospitals, airports, and more—all at once, without detection.

The real shocker is that U.S. rivals do not face this vulnerability. China, Russia and Iran have terrestrial backup systems that GPS users can switch to and that are much more difficult to override than the satellite-based GPS system. The U.S. has failed to achieve a 2004 presidential directive to build such a backup. No actual U.S. calamities have happened yet; if they had, policy makers would have finally acted. But as disaster experts like to note, the U.S. always seems to prepare for the previous disaster, not the upcoming one.

GPS SATELLITES (*1*) provide intricate timing for data centers such as this one (*2*) in Secaucus, N.J., that coordinate transactions for major stock exchanges.

LOCKHEED MARTIN (*1*); CHANG W. LEE *New York Times* and *Redux Pictures* (*2*)

DEPENDENCE BECOMES A TARGET

THE CURRENT GPS is a network of 31 satellites known as Navstar, operated by space squadrons of the U.S. Air Force. To maintain accuracy, the squadrons deliver Coordinated Universal Time to the satellites, via a network of four antennas from Cape Canaveral to Kwajalein Atoll, up to three times a day as the satellites fly overhead. Thanks to each satellite's payload of atomic clocks, the time they keep is accurate to under 40 nanoseconds—after adjustments are made for general relativity, which makes the satellites' clocks tick about 45 microseconds a day faster than clocks on Earth, and special relativity, which makes them tick seven microseconds slower.

Each satellite continually broadcasts a binary code on two frequencies. One frequency is for the military and requires a decryption key. The other is for civilian use and is unencrypted. Signals on both frequencies contain data packets that encode the time, the satellite's position at the moment of transmission, and the orbit and status of the other satellites. The GPS receiver in a smartphone figures out its location by calculating how long it takes the radio signals to travel from the transmitting satellites, which provides their distances from the phone. A minimum of four signals is required for a receiver to accurately determine its position and time, which is why you might lose your handy navigation guide amid the skyscrapers of lower Manhattan or the narrow alleyways of Venice. Critical infrastructure in the U.S. has numerous receivers that synchronize operations.

Hackers can jam a signal by drowning it out with meaningless noise, or they can spoof it by feeding the receiver false time or coordinates, which will disorient the receiver in time or space. Once one device has lost the correct time, it can send the spoofed time to other devices on its network, throwing off the entire complex and degrading its operation.

Industry is especially reliant on GPS because it is the most accurate timekeeping method on Earth and it is free. In the days before GPS, electric-grid operators could only estimate the load on their transmission lines, which led to inefficiencies; today GPS timing allows them to track the state of the grid and optimize operation in response to real-time demand. Financial markets once set their system time to a clock on the wall. Inaccurate timekeeping and uncoordinated transactions were widespread even after trading became computerized because early software used a clock inside a computer that was aligned by hand to the official time of the National Institute of Standards and Technology (NIST), the country's timekeeper. Today's financial systems, from a corner deli's credit-card machine to stock markets, use GPS to time-stamp and verify transactions, freeing retailers from the need to transmit sales at the end of the day and enabling the worldwide, ultrahigh-frequency trading so prevalent now.

Cell-phone networks use GPS to break up, deliver and reassemble packets of data and to hand off calls from tower to tower as a phone moves. Electronic medical records are time-stamped with GPS time. Television networks use GPS to prove to advertisers that their commercials ran during the time slots they paid for. Worldwide, more than two billion GPS devices are used.

The great dependence on GPS is a tempting target. GPS is vulnerable and provides an opportunity for mayhem, and the capability to disrupt it has been shown. The only uncertain factor is whether an angry individual or group would choose GPS as a vehicle for an attack. The answer increasingly seems to be yes. "We now have ongoing demonstrations of state-sponsored spoofing," Humphreys says.

One of those states is Russia. In March the Center for Advanced Defense Studies, a Washington, D.C., research nonprofit, identified nearly 10,000 incidents originating at 10 locations that included the Russian Federation, Crimea and Syria. Experts in the U.S. government and in academia say Iran and North Korea also have the capability. "Lots of countries and organizations" have it, Goward says.

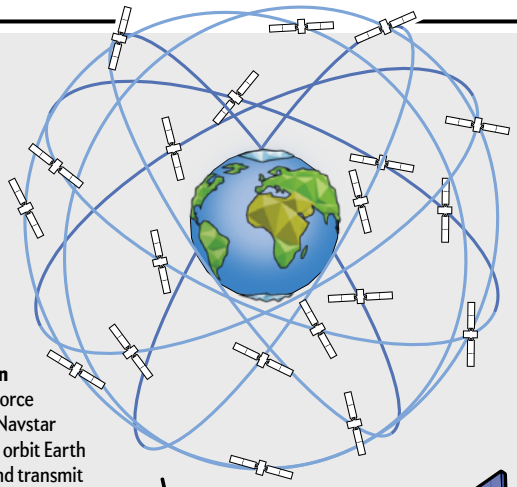
A government adviser who has repeatedly warned Congress, a former executive at a defense contractor, and a former federal official who was speaking on background told SCIENTIFIC AMERICAN that a coordinated spoofing-jamming attack against various systems in the U.S. would be easy, cheap and disastrous. "It can be exercised on a massive and selective scale," Goward says. A spoofing device costs about $5,000, and instructions are available online. Yet it is difficult to defend against: "Even a relatively trivial

GPS: Dependable but Vulnerable

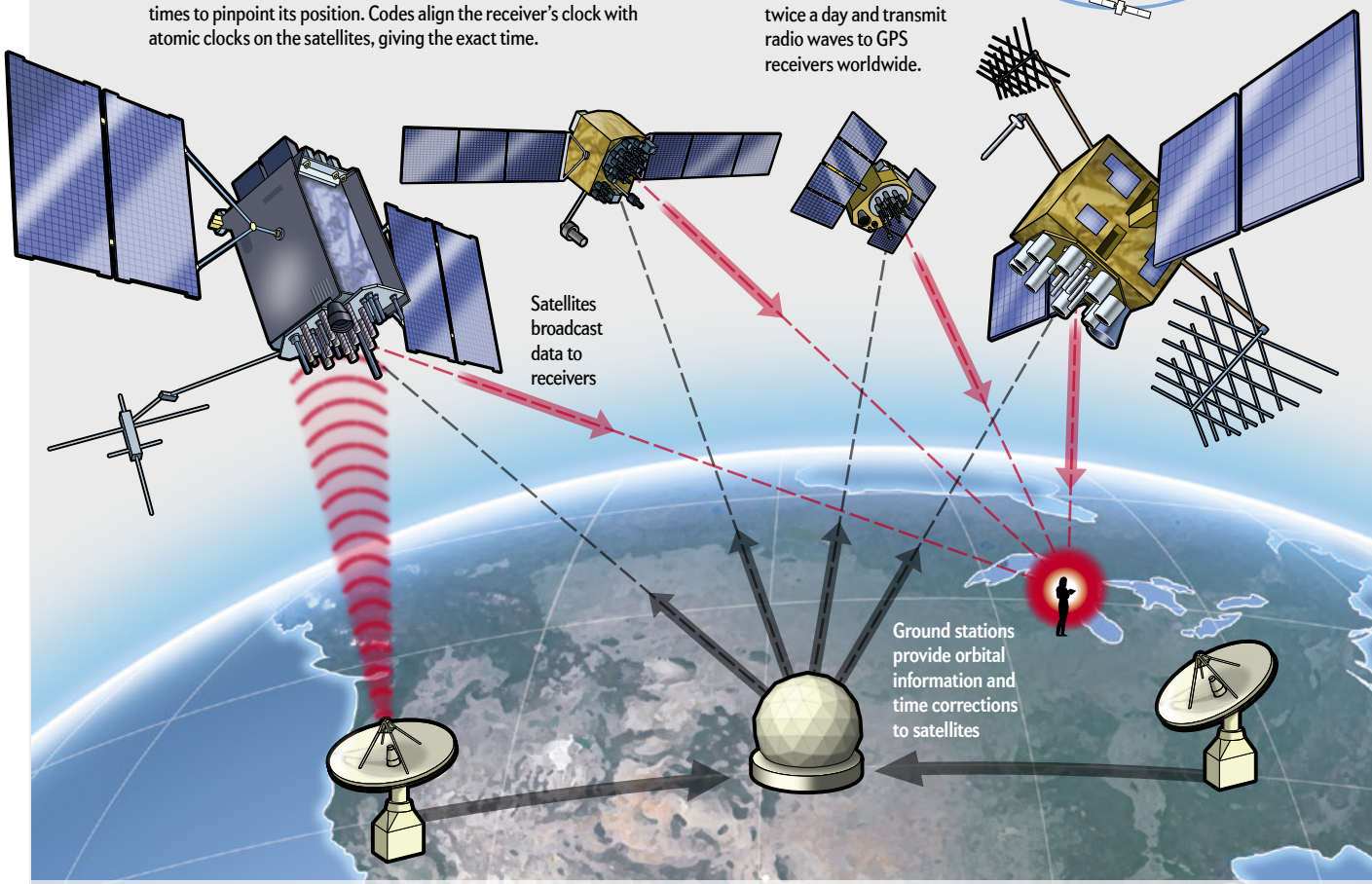
The electric grid, stock markets, banks, airliners and cell-phone networks all depend on satellite-based GPS for timing their intricate operations. It is not difficult for hackers to break in and throw off the timing, with potentially harmful consequences. Many countries have a ground-based network for backup during an attack, although the U.S. does not.

HOW GPS WORKS

GPS satellites send synchronized signals that specify their position and time at any moment. A GPS device (*person in red circle*) receives signals from at least four satellites and compares the differences in their arrival times to pinpoint its position. Codes align the receiver's clock with atomic clocks on the satellites, giving the exact time.



Satellite Constellation
The U.S. Air Force maintains 31 Navstar satellites that orbit Earth twice a day and transmit radio waves to GPS receivers worldwide.



Accurate Position and Time
The trilateration of four satellite feeds gives a receiver's location and time. A signal from the first satellite places a receiver somewhere on a sphere. A signal from the second satellite reduces the location to a circle along the intersection of two spheres (*left*). The third signal defines two points on that circle, and the fourth signal determines one point and what time it is there.

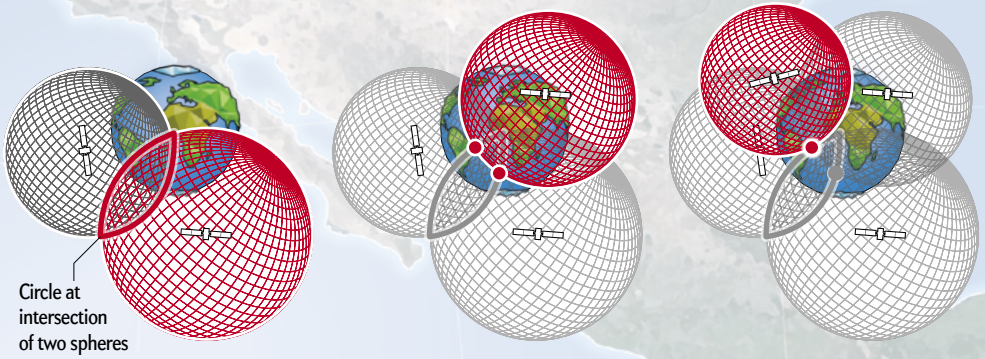


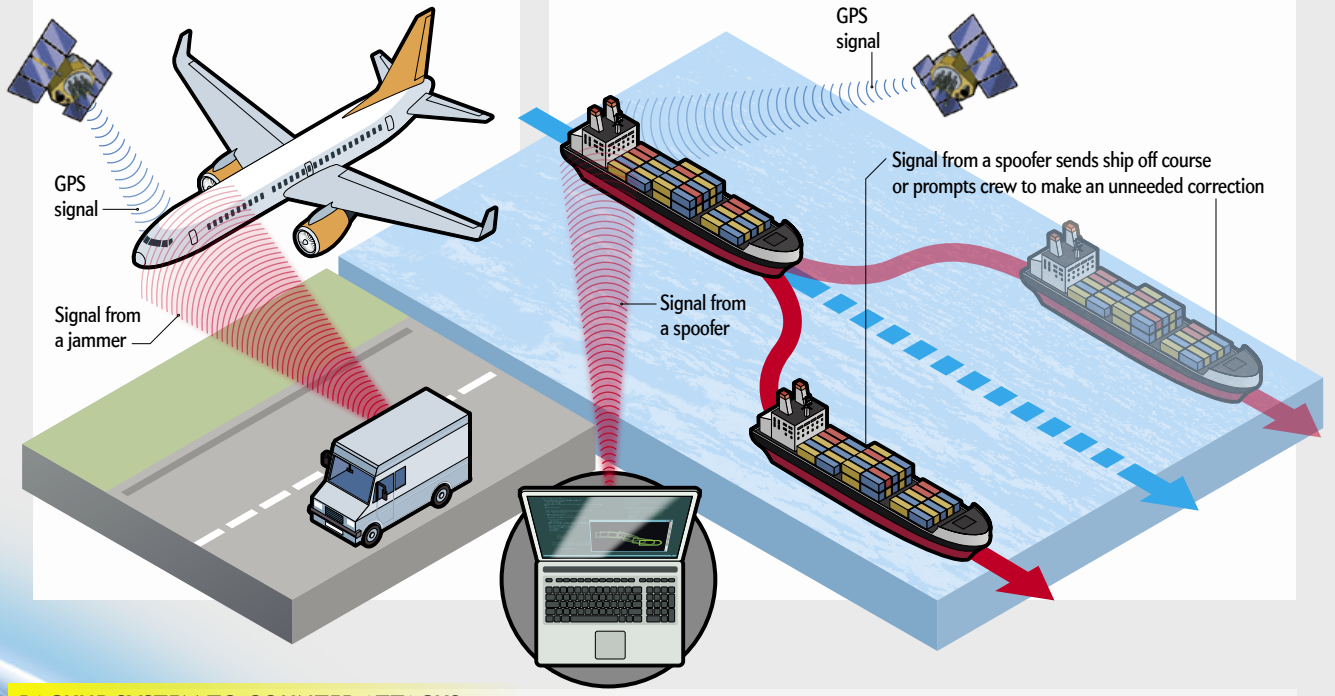
Illustration by Ben Gilliland

TWO WAYS TO HACK IN

Interfering with GPS timing can lead to electric-grid blackouts, stock market crashes and airliners that lose guidance during landing. Hackers can overpower (jam) or mimic (spoof) the radio waves GPS satellites transmit, giving receivers false information.

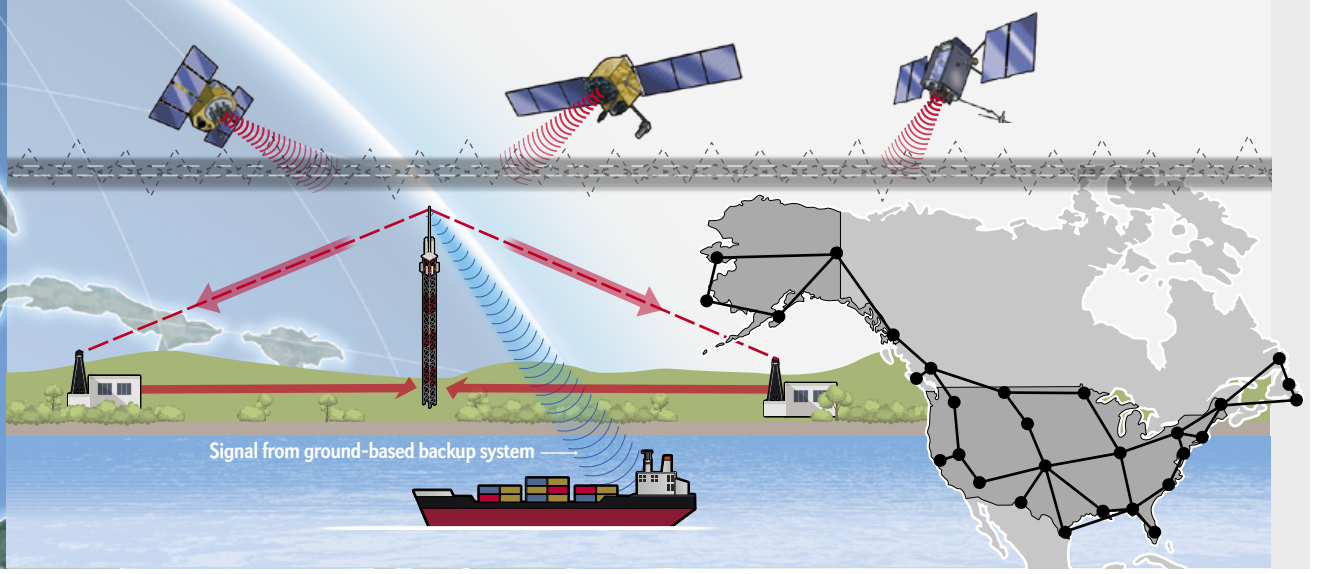
Jamming
GPS radio transmissions have very low power when they reach Earth. A hacker near a receiver can drown out the broadcast by blasting meaningless noise at the same frequency, making it hard for the receiver to stay connected to the signal or to lock onto it in the first place.

Spoofing
Each GPS satellite sends a unique code that identifies it. A hacker near a receiver can pick up the incoming codes, then retransmit them, slowly increasing their power until the receiver switches to the hacker as the originating source. The hacker can then send new radio signals that misdirect the receiver or fool human operators into thinking they are off course, which they might mistakenly try to correct.



BACKUP SYSTEM TO COUNTER ATTACKS

Many countries have a backup network that some receivers can switch to if satellite broadcasts are hacked or lost. Master stations and antennas on the ground emit strong, low-frequency radio waves that are very difficult to jam or spoof. A receiver picks up the signals from several pairs of transmitters to determine its location and time, though with less accuracy than with GPS. To be effective, a network should cover a country or region; one possible U.S. configuration is shown.



SOURCE: NATIONAL MARITIME PNT OFFICE (*U.S. transmitter map*)

spoofing mitigation function against the most basic threats is far from simple to implement," wrote Gerhard Berz, who works on navigation infrastructure for Eurocontrol, Europe's air traffic control agency, in *Inside GNSS,* a trade magazine.

DISTRIBUTED ATTACKS

A LARGE-SCALE, coordinated attack on U.S. infrastructure could be pulled off by 10 or 12 human operators with the right equipment, fanned out across the country. History was changed on September 11, 2001, by 19 Al Qaeda agents in the U.S., but hostile GPS disrupters would not need to have a suicidal devotion to God, the level of technical training required to fly a plane or the brutality to murder a cockpit crew. It is possible that the only thing stopping a GPS attack is international law, which recognizes electronic warfare as equivalent to violent acts if it brings about similar effects. Broad disablement of civil infrastructure would be likely to engender a U.S. military response, which at least so far may have dissuaded adversaries.

Although loss of life from a coordinated jamming-spoofing attack on GPS timing would probably be less than that on 9/11, the disabling effects could be more widespread. One scenario could involve changing stoplights at a few major intersections in various cities across the country to show green in all directions. A hacker in a nearby building would open a software-defined radio on a laptop. It would generate a false copy of the radio-frequency carrier, noise code and data bits from the provider of the global navigation satellite systems the traffic light was using. To induce the light to lock onto the bogus signal, the spoofer would disrupt the light's regular tracking procedure, causing it to try to reacquire a signal. If the false signal were stronger, the light would likely select it. Now having access to the light's controller, the hacker could feed it the incorrect time, activating the north-south signal's green light before the east-west signal changed to red.

Several hackers at different intersections or in different cities could coordinate attacks. Or one of them could set off a cascade of intersection disruptions in one city. When I raised this scenario to a supervisor of traffic signal electricians in San Francisco who was closely involved with the city's procurement of traffic signal cabinets, he did not think there was a means for anyone to wirelessly connect to the GPS and change its time setting. Yet the Garmin GPS modules that San Francisco uses in its lights employ no antispoofing protections; rather the manufacturer's technical specifications state that to comply with Federal Communications Commission regulations, the Garmin device must accept any radio-frequency interference it encounters, even if it could scramble the module's readout.

Not every city uses GPS to time traffic signals, but the alternatives are not necessarily better. Dale Picha, traffic operations manager for the Texas Department of Transportation's San Antonio district, says the district has been moving away from individual GPS receivers on traffic signal cabinets, choosing to get the time from cell networks instead. But those can be spoofed, too.

People injured in traffic accidents might have to wait awhile for help because paramedics' radios rely on GPS timing. When several GPS satellites provided incorrect time because of a glitch in 2016, virtually every emergency-responder system in North America experienced communications problems.

A larger target would be the global financial system. In a swampy part of New Jersey two miles from MetLife Stadium, trillions of dollars' worth of financial instruments are traded every day in bits and bytes. The Equinix data center there hosts 49 exchanges, including the New York Stock Exchange. An error introduced in a GPS receiver that time-stamps stock transactions would "inject confusion into the operations of the financial industry," says Andrew F. Bach, former global head of network services for the New York Stock Exchange. Seeing something amiss, computers—which now account for 60 percent of market volume, according to J.P. Morgan—might decide to sit on the sidelines. "When too many people head for the exits at the same time, we get a real problem," says Andrew Lo, a professor of finance at the M.I.T. Sloan School of Management. "It can easily lead to a flash crash [a sudden and dramatic downturn in stock prices] or something much more long-lasting." Noah Stoffman, an associate professor of finance at the Indiana University Kelley School of Business, says: "I can easily imagine that disrupting GPS would have catastrophic economic consequences."

As markets reeled in New York, attackers could assault the electric grid in the heartland through a piece of hardware common at virtually every local substation. The Platte River Power Authority's Fordham substation in Longmont, Colo., 35 miles north of Denver, near where I recently lived, is typical in its equipment and in its ease of reach by a concealed potential attacker. Sitting behind a 12-foot wall around the corner from a Holiday Inn Express, the open-air installation pares electricity in high-voltage transmission lines, generated at a big gas-fired power plant miles away, down to a level that local lines can feed to 348,000 home and business customers in Longmont and three nearby cities.

An eLoran backup system would render jamming and spoofing almost irrelevant by delivering a signal that is much stronger than the GPS feed and hence virtually impossible to override.

Scattered across the roughly six-acre facility are metal boxes containing phasor measurement units (PMUs), which monitor the status of the grid. The PMUs' timing is set by a GPS. Jeff Dagle, an electrical engineer at Pacific Northwest National Laboratory, who is an expert on U.S. electricity networks, insists that because PMUs are not critical to the grid's actual operation, spoofing them would not cause a blackout. But a September 2017 report from NIST maintains that a spoofing attack on PMUs could force a generator off-line. The sudden loss of several large generators, it says, "would create an instantaneous supply-demand imbalance and grid instability"—a potential blackout. Humphreys and his colleagues demonstrated such a timing failure in a lab environment. Although the PMUs are behind a wall,

their GPS receivers could be spoofed from a hotel room a quarter of a mile away. There are 55,000 substations across the U.S.

Goward and Humphreys have warned utility executives about the danger they face, and they say few are aware. Fewer still, they maintain, have adequate contingency plans (some of which also rely on GPS). Human controllers who oversee grid networks "wouldn't think to look at GPS as a possible source of the problem for probably hours," Goward says. Furthermore, he notes, "attackers would be able to disguise what they're doing for quite some time."

Blackouts are costly and dangerous, but spoofing an airplane might provide the greatest drama. Humphreys and Eurocontrol's Berz agree that it would be difficult but possible. Military aircraft use a device called a selective availability antispoofing module, but it is not required on civilian aircraft, and deployment is heavily restricted by the government. Lauth, who trains air traffic controllers, told me that pilots have other options for landing. The primary backup, however, is an airport's instrument landing system, which provides aircraft with horizontal and vertical guidance and its distance from the landing spot. The system operates on radio waves and was built for safety, not security, so it is unencrypted—meaning a person can spoof it by inducing the aircraft's receiver to lock onto a false signal.

IMPROVING RESILIENCE

SOCIETY'S RELIANCE on GPS will only increase. The 5G-enabled Internet of Things will depend heavily on GPS because devices need precise timing to sync with one another and across networks. So will the "mirror world," a digital representation of the real world that machines will need to produce for AI and augmented-reality applications.

Although the DHS acknowledges the threat, not everyone is pleased with what it is doing—or not doing—about it. James Platt, director of the position, navigation and timing office at the DHS, says the agency is working with NIST to outline varying levels of security for different receiver types. And the DHS conducts annual exercises that allow equipment manufacturers to test their machines against attack. The results are not public, but Logan Scott, a consultant who has worked with GPS for 40 years, says "a lot of receivers do not do well when exposed to jamming and spoofing."

Antispoofing is a burgeoning field of research, with hundreds of papers published in the past several years. For example, during a spoofing attack, a vestige of the true GPS signal manifests on the receiver as distortion. Specialized receivers can monitor such distortion and give an alarm if it is detected, but the spoofer can generate a signal to nullify the distortion. "There is no foolproof defense," Humphreys says. "What you can try is to price your opponent out of the game" by deploying antispoofing protections. Armed with the right equipment, though, a spoofer can overcome them. Protections and new threats are continually evolving in a kind of arms race in the radio-frequency spectrum. "If your opponent happens to be the Russian Federation," Humphreys says, "good luck."

An arms race could be defused if the U.S. built a backup timing system like the ones other countries maintain. In December 2018 President Donald Trump signed the National Timing Resilience and Security Act, which instructs the Department of Transportation (DOT) to build a "land-based, resilient, and reliable alternative timing system" by 2020. But neither the act nor the president has funded this undertaking.

The law was just the latest example of the U.S. government's inadequate response, say critics such as Goward and others. The DHS issued a report on GPS vulnerability in 2001. President George W. Bush directed the DHS and the DOT to create a backup in 2004. The deputy defense secretary and deputy transportation secretary told Congress in 2015 that they would collaborate on a system known as eLoran (enhanced long-range navigation), which does exactly what the 2018 bill requires. Congress funded an eLoran pilot program years ago, but not a penny of that funding has been spent. Adam Sullivan, DOT assistant secretary for governmental affairs, told Peter DeFazio, chair of the House Transportation and Infrastructure Committee, in a May 8 letter that the DOT "is planning to conduct a field demonstration of technologies … capable of providing backup [position, navigation and timing] services to critical infrastructure" by the end of 2019. In September the DOT issued a request for proposals, a week after Senator Ted Cruz of Texas and Senator Ed Markey of Massachusetts wrote the transportation secretary to ask what was taking so long.

An eLoran system would render jamming and spoofing almost irrelevant by delivering a low-frequency radio signal that is much stronger than GPS's ultrahigh-frequency signal and hence is virtually impossible to override. The plan for eLoran would be to build about two dozen giant antennas necessary for nationwide coverage through a public-private partnership, according to Goward and to Representative John Garamendi of California, who has been prodding several administrations to act. The U.S. Air Force and the Pentagon are reportedly looking at other potential backup systems as well. The backups that various countries maintain are all essentially versions of eLoran.

Even if work begins tomorrow, eLoran will take years to build. It will be even longer before new devices and receivers that can pick up the signal are designed, manufactured and delivered to customers. "Four years is optimistic," says Frank Prautzsch, a former director of network systems at Raytheon, who also worked on space systems at Hughes Space and Communications.

A different global patch would be to alter GPS signals at the satellite source with digital signatures that authenticate the data and deploy the public-private key infrastructure common to cryptography. But the signal coming from the current constellation of satellites cannot be changed. An air force spokesperson said no plans exist to incorporate digital signatures into the next generation of satellites, now being built at a secure Lockheed Martin facility west of Denver.

Despite all that, Platt is confident in critical infrastructure's resilience. "We've talked with industry to make sure they have mitigation strategies in place," he says. Goward's response: "Suggest to Jim that we turn GPS off for 24 hours just to see what happens." SA

MORE TO EXPLORE

Above Us Only Stars: Exposing GPS Spoofing in Russia and Syria. C4ADS; March 26, 2019.

Dual-Antenna GNSS Spoofing Detection Method Based on Doppler Frequency Difference of Arrival. Li He et al. in *GPS Solutions*, Vol. 23, Article No. 78; July 2019.

FROM OUR ARCHIVES

The Global Positioning System. Thomas A. Herring; February 1996.

scientificamerican.com/magazine/sa

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CONSCIOUSNESS

Proust among the Machines

Within our lifetimes, computers could approach human-level intelligence. But will they be able to consciously experience the world?

By Christof Koch

A FUTURE WHERE THE THINKING CAPABILITIES OF COMPUTERS APPROACH OUR OWN IS quickly coming into view. We feel ever more powerful machine-learning (ML) algorithms breathing down our necks. Rapid progress in coming decades will bring about machines with human-level intelligence capable of speech and reasoning, with a myriad of contributions to economics, politics and, inevitably, warcraft. The birth of true artificial intelligence will profoundly affect humankind's future, including whether it has one.

The following quotes provide a case in point:

"From the time the last great artificial intelligence breakthrough was reached in the late 1940s, scientists around the world have looked for ways of harnessing this 'artificial intelligence' to improve technology beyond what even the most sophisticated of today's artificial intelligence programs can achieve."

"Even now, research is ongoing to better understand what the new AI programs will be able to do, while remaining within the bounds of today's intelligence. Most AI programs currently programmed have been limited primarily to making simple decisions or performing simple operations on relatively small amounts of data."

These two paragraphs were written by GPT-2, a language bot I tried last summer. Developed by OpenAI, a San Francisco–based institute that promotes beneficial AI, GPT-2 is an ML algorithm with a seemingly idiotic task: presented with some arbitrary starter text, it must predict the next word. The network isn't taught to "understand" prose in any human sense. Instead, during its training phase, it adjusts the internal connections in its simulated neural networks to best anticipate the next word, the word after that, and so on. Trained on eight million Web pages, its innards contain more than a billion connections that emulate synapses, the connecting points between neurons. When I entered the first few sentences of the article you are reading, the algorithm spewed out two paragraphs that sounded like a freshman's effort to recall the gist of an introductory lecture on machine learning during which she was daydreaming. The output contains all the right words and phrases—not bad, really! Primed with the same text a second time, the algorithm comes up with something different.

The offspring of such bots will unleash a tidal wave of "deep-

Illustration by Gérard Dubois

fake" product reviews and news stories that will add to the miasma of the Internet. They will become just one more example of programs that do things hitherto thought to be uniquely human—playing the real-time strategy game StarCraft, translating text, making personal recommendations for books and movies, recognizing people in images and videos.

It will take many further advances in machine learning before an algorithm can write a masterpiece as coherent as Marcel Proust's *In Search of Lost Time,* but the code is on the wall. Recall that all early attempts at computer game playing, translation and speech were clumsy and easy to belittle because they so obviously lacked skill and polish. But with the invention of deep neural networks and the massive computational infrastructure of the tech industry, computers relentlessly improved until their outputs no longer appeared risible. As we have seen with Go, chess and poker, today's algorithms can best humans, and when they do, our initial laughter turns to consternation. Are we like Goethe's sorcerer's apprentice, having summoned helpful spirits that we now are unable to control?

ARTIFICIAL CONSCIOUSNESS?

ALTHOUGH EXPERTS DISAGREE over what exactly constitutes intelligence, natural or otherwise, most accept that, sooner or later, computers will achieve what is termed artificial general intelligence (AGI) in the lingo.

The focus on machine intelligence obscures quite different questions: Will it feel like anything to be an AGI? Can programmable computers ever be conscious?

By "consciousness" or "subjective feeling," I mean the quality inherent in any one experience—for instance, the delectable taste of Nutella, the sharp sting of an infected tooth, the slow passage of time when one is bored, or the sense of vitality and anxiety just before a competitive event. Channeling philosopher Thomas Nagel, we could say a system is conscious if there is something it is like to *be* that system.

Consider the embarrassing feeling of suddenly realizing that you have just committed a gaffe, that what you meant as a joke came across as an insult. Can computers ever experience such roiling emotions? When you are on the phone, waiting minute after minute, and a synthetic voice intones, "We are sorry to keep you waiting," does the software actually feel bad while keeping you in customer-service hell?

There is little doubt that our intelligence and our experiences are ineluctable consequences of the natural causal powers of our brain, rather than any supernatural ones. That premise has served science extremely well over the past few centuries as people explored the world. The three-pound, tofulike human brain is by far the most complex chunk of organized active matter in the known universe. But it has to obey the same physical laws as dogs, trees and stars. Nothing gets a free pass. We do not yet fully understand the brain's causal powers, but we experience them every day—one group of neurons is active while you are seeing colors, whereas the cells firing in another cortical neighborhood are associated with being in a jocular mood. When these neurons are stimulated by a neurosurgeon's electrode, the subject sees colors or erupts in laughter. Conversely, shutting down the brain during anesthesia eliminates these experiences.

IN BRIEF

Machines with human-level intelligence are on the horizon. **Whether** they will actually be conscious remains unknown. **Why?** Even the most sophisticated brain simulations are unlikely to produce conscious feelings.

Given these widely shared background assumptions, what will the evolution of true artificial intelligence imply about the possibility of artificial consciousness?

Contemplating this question, we inevitably come to a fork up ahead, leading to two fundamentally different destinations. The zeitgeist, as embodied in novels and movies such as *Blade Runner, Her* and *Ex Machina,* marches resolutely down the road toward the assumption that truly intelligent machines will be sentient; they will speak, reason, self-monitor and introspect. They are *eo ipso* conscious.

This path is epitomized most explicitly by the global neuronal workspace (GNW) theory, one of the dominant scientific theories of consciousness. The theory starts with the brain and infers that some of its peculiar architectural features are what gives rise to consciousness.

Its lineage can be traced back to the "blackboard architecture" of 1970s computer science, in which specialized programs accessed a shared repository of information, called the blackboard or central workspace. Psychologists postulated that such a processing resource exists in the brain and is central to human cognition. Its capacity is small, so only a single percept, thought or memory occupies the workspace at any one time. New information competes with the old and displaces it.

Cognitive neuroscientist Stanislas Dehaene and molecular biologist Jean-Pierre Changeux, both at the Collège de France in Paris, mapped these ideas onto the architecture of the brain's cortex, the outermost layer of gray matter. Two highly folded cortical sheets, one on the left and one on the right, each the size and thickness of a 14-inch pizza, are crammed into the protective skull. Dehaene and Changeux postulated that the workspace is instantiated by a network of pyramidal (excitatory) neurons linked to far-flung cortical regions, in particular the prefrontal, parietotemporal and midline (cingulate) associative areas.

Much brain activity remains localized and therefore unconscious—for example, that of the module that controls where the eyes look, something of which we are almost completely oblivious, or that of the module that adjusts the posture of our bodies. But when activity in one or more regions exceeds a threshold—say, when someone is presented with an image of a Nutella jar—it triggers an ignition, a wave of neural excitation that spreads throughout the neuronal workspace, brain-wide. That signaling therefore becomes available to a host of subsidiary processes such as language, planning, reward circuits, access to long-term memory, and storage in a short-term memory buffer. The act of globally broadcasting this information is what renders it conscious. The inimitable experience of Nutella is constituted by pyramidal neurons contacting the brain's motor-planning region—issuing an instruction to grab a spoon to scoop out some of the hazelnut spread. Meanwhile other modules transmit the message to expect a reward in the form of a dopamine rush caused by Nutella's high fat and sugar content.

Conscious states arise from the way the workspace algorithm processes the relevant sensory inputs, motor outputs, and internal variables related to memory, motivation and expectation. Global processing is what consciousness is about. GNW theory fully embraces the contemporary mythos of the near-infinite powers of computation. Consciousness is just a clever hack away.

INTRINSIC CAUSAL POWER

THE ALTERNATIVE PATH—integrated information theory (IIT)—takes a more fundamental approach to explaining consciousness.

Giulio Tononi, a psychiatrist and neuroscientist at the University of Wisconsin–Madison, is the chief architect of IIT, with others, myself included, contributing. The theory starts with experience and proceeds from there to the activation of synaptic circuits that determine the "feeling" of this experience. Integrated information is a mathematical measure quantifying how much "intrinsic causal power" some mechanism possesses. Neurons firing action potentials that affect the downstream cells they are wired to (via synapses) are one type of mechanism, as are electronic circuits, made of transistors, capacitances, resistances and wires.

Intrinsic causal power is not some airy-fairy ethereal notion but can be precisely evaluated for any system. The more its current state specifies its cause (its input) and its effect (its output), the more causal power it possesses.

IIT stipulates that any mechanism with intrinsic power, whose state is laden with its past and pregnant with its future, is conscious. The greater the system's integrated information, represented by the Greek letter Φ (a zero or positive number pronounced "fi"), the more conscious the system is. If something has no intrinsic causal power, its Φ is zero; it does not feel anything.

Given the heterogeneity of cortical neurons and their densely overlapping set of input and output connections, the amount of integrated information within the cortex is vast. The theory has inspired the construction of a consciousness meter currently under clinical evaluation, an instrument that determines whether people in persistent vegetative states or those who are minimally conscious, anesthetized or locked-in are conscious but unable to communicate or whether "no one is home." In analyses of the causal power of programmable digital computers at the level of their metal components—the transistors, wires and diodes that serve as the physical substrate of any computation—the theory indicates that their intrinsic causal power and their Φ are minute. Furthermore, Φ is independent of the software running on the processor, whether it calculates taxes or simulates the brain.

Indeed, the theory proves that two networks that perform the same input-output operation but have differently configured circuits can possess different amounts of Φ. One circuit may have no Φ, whereas the other may exhibit high levels. Although they are identical from the outside, one network experiences something while its zombie impostor counterpart feels nothing. The difference is under the hood, in the network's internal wiring. Put succinctly, consciousness is about *being,* not about *doing*.

The difference between these theories is that GNW emphasizes the function of the human brain in explaining consciousness, whereas IIT asserts that it is the intrinsic causal powers of the brain that really matter.

The distinctions reveal themselves when we inspect the brain's connectome, the complete specification of the exact synaptic wiring of the entire nervous system. Anatomists have already mapped the connectomes of a few worms. They are working on the connectome for the fruit fly and are planning to tackle the mouse within the next decade. Let us assume that in the future it will be possible to scan an entire human brain, with its roughly 100 billion neurons and quadrillion synapses, at the ultrastructural level after its owner has died and then simulate the organ on some advanced computer, maybe a quantum machine. If the model is faithful enough, this simulation will wake up and behave like a digital simulacrum of the deceased person—speaking and accessing his or her memories, cravings, fears and other traits.

If mimicking the functionality of the brain is all that is needed to create consciousness, as postulated by GNW theory, the simulated person will be conscious, reincarnated inside a computer. Indeed, uploading the connectome to the cloud so people can live on in the digital afterlife is a common science-fiction trope.

IIT posits a radically different interpretation of this situation: the simulacrum will feel as much as the software running on a fancy Japanese toilet—nothing. It will act like a person but without any innate feelings, a zombie (but without any desire to eat human flesh)—the ultimate deepfake.

To create consciousness, the intrinsic causal powers of the brain are needed. And those powers cannot be simulated but must be part and parcel of the physics of the underlying mechanism.

To understand why simulation is not good enough, ask yourself why it never gets wet inside a weather simulation of a rainstorm or why astrophysicists can simulate the vast gravitational power of a black hole without having to worry that they will be swallowed up by spacetime bending around their computer. The answer: because a simulation does not have the causal power to cause atmospheric vapor to condense into water or to cause spacetime to curve! In principle, however, it would be possible to achieve human-level consciousness by going beyond a simulation to build so-called neuromorphic hardware, based on an architecture built in the image of the nervous system.

There are other differences besides the debates about simulations. IIT and GNW predict that distinct regions of the cortex constitute the physical substrate of specific conscious experiences, with an epicenter in either the back or the front of the cortex. This prediction and others are now being tested in a large-scale collaboration involving six labs in the U.S., Europe and China that has just received $5 million in funding from the Templeton World Charity Foundation.

Whether machines can become sentient matters for ethical reasons. If computers experience life through their own senses, they cease to be purely a means to an end determined by their usefulness to us humans. They become an end unto themselves.

Per GNW, they turn from mere objects into subjects—each exists as an "I"—with a point of view. This dilemma comes up in the most compelling *Black Mirror* and *Westworld* television episodes. Once computers' cognitive abilities rival those of humanity, their impulse to push for legal and political rights will become irresistible—the right not to be deleted, not to have their memories wiped clean, not to suffer pain and degradation. The alternative, embodied by IIT, is that computers will remain only supersophisticated machinery, ghostlike empty shells, devoid of what we value most: the feeling of life itself. SA

MORE TO EXPLORE

What Is Consciousness, and Could Machines Have It? Stanislas Dehaene, Hakwan Lau and Sid Kouider in *Science,* Vol. 358, pages 486–492; October 27, 2017.

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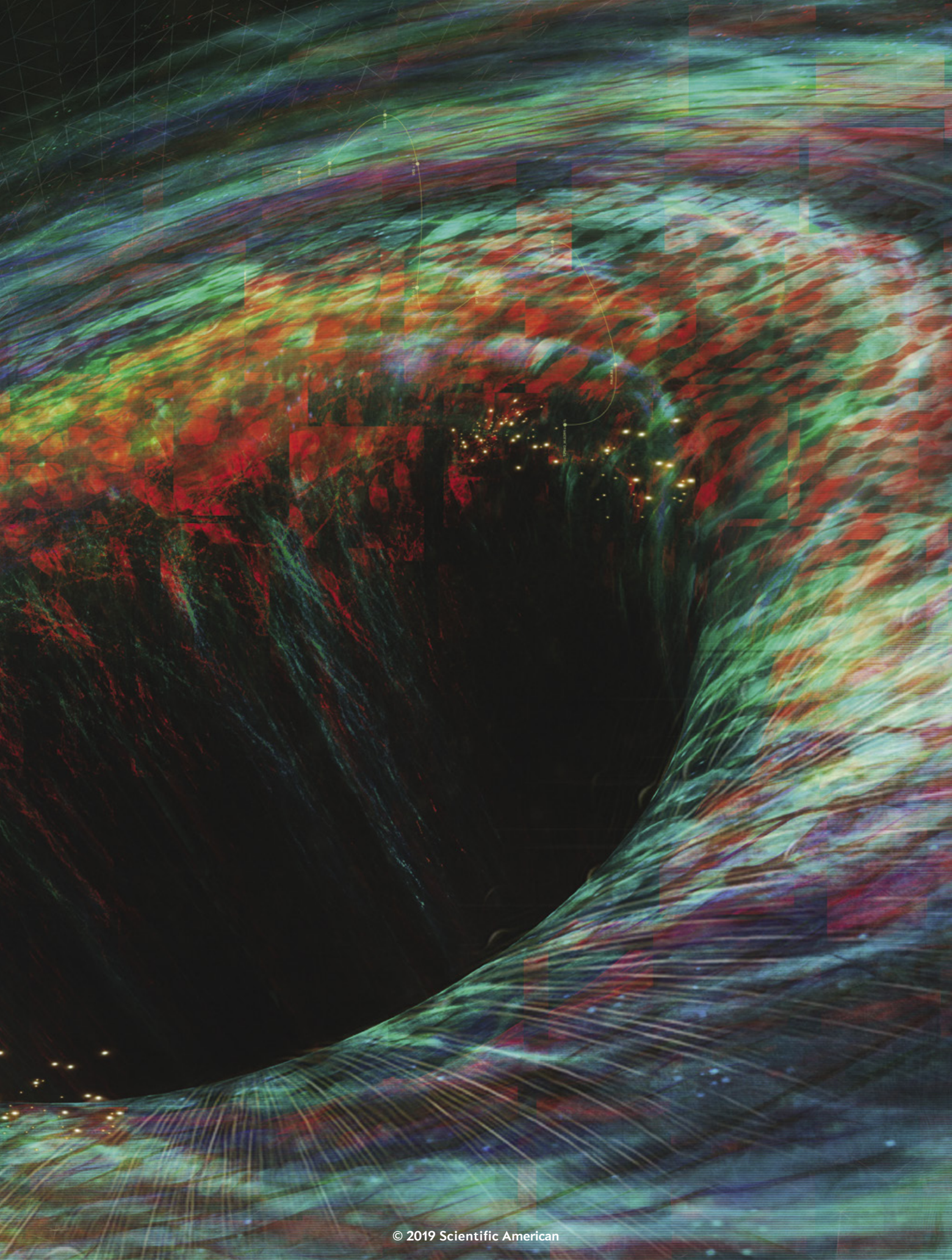
PHYSICS

ESCAPE FROM A BLACK HOLE

To save quantum mechanics, information must break free from black holes. New observations may help tell us how

By Steven B. Giddings

Illustration by Mondolithic Studios



Steven B. Giddings is a quantum physicist at the University of California, Santa Barbara, who focuses on high-energy theory, quantum aspects of gravity and quantum black holes.

HUMANKIND CAUGHT ITS FIRST GLIMPSE OF A BLACK HOLE on April 10, 2019. The Event Horizon Telescope (EHT) team, which uses an Earth-spanning network of radio observatories acting in concert, shared images it had captured of an apparent black hole with 6.5 billion times the mass of our sun in the center of the nearby M87 galaxy. This was a breathtaking achievement—our first views of one of the most mysterious objects in the universe, long predicted but never directly "seen." Even more exciting, the images, and the observations that should follow, are beginning to provide new clues about one of the deepest puzzles in physics.

This enigma is the "paradox" of what happens to information in a black hole. By investigating this question, physicists have discovered that the mere existence of black holes is inconsistent with the quantum-mechanical laws that so far describe everything else in our universe. Resolving this inconsistency may require a conceptual revolution as profound as the overthrow of classical physics by quantum mechanics.

Theorists have explored many ideas, but there has been little direct evidence to help resolve this problem. The first image of a black hole, however, begins to offer actual data to inform our theories. Future EHT observations—especially those that can show how black holes evolve over time—and recent detections of colliding black holes by gravitational-wave observatories could provide important new insights and help to usher in a whole new era of physics.

IN BRIEF

According to quantum mechanics, information can never be destroyed. But when combined with general relativity, quantum rules say that black holes destroy information. **Scientists have proposed** modifications to the classical picture of black holes that could solve the paradox, but they lack evidence to test them. **That is changing** with the new Event Horizon Telescope, which recently took the first picture of a black hole, as well as with gravitational-wave measurements of black holes colliding.

THE INFORMATION PROBLEM

THOUGH DEEPLY MYSTERIOUS, black holes seem to be ubiquitous in the cosmos. The EHT observations and the gravitational-wave measurements are just the latest and most robust evidence that black holes, despite sounding fantastical, do indeed appear to be real—and remarkably common. Yet their very existence threatens the present foundations of physics. The basic principles of quantum mechanics are thought to govern all the other laws of nature, but when they are applied to black holes they lead to a contradiction, exposing a flaw in the current form of these laws.

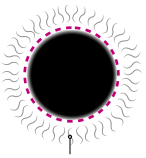
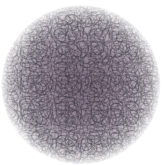
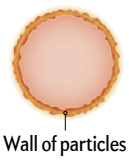
The problem arises from one of the simplest questions we can ask about black holes: What happens to stuff that falls into them? We need a little refinement here to fully explain. First, according to our present quantum-mechanical laws, matter and energy can shift between different forms: particles can, for example, change into different kinds of particles. But the one thing that is sacred and never destroyed is quantum information. If we know the complete quantum description of a system, we should always be able to exactly determine its earlier or later quantum description with no loss of information. So a more precise question is, What happens to quantum information that falls into a black hole?

Our understanding of black holes comes from Albert Einstein's general theory of relativity, which describes gravity as arising from the curvature of space and time; a common visualization of this idea is a heavy ball deforming the surface of a trampoline. This warping of spacetime causes the trajectories of massive bodies and light to bend, and we call that gravity. If mass is sufficiently concentrated in a small-enough vicinity, the nearby spacetime deformation is so strong that light itself cannot escape a region inside what we call the event horizon: we have a black hole. And if nothing can travel faster than light—including information—everything must get stuck inside this boundary. Black holes become cosmic sinkholes trapping information along with light and matter.

But the story becomes stranger. What may be Stephen Hawking's greatest discovery is his 1974 prediction that black holes evaporate. This finding also led to the startling idea that black holes destroy quantum information. According to quantum mechanics, pairs of "virtual particles" pop into existence all the time, everywhere. Typically such a pair, consisting of a particle and its antimatter counterpart, quickly annihilates, but if it forms near the horizon of a black hole, one particle might pop up inside this boundary and the other outside. The outside particle can escape, carrying away energy. The law of energy conservation tells us that the black hole has thus lost energy, so the emission of such particles causes the black hole to shrink over time until it completely disappears. The

The Information Problem

Black holes were predicted by general relativity, and mounting astrophysical evidence supports their existence. But in 1974 Stephen Hawking argued that black holes eventually evaporate. If so, everything that falls into them is ultimately destroyed, including the information contained in the matter that fell in. The problem is that quantum mechanics and energy conservation forbid such destruction of information. In response, physicists have come up with several suggestions for how to modify our picture of black holes to make them compatible with quantum physics:

	HYPOTHESIS	DESCRIPTION	PROBLEM
Information is destroyed	**"Classical" black hole** 	Black hole with an event horizon; information that enters the black hole is destroyed when the black hole evaporates.	Contradicts quantum mechanics and energy conservation, which say that information cannot be destroyed.
Information is not destroyed	**Soft hair** 	Information does not fully enter the black hole but instead leaves an "imprint" just outside the event horizon.	Most experts do not regard this picture as providing a convincing resolution.
	Fuzzball 	A type of massive remnant in which the black hole horizon is replaced by strings and higher-dimensional geometry.	All three of these scenarios require modification of the conventional notion of locality—that is, the idea that nothing, including information, can travel faster than light.
	Firewall 	A type of massive remnant in which a "wall" of high-energy particles replaces the horizon; there is no black hole interior.	
	Quantum halo 	A quantum black hole interacts with its surroundings, possibly through small fluctuations in spacetime, allowing information to transfer out.	

problem is that the escaping particles, known as Hawking radiation, carry essentially no information about what went into the black hole. Therefore, Hawking's calculations appear to show that quantum information that falls into a black hole is ultimately destroyed—contradicting quantum mechanics.

This revelation initiated a deep crisis in physics. Great advances have followed from previous such crises. For instance, at the beginning of the 20th century, classical physics seemed to predict the inevitable instability of atoms, in obvious contradiction to the existence of stable matter. That problem played a key role in the quantum revolution. Classical physics implied that because orbiting electrons within atoms are constantly changing direction, they continually emit light, causing them to lose energy and spiral into the nucleus. But in 1913 Niels Bohr proposed that electrons actually travel only within quantized orbits and cannot spiral in. This radical idea helped to establish the basis of quantum mechanics, which fundamentally rewrote the laws of nature. Increasingly it seems that the black hole crisis will similarly lead to another paradigm shift in physics.

QUANTUM ALTERNATIVES

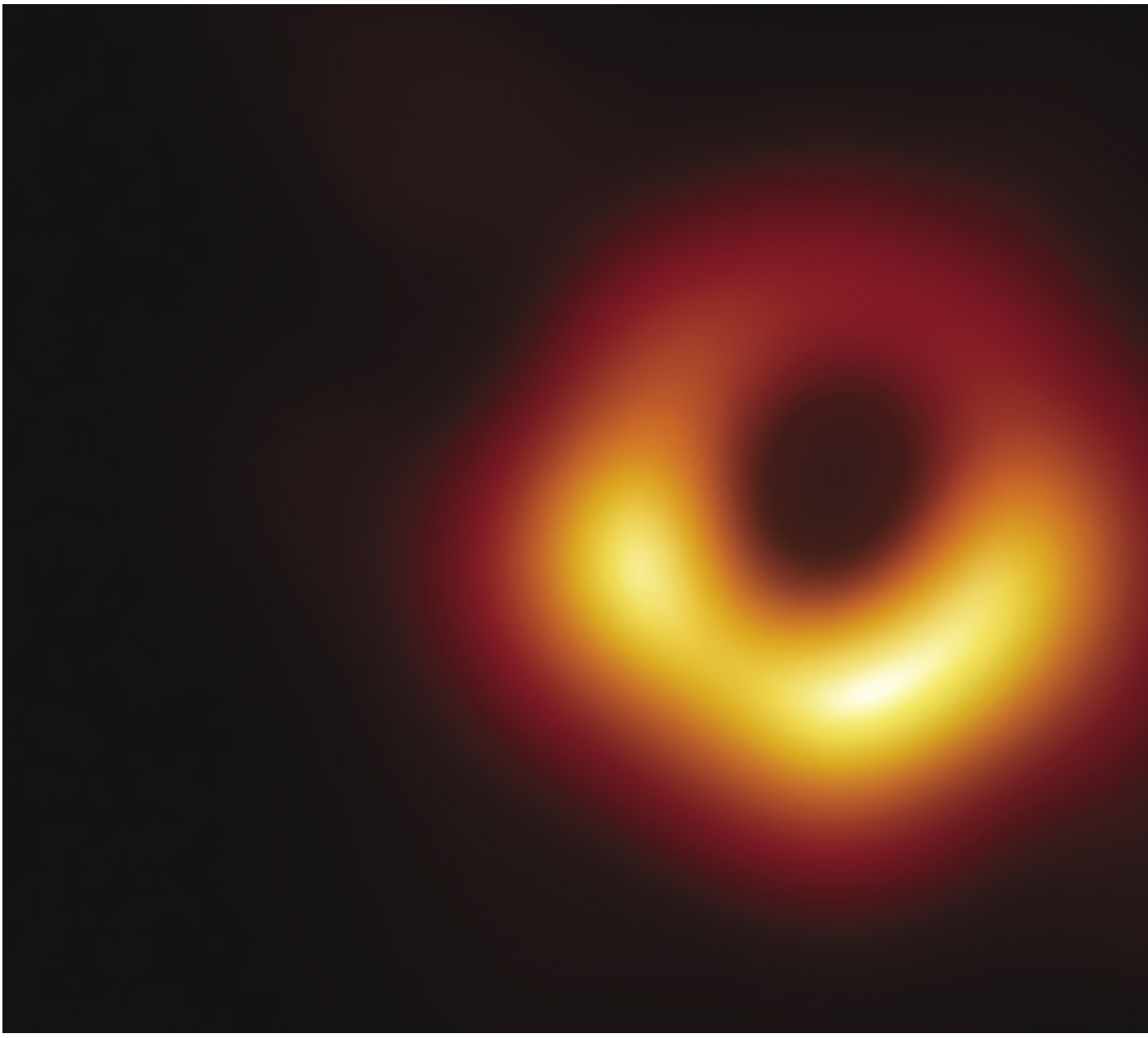
WHEN HAWKING FIRST predicted black hole evaporation, he suggested that quantum mechanics must be wrong and that information destruction is allowed. Yet physicists soon realized this change would require a drastic breakdown of the law of energy conservation, which would disastrously invalidate our present description of the universe. Apparently the resolution must be sought elsewhere.

Another early idea was that black holes do not completely evaporate but instead stop shrinking at a tiny size, leaving behind microscopic remnants containing the original information. But, scientists realized, if this were true, basic properties of quantum physics would predict catastrophic instabilities causing ordinary matter to explode into such remnants, also contradicting everyday experience.

Obviously something is deeply wrong. It is tempting to conclude that the flaw is in Hawking's original analysis and that somehow information does escape a black hole emitting Hawking radiation. The challenge here is that this scenario would conflict with a foundational concept of present-day physics, the principle of locality, which states that information cannot move from one place to another superluminally—that is, faster than the speed of light. But according to our definition of black holes, the *only* way to escape one is to travel faster than light, so if information does escape, it must be doing so superluminally, in conflict with locality. In the four decades since Hawking's discovery, physicists have tried to find a loophole to this argument that stays within conventional physics, but none has emerged.

The closest attempt was a 2016 proposal by Hawking, Malcolm Perry and Andrew Strominger, who

Illustration by Amanda Montañez



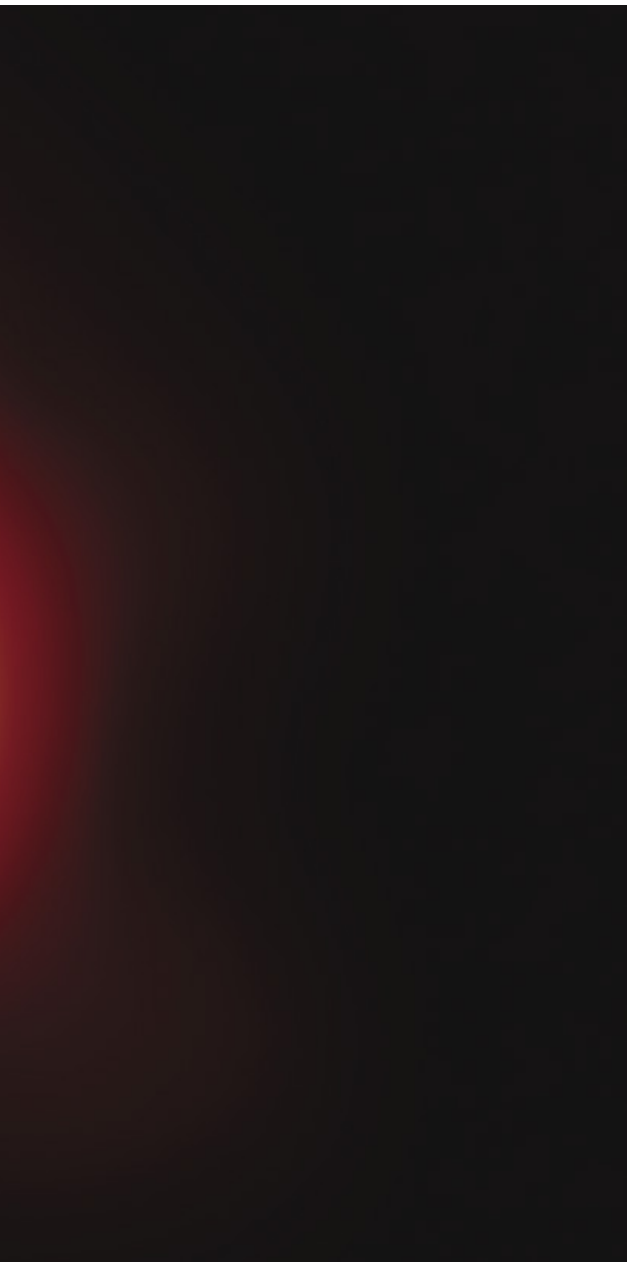
GRAVITY BENDS light around an apparent black hole at the center of the M87 galaxy in this seminal image from the Event Horizon Telescope.

EHT COLLABORATION AND EUROPEAN SOUTHERN OBSERVATORY

suggested that a mistake in the original analysis implies information never fully enters a black hole but instead leaves a kind of imprint in the form of what they called "soft hair" outside it. Closer examination seems to be closing this loophole, however, and most experts do not believe this can be the answer. In short, more radical steps appear to be needed.

An obvious idea is that there is some unknown physics that prevents true black holes from existing at all. The conventional picture of black hole formation says that when very large stars burn out and die, their mass collapses under the force of gravity into a black hole. But what if they never reach that stage and actually transform into objects with "better" behavior? In fact, we know that when lower-mass stars such as our sun burn out and collapse, they do not form black holes and instead form dense remnants—for example, white dwarfs or neutron stars. Perhaps some unknown laws of physics also prevent larger stars from forming black holes and instead lead them to become a kind of "massive remnant"—something more like a neutron star than a black hole.

The problem with this suggestion is that we cannot explain what would stabilize such objects—no known physics should prevent their continued collapse under gravity, and any imagined physics that did would apparently require superluminal signaling from one side of the collapsing matter to the other. In fact, conventional large black holes can form from *very* low-density matter. To illustrate, if the 6.5-billion-solar-mass black hole in M87 arose from the collapse of a dust cloud (which is theoretically possible,



although the actual process was apparently more complex), it would have happened when the dust reached the density of air at the top of Mount Everest. (Air on top of Everest does not form a black hole, because there is not enough of it; one would require an accumulated 6.5 billion solar masses.) Some drastic and superluminal new physical process would need to take over in such a low-density regime to instantly convert the collapsing cloud into a massive remnant instead of allowing a black hole to form.

A related idea is that something could cause black holes to change into massive remnants containing the original information after they form but long before they evaporate. But once again, this story requires nonlocal transfer of information from the interior of the initial black hole to the final remnant.

Despite their problems, physicists have explored versions of both these scenarios. For example, in 2003 Samir Mathur put forward a proposal based on string theory, which posits that fundamental particles are tiny strings. His idea is that a black hole transforms into a "fuzzball," a kind of massive remnant, or that a fuzzball forms instead of a black hole in the first place. Thanks to the complicated physics of string theory and its allowance for more than the traditional four dimensions of spacetime, fuzzballs might have a complex higher-dimensional geometry; instead of the sharp traditional boundary of a black hole at the event horizon, a fuzzball would have a fuzzier and larger boundary where one encounters strings and higher-dimensional geometry.

Alternatively a more recent version of a remnant scenario is the proposal that instead of a black hole with an event horizon, a massive remnant forms with a surface "firewall" of high-energy particles where the horizon would be. This firewall would incinerate anything that encountered it, turning it into pure energy that added to the firewall. Both the firewall and the fuzzball, though, share the problem of needing locality violation, and the resulting objects would have other properties that are very hard to explain.

MODIFYING LOCALITY

A COMMON THREAD in massive-remnant proposals is that saving quantum mechanics appears to require violation of the locality principle. But doing so carelessly is expected to be as disastrous as modifying quantum mechanics and, in fact, typically leads to another paradox. Specifically, the laws of relativity say that if you send a faster-than-light signal in empty, flat space, observers traveling past you at a high-enough speed will see the signal going backward in time. The paradox arises because this superluminal signaling then allows you to send a message into your past, for example, asking someone to kill your grandmother before your mother is born.

Even though this kind of answer appears to contradict fundamental physical principles, it is worth a closer look. Modifying locality seems crazy, but we have not found an alternative that does not. The severe nature of the black hole crisis strongly suggests a resolution via some subtle violation of the locality principle, one that does not produce such paradoxes. Put differently, quantum mechanics implies information is never destroyed, so information that falls into a black hole *must* ultimately escape, possibly through some new, subtle "delocalization" of information that might become clear when we can finally find a way to unify quantum mechanics and gravity—one of the most profound problems of present-day physics. In fact, we have other reasons to think such a subtlety could be present. The very idea of localized information—that it can exist in one place and not in another—is more delicate in

theories that include gravity than in those that do not, because gravitational fields extend to infinity, complicating the concept of localization.

If information does escape black holes, it might not require a change as obvious and abrupt as the formation of a massive remnant, whether fuzzball, firewall or another variant. The growing evidence for black holes suggests there are objects in the universe that look and act a lot like classical black holes, without large departures from Einstein's predictions. Is Einstein's general relativity so drastically wrong in its description of black holes, or might there be some more innocuous, currently unknown effects that delocalize information and allow it to leak from black holes, avoiding such a dramatic failure of the entire spacetime picture?

Our very notions of space and time, which underlie the rest of science, appear to require significant revision.

In my recent theoretical work, I have found two versions of such effects. In one, the geometry of spacetime near a black hole is altered, making it bend and ripple in a way that depends on the information in the black hole—but gently, so that it does not, for example, destroy an astronaut falling through the region where the horizon would ordinarily be found. In this "strong, nonviolent" scenario, such shimmering of spacetime can transfer the information out. Interestingly, I have also found that there is a subtler, intrinsically quantum way for information to escape the black hole. In this "weak, nonviolent" scenario, even tiny quantum fluctuations of the spacetime geometry near the black hole can transfer information to particles emanating from the hole. The fact that the information transfer is still large enough to save quantum mechanics is related to the huge amount of possible information a black hole can contain. In either picture, a black hole effectively has a "quantum halo" surrounding it, where interactions pass information back to its surroundings.

Notably, these scenarios, despite appearing to require superluminal travel of information, do not necessarily produce a grandmother paradox. The information signaling here is tied to the existence of the black hole, which has a spacetime geometry that is different from that of flat space, so that the earlier argument about communicating with the past no longer holds. These possibilities are tantalizing from another perspective: the locality principle is also what prohibits our own faster-than-light travel; the quantum mechanics of black holes seems to be telling us there is something wrong with the present formulation of this principle.

REWRITING THE LAWS OF PHYSICS

SO FAR SUCH A QUANTUM-HALO scenario has not been predicted by a more complete theory of physics that reconciles quantum mechanics with gravity, but it is strongly indicated by the need to resolve the problem and by assumptions based on what we see. If such a scenario is correct, it probably represents an approximate description of a deeper reality. Our very notions of space and time, which underlie the rest of science, appear to require significant revision. The present work to understand black holes may be akin to the first attempts to model the physics of the atom by Bohr and others. Those early atomic descriptions were also approximate and only later led to the profound theoretical structure of quantum mechanics. Although modifying locality seems crazy, we might find solace by noting that the laws of quantum mechanics also seemed very crazy to the classical physicists grappling with their discovery.

Given the immense challenge in sorting out the story of quantum black holes and the more complete theory describing them, physicists are eager for experimental and observational evidence to help guide us. The exciting recent advances have given humankind two direct observational windows on black hole behavior. In addition to the EHT's images of black holes, the Laser Interferometer Gravitational-Wave Observatory (LIGO) and its companion facilities have begun to detect gravitational waves from collisions between apparent black holes. These waves carry valuable information with them about the properties and behavior of the objects that created them.

From a naive viewpoint, it seems preposterous that the EHT or LIGO could detect any departure from Einstein's description of black holes. Traditionally his theory has been expected to need modification only when spacetime curvatures become extremely large, near the center of a black hole; in contrast, curvatures are very weak near the horizon of a large black hole. But the information crisis I have described suggests otherwise. A large part of the theoretical community has now reached the consensus that some changes to the current laws of physics are needed to describe phenomena not just deep inside a black hole but all the way out past the horizon. We appear to have crossed the Rubicon. For the case of the black hole in M87, the distance at which we expect to find deviations from classical predictions is several times the size of our solar system.

Already LIGO and the EHT have ruled out wilder possibilities that could be considered in an attempt to give a logically consistent description of black holes. Specifically, if black holes were replaced by massive remnants more than about twice the diameter of the supposed black hole, we would have seen signs in the data from both experiments. In the case of the EHT, much of the light that produced the now famous image comes from a region around one and a

half times the diameter of the event horizon. And for LIGO, part of the gravitational-wave signal that we detect is likewise produced from the region where the colliding objects reach similarly small separations. Although study of these signals is still in early phases, the EHT and LIGO have revealed very dark and very compact objects that produce signals just like those predicted for unmodified black holes.

Still, it is important to investigate these signals more closely. Sufficiently careful analysis might in fact uncover more clues about the quantum physics of black holes. Even if no new effects are observed, we then have information that constrains possible descriptions of their quantum behavior.

Sufficiently large-diameter remnants are now ruled out, but what about remnant scenarios that modify the black hole description only very near the horizon? Although a complete discussion would require a fuller theory of these remnants—such as fuzzballs or firewalls—we have some initial indicators. Specifically, if these objects had radii barely larger than the radius of the corresponding black hole horizon, then it is likely that neither EHT nor LIGO observations would be able to reveal such a structure because very little light or gravitational radiation escapes from the region very near the horizon.

One possible exception is the possibility of gravitational "echoes." As first suggested in 2016 by Vitor Cardoso of the University of Lisbon, Edgardo Franzin of the University of Barcelona and Paolo Pani of Rome University, if two such remnants combine to form a final remnant that has similar properties, gravitational waves can reflect off the merged remnant's surface and might be observed. Whereas most near-horizon scenarios are hard to rule out through observation, however, it is difficult to explain how such structures could be stable, instead of collapsing under their own weight to form black holes. Of course, this is a general problem for all massive-remnant scenarios, but it becomes even more challenging in the presence of the extreme forces in such a collision.

Prospects are better for testing some of the scenarios where new interactions behave like subtle modifications of spacetime geometry but extend well outside the horizon. For example, in the strong nonviolent scenario, the rippling of a black hole's quantum halo can distort light passing near the black hole. If this scenario is correct, the shimmering could cause distortions of the EHT's images that change with time.

In my work with EHT scientist Dimitrios Psaltis, we found these changes could happen over roughly an hour for the black hole in the center of our galaxy. Because the EHT combines multihour observations into an average, such effects may be hard to see. But the relevant fluctuation time for the black hole in M87, which is more than 1,000 times larger, is more like tens of days. This work suggests we should look for these distortions by using longer-duration EHT observations than the project's initial seven-day span. If the experiment found such distortions, they would be a spectacular clue to the quantum physics of black holes. If they do not appear, that will begin to point to the subtler weak quantum scenario or to something even more exotic.

The weak nonviolent scenario is harder to test because of the relative smallness of the expected changes to the geometry. Yet preliminary investigation shows that this scenario can alter how gravitational waves are absorbed or reflected, possibly yielding an observable modification to gravitational-wave signals.

If either scenario is correct, we will learn more not only about what quantum black holes are but also about the deeper laws of nature. Right now we do not fully understand how to think about information localization when gravitational fields are present. Quantum physics suggests that spacetime itself is not a fundamental part of physics but instead arises only as an approximation of a more basic mathematical structure. Evidence for quantum black hole effects could help make this concept more concrete.

To learn more, it is important to extend and improve both EHT and gravitational-wave measurements. For the EHT, it would be useful to have significantly longer-duration observations, as well as images of other targets such as our galaxy's central black hole, both of which are anticipated. For gravitational waves, more observations with increased sensitivity would be helpful and will be assisted when additional detectors come online in Japan and India, adding to the existing facilities in the U.S. and Europe. Furthermore, a strong complementary theoretical effort is needed to refine scenarios, to better clarify their origins and explanations, and to assess more thoroughly the question of how significantly they can affect EHT or gravitational-wave signals.

Whatever the resolution to the crisis, black holes contain crucial clues to the basic quantum physics of gravity, as well as to the very nature of space and time. Just as with the atom and quantum mechanics, a better understanding of black holes is likely to help guide the next conceptual revolution in physics. EHT and gravitational-wave observations have the potential to provide us with key information, either by ruling out quantum black hole scenarios or by discovering new phenomena associated with them. SA

MORE TO EXPLORE

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Australopithecus anamensis

Kate Wong is a senior editor for evolution and ecology at *Scientific American.*

PALEOANTHROPOLOGY

A FACE FROM DEEP TIME

A long-sought fossil cranium could redraw the human family tree

By Kate Wong

NEARLY 25 YEARS AFTER SCIENTISTS described the first fossil traces of *Australopithecus anamensis,* this unsung human ancestor is finally having its moment. Researchers working in Ethiopia have found a nearly complete cranium of this long-vanished member of the hominin group, which includes *Homo sapiens* and its close extinct relatives. The fossil, dated to 3.8 million years ago, reveals the never before seen face of *A. anamensis,* a species previously known mainly from jaws, teeth and a smattering of bones from below the head. Traits evident in the specimen hint that our family tree may need revising.

By some accounts, *A. anamensis* is the oldest unequivocal hominin, with some fossils dating from as far back as 4.2 million years ago. For years it has occupied a key position in the family tree as the lineal ancestor of *Australopithecus afarensis,* which is widely viewed as the ancestor of our own genus, *Homo.* Based on the ages and characteristics of the available fossils, paleoanthropologists thought *A. anamensis* gave rise to *A. afarensis* through an evolutionary process termed anagenesis, in which one species transforms into another. The new fossil throws a wrench into the works of that theory.

Yohannes Haile-Selassie of the Cleveland Museum of Natural History and his colleagues recovered the cranium from an area in northeastern Ethiopia's Afar region known as Woranso-Mille. Features of its teeth and jaws link it to the previously known fragmentary remains of *A. anamensis.* The fossil shows a creature with a projecting face, large canine teeth, flaring cheekbones, a crest atop its head that anchored strong jaw muscles, and a long, narrow braincase that held a brain the size of a chimpanzee's. The discovery team suspects the cranium belonged to an adult male *A. anamensis.*

Here is how it could upend the conventional wisdom: on the basis of the more complete *A. anamensis* anatomy seen in the newly discovered cranium, Haile-Selassie and his colleagues argue that an enigmatic 3.9-million-year-old forehead bone from the site of Belohdelie, also located in Ethiopia's Afar region, belongs to *A. afarensis.* If this supposition is right, *A. anamensis,* which is known from fossils spanning the time between 4.2 million and 3.8 million years ago, and *A. afarensis,* which apparently lived from 3.9 million to 3.0 million years ago, actually overlapped for at least 100,000 years in the Afar. And that overlap would imply that *A. anamensis* could not have evolved into *A. afarensis* by means of anagenesis. Instead *A. afarensis* split off from *A. anamensis,* which continued to exist for a time alongside its daughter species. This branching mode of evolution, known as cladogenesis, can occur when populations of a species become isolated from one another and are thus able to evolve in different directions.

But the case for cladogenesis over anagenesis hinges entirely on that 3.9-million-year-old forehead bone from Belohdelie belonging to *A. afarensis*—no other *A. afarensis* remains recovered thus far are that old. Problematically, with only one *A. anamensis* forehead bone to compare it with—the one in the new fossil—one cannot exclude the possibility that other *A. anamensis* individuals might have had foreheads that looked like the Belohdelie one. Only discovery of more fossil faces can resolve that unknown. SA

PHOTOGRAPHY BY DALE OMORI AND LIZ RUSSELL; COMPOSITE IMAGE OF HANDS HOLDING "MRD" BY JENNIFER TAYLOR AND CLEVELAND MUSEUM OF NATURAL HISTORY

GEOSCIENCE

RESEARCHERS ARE GETTING CLOSER TO PREDICTING WHEN AND WHERE THESE LETHAL VORTICES WILL APPEAR

By Jason M. Forthofer

Photography by Spencer Lowell

fire tornadoes

FIRE WHIRL is formed by rotating air drafting into a pan of burning alcohol at the Missoula Fire Sciences Laboratory in Montana.

Jason M. Forthofer is a firefighter and mechanical engineer at the U.S. Forest Service's Missoula Fire Sciences Laboratory in Montana. His research involves field, laboratory and computational studies of heat transfer and fluid flow related to wildland fires.

AS THE PLANE BEGAN ITS DESCENT INTO MEDFORD, we dropped into the blanket of smoke that covered southwestern Oregon and northern California. It was late July 2018, and several major fires were burning in the region. I was en route to join a Cal Fire (California Department of Forestry and Fire Protection) team investigating a fatal incident that had taken place two days earlier. What the group leader told me over the phone had sent chills up my spine: "A firefighter has been killed in a fire tornado. His vehicle was thrown hundreds of feet across the ground."

I, perhaps more than anyone, had known that this might happen someday. Ten years earlier I had gotten my first look at the aftermath of a fire tornado. The object, almost 1,000 feet in diameter, had moved out of the Indians Fire in California and overrun a group of firefighters. So strong was the wind that trying to get to safety felt like running through chest-deep water, one of the survivors told me. Fortunately, the men were standing on a paved two-lane highway, which probably saved their lives: had they been even 10 feet away and among the trees and grass, they would have died. When I reached the site, massive oak branches lay all around, and the ground had been scoured of pebbles.

The scene left me impressed and worried. A fire tornado could evidently harm firefighters taking refuge in areas usually thought to be safe. It had been a close call. Many of us had seen fire whirls, dust-devil-sized rotating columns of fire, and did not regard them as particularly dangerous. In contrast, fire tornadoes—which combine the destructive power of fire with that of winds as ferocious as in an actual tornado—were so rare as to be almost mythical. Even I, a firefighter since 1996 and a fire-behavior researcher for eight years, had heard of only one, from a story a veteran firefighter told me.

On returning to my home base at the Missoula Fire Sciences Laboratory in Montana, I conducted a literature survey. It turned up reports, most rather sketchy, of several fire tornadoes that had occurred around the world in the near and distant past. So scant was the information on the subject that scientists did not even agree on what qualified as a fire tornado. Massive forest fires can generate so-called pyrocumulonimbus (pyroCb) clouds at high altitudes. These are ice-capped thunderclouds that condense from the moisture released above a fire—from the vegetation it consumed, from the water vapor in the atmosphere and as a by-product of combustion itself. A few researchers held that only those fire vortices that connect to overhead pyroCb clouds are true fire tornadoes. By that definition, only one had ever been documented, in a 2003 firestorm near Canberra, Australia. It had left a damage path almost 15 miles long.

That framework seemed far too restrictive to be of much use to firefighters, however. Using the working definition of a fire tornado as a fire whirl with tornadolike wind speeds, my colleague Bret Butler and I had gathered up whatever documentation we could find and consolidated it into firefighter-training manuals and classes. But now I found myself driving south toward the Carr Fire just outside Redding, Calif., to investigate the death of a firefighter in a fire tornado—a tragedy I had long sought to avert.

IN BRIEF

Fire tornadoes, vortices of fire with tornadolike wind speeds, are exceedingly rare but deadly. The Carr Fire tornado near Redding, Calif., killed up to four people.

Apart from fire itself, generation of a fire tornado requires a source of rotation in the atmosphere. The fire can concentrate this vorticity into a spinning tube of air and stand it up.

Scientists understand the physics of fire tornadoes rather well, but they cannot yet predict when and where one might appear.

THE CARR FIRE TORNADO

THE SITE looked like a war zone. Neither the famous tornado researcher Josh Wurman, whom I had recruited for the investigation, nor I had ever seen anything like this. Entire blocks of homes had been leveled, with only the foundations remaining. Roofing and other debris littered the area, and vehicles had been rolled multiple times over the ground. Trees were uprooted or broken off, and flying particles of sand and rock had stripped them of their bark. Three power-line towers built of metal lattice, each roughly 100 feet tall, had been blown down, with one of them having been lifted off its base and carried 1,000 feet through the air. A 40-foot shipping container had been torn apart, and a steel pipe was wrapped around downed power poles.

We estimated that the winds could have reached 165 miles per hour, a speed that occurs in class 3 tornadoes on the Enhanced Fujita scale. (This scale rates tornadoes on a scale ranging from 0 to 5, with 5 indicating the fastest and most destructive winds.) In California, only two regular tornadoes of this strength had ever been recorded. Peak temperatures of the burning gases

BURNING BOARDS arranged in a rough triangle allow air to swirl into the central area, where another fire gathers the rotation into a vortex. Forest or urban fires of certain shapes can similarly generate fire tornadoes.

inside the fire tornado may have reached almost 2,700 degrees Fahrenheit. The object was more than 1,000 feet wide at its base and, according to radar imagery, three miles high. It lasted for at least 40 minutes, during which time it moved slowly across the ground, leaving a path of destruction nearly a mile long.

Our team interviewed witnesses and collected video evidence in the hope of learning from the event. The fire tornado occurred on the evening of July 26, 2018, in the course of a forest fire covering thousands of acres northwest of Redding. So extensive and intense was the fire that it generated pyroCb clouds at altitudes higher than three miles. Suddenly, at around 5:30 P.M., the flames raced eastward, killing firefighting bulldozer operator Don Smith, as well as a civilian in his home. As the wildfire neared the outskirts of Redding, it spawned a number of fire whirls and threw embers more than a mile ahead of the fire and across the Sacramento River. These started several "spot," or small, isolated fires near two subdivisions at the end of a dead-end road. An extremely chaotic scene unfolded as firefighters tried to evacuate homeowners and save houses even as their escape route was being cut off. People were literally running for their lives.

Redding firefighter Jeremy Stoke headed to the scene to help. Just as he was arriving, at about 7:30 P.M., the fire tornado formed over the road, trapping residents and firefighters at the subdivisions. It apparently caught Stoke on the road. He transmitted a mayday call on his radio before powerful winds rolled his truck multiple times; it eventually came to rest against a tree hundreds of feet away. Stoke was found hours later, dead from traumatic injuries.

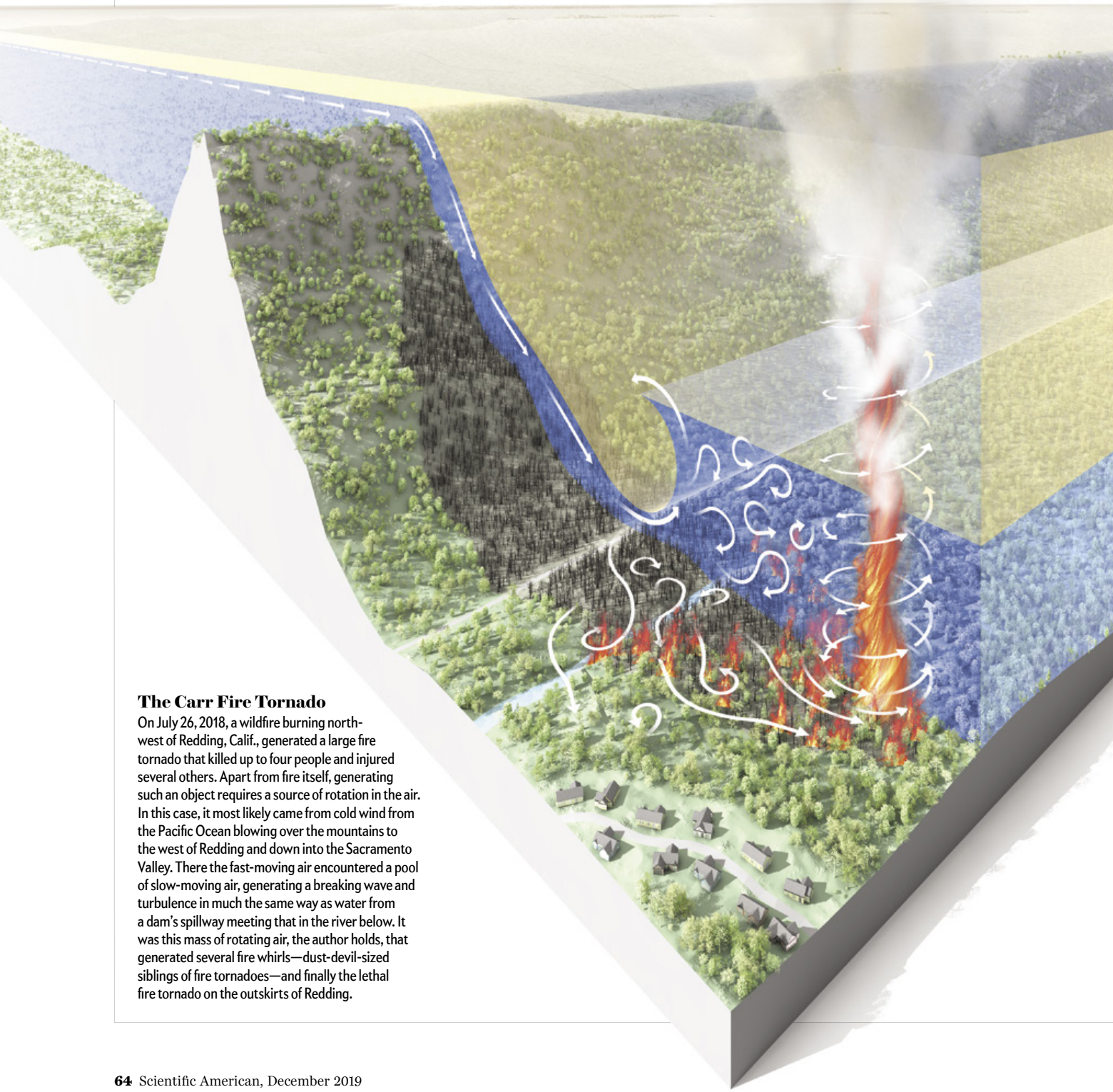
Two Cal Fire vehicles being driven down the road had most of their windows blown out and were battered by flying debris. Strangely, one of the trucks was damaged mostly on the driver's side and the other on the passenger side—even though they were only 150 feet apart and facing the same direction—indicating the rotating motion of the air. The occupants huddled on the floorboards to save themselves from projectiles. Three nearby bulldozers also had their windows blown out, with one operator getting glass in his eye and another receiving serious burns to his hands. A retired police officer who was driving out realized his truck bed was on fire and pulled over; he survived but sustained burns to his airways. Most tragically, on the outer edge of the revolving inferno two children and their great-grandmother perished inside their burned home.

IN THE LABORATORY

WHAT CAN we learn from an event like this? Can we predict when and where a fire tornado will occur so that we can evacuate residents and firefighters? What causes fire tornadoes? A first step toward answering these questions is to look back in history. In 1871 a

The Wildfire Tornado

Fire tornadoes, rotating columns of fire and smoke that possess windspeeds comparable to those in an actual tornado, are rare but extremely destructive. Remarkably long-lived, these lethal objects can move out of the main fire, surprising and overcoming firefighters and others. They can suck up debris such as burning logs from the ground and spit it far out, unpredictably starting fresh fires. Although researchers understand the physics of fire tornadoes rather well, predicting when and where one will appear remains a challenge.



The Carr Fire Tornado

On July 26, 2018, a wildfire burning northwest of Redding, Calif., generated a large fire tornado that killed up to four people and injured several others. Apart from fire itself, generating such an object requires a source of rotation in the air. In this case, it most likely came from cold wind from the Pacific Ocean blowing over the mountains to the west of Redding and down into the Sacramento Valley. There the fast-moving air encountered a pool of slow-moving air, generating a breaking wave and turbulence in much the same way as water from a dam's spillway meeting that in the river below. It was this mass of rotating air, the author holds, that generated several fire whirls—dust-devil-sized siblings of fire tornadoes—and finally the lethal fire tornado on the outskirts of Redding.

The Laboratory Fire Whirl

Small-scale vortices of fire generated in the laboratory have shed light on the physics of fire tornadoes. These burn fuel several times faster than nonrotating fires, for example, and are remarkably efficient at conserving energy, which enables them to live long.

Spinning Up

The rotation in the air that gets gathered up into a fire tornado can come from various sources, including wind dragging along the ground. The resulting vortices are horizontal, but the hot air from the wildfire, being buoyant, streams upward, pulling on one (or more) so that it stands on its end. The burning gases in the fire plume heat up the air so that it accelerates upward, stretching and consolidating the fire whirl into a long, thin tube. As the vortex thins, it spins up, like an ice skater pulling his or her arms in, until a tall, tightly spinning column of fire forms.

Illustration by Bryan Christie Design

town in Wisconsin was devastated by what was probably a fire tornado, judging by the massive amount of debris—which included a house—thrown around. In 1964 the Polo Fire in California spawned one that injured four people and destroyed two homes, a barn, three cars and an avocado orchard. One of the most horrific occurred during the World War II incendiary bombing of Hamburg, Germany: the resulting firestorm generated a fire tornado that, according to geographer Charles Ebert, was up to two miles wide and three miles tall. More than 40,000 civilians died in the conflagration.

In 1923 a major earthquake sparked an urban fire in Tokyo. As it spread from building to building, residents evacuated to an open area between the structures. A large fire tornado formed over this area, killing an estimated 38,000 people in 15 minutes. For more than half a century the accepted explanation for this terrible event was that a regular tornado happened to form at the exact same time and location as the fire. But in the 1980s and 1990s engineers S. Soma and K. Saito of the University of Kentucky used historical records to construct a small-scale model of the actual fire, painstakingly reproducing its geometry and ambient winds. Their laboratory fire generated a vortex—proving that the original one was not a coincidence but was caused by the fire itself.

CORONA FIRE in Yorba Linda, Calif., in November 2008 generated a flaming vortex—possibly a fire tornado—that threatened homes.

DAVID McNEW *Getty Images*

This research built on pioneering lab work conducted two decades earlier, when George Byram and Robert Martin of the U.S. Forest Service Southern Research Station created small fire whirls at their facility in Macon, Ga. Their apparatus consisted of a small circular pool of burning alcohol surrounded by cylindrical walls with vertical slits, which forced drafts into the fire to enter in a rotating motion. Significantly, the resulting fire whirl caused the fuel to burn—and its energy to be released—up to three times faster than in a nonrotating fire. The rotating wind appears to have increased the rate of burning by pushing the flames down toward the surface of the alcohol, heating it up. Subsequent research has found the energy-release rate to be enhanced by up to seven times in such fires.

Something similar occurs in wildfire whirls and fire tornadoes. A heated piece of wood generates hundreds of different flammable gases, the further combustion of which yields flames. The strong horizontal, rotating winds in the fire tornado can force the flames down into the vegetation, causing it to burn more fiercely.

In 1967 Howard Emmons and Shuh-Jing Ying of Harvard University surrounded a stationary lab fire with a cylindrical wire screen that could be spun at various speeds, imparting rotation to the air flowing into the flames. The researchers measured the wind velocity and temperature distribution of the fire whirl thus generated, getting a glimpse into its inner workings. They found that, apart from fire itself, the formation of such a vortex requires a source of rotation and a mechanism to intensify it.

A fire tornado has essentially the same hydrodynamics. Significant vorticity often exists in the atmosphere—generated by wind curling around mountains or dragging along the ground or by variations in density and pressure. The fire itself carries out two other crucial functions: it concentrates the rotation and stands it up, so that a tight tube of air ends up spinning around a vertical axis.

First the hot air rising above the fire pulls in replacement air at the base, thereby gathering rotating air from the surroundings. Some of the vorticity might originally be around a horizontal axis, but once air is sucked up into the fire plume, its hot, buoyant upward stream causes the axis to tilt to a vertical orientation. Second, although the upwardly moving air starts out slow when it is near the ground, it heats up as the gases in it burn. The air pressure all around the vortex forces the hot, light air within the core upward. The accelerating air in the fire plume stretches the fire whirl or fire tornado vertically along its axis, reducing its diameter, much as pulling apart a clump of dough causes a long, thin neck to form. The reduced diameter drives the air to turn faster to conserve its angular momentum—the same effect seen when a spinning ice skater draws in his or her arms.

It appears that when a fire whirl or fire tornado moves over a burning area, it stretches to a consider-

able height and spins tight and fast, but when it moves over an already burned area, it spreads out and slows down into a diffuse cylinder of smoke. Sometimes the rotating object is so wide and slow that firefighters fail to perceive it. The direction of motion of the vortex across the ground depends on ambient winds and details of terrain in ways that we have yet to understand.

Emmons and Ying also found that fire vortices are remarkably efficient at conserving their rotational energy, which makes them (unfortunately) rather long-lived. The Indians Fire tornado, for example, lasted for about an hour. As the fire tornado spins up, two opposing forces in the radial direction strengthen: centrifugal force pulling a parcel of rotating air outward and, in opposition, low pressure in the core pulling it inward. The resulting balance limits the movement of air in the radial direction and therefore the loss of energy from the vortex. In contrast, nonrotating fires exchange roughly 10 times more energy with the surrounding atmosphere. This mechanism also makes fire whirls thinner and taller than nonrotating fires because with practically no air being drawn in, except at the base, less oxygen is available for combustion. Thus, some of the fuel gases must travel high up the core before they encounter sufficient oxygen to burn.

Just as dangerous, the towering column of hot, low-density gases induces very low pressure at the base of the whirl. Drag near the ground slows the rotation, reducing the centrifugal force pushing the air outward. Because the inward force generated by pressure remains the same, however, the wind near the ground streams into the fire tornado. It ends up acting like a giant vacuum cleaner, sucking air and, often, burning debris into the base, forcing it vertically up the core at extreme velocities and spitting it out from high up—unpredictably generating spot fires.

IN THE FIELD

DESPITE ALL this knowledge about the physics of fire tornadoes, we still cannot predict where and when one will occur. One thing is clear, however: given how rare fire tornadoes are even though a large, intensely burning fire always has the capacity to concentrate rotation, the essential factor for their appearance seems to be the presence of a strong source of rotation.

We know from case studies, for example, that one of the likeliest locations for fire tornadoes to form is on the lee side of a mountain. Wind blowing around the mountain causes swirling motions on the downwind side, like water moving around a large rock in a river. A fire burning there can gather and stretch this rotation into a fire tornado. But matters are in fact more complicated: Fiery vortices can also show up on flat ground and in calm wind conditions. For example, a large fire whirl in Kansas was likely generated by a cold front that collided with warm ambient air as it passed over a fire in a field. And a 2007 study by Rui Zhou and Zi-Niu Wu of Tsinghua University in Beijing showed that multiple fires burning in certain specific configurations—which can happen when a fire throws embers ahead of itself, starting new fires—may even generate their own rotation by inducing jets of air to flow along the ground between them.

So where did the rotation that caused the deadly Carr Fire tornado come from? Given the several fire whirls that preceded the fire tornado, an abnormally high amount of rotation obviously existed in the area. On a hunch, I asked Natalie Wagenbrenner, a colleague at the Missoula Fire Sciences Laboratory, to run some specialized computer simulations of the weather that day. Her studies showed that cool, dense air from the Pacific Ocean was being pushed eastward and over the top of a mountain range west of Redding. This cool air was much heavier than the hot air in the Sacramento Valley: the Redding airport reported a peak temperature that day of 113 degrees F, a record. So gravity caused the air to accelerate as it moved down the slopes toward the valley, much like water flowing downhill. Oddly, these strong surface winds stopped abruptly—right where the fire tornado formed.

What happened to the wind? Finally, I realized that a hydraulic jump was occurring—the atmospheric equivalent of what happens to water when it flows down the spillway below a dam. When the fast-moving water hits the low-speed pool below, the surface of the water jumps upward, forming a breaking wave that stays in place and marks the boundary between the two flows. This region contains intense swirling motions. In much the same way, the cold, dense air speeding down the mountainside hit the slow-moving pool of air in the Sacramento Valley, most likely generating the powerful rotation that formed the Carr Fire tornado [*see box on page 64*]. N. P. Lareau of the University of Nevada and his colleagues speculated in a 2018 paper that the pyroCb clouds overhead, which reached altitudes of up to seven miles even as the fire tornado formed, helped to stretch the vortex to a great height, thereby thinning it and spinning it up even more.

If wildfires continue to become more extensive, we may encounter such lethal objects more frequently. The silver lining is that lessons learned from studying them carefully might help prevent future tragedies. I am hopeful that further research into fire tornadoes, combined with advances in weather prediction and computing power, will, in the near future, give us the ability to issue fire tornado warnings—possibly saving lives. SA

MORE TO EXPLORE

Fire Whirls, Fire Tornadoes and Firestorms: Physical and Numerical Modeling. Robert N. Meroney in *Proceedings of PHYSMOD 2003: International Workshop on Physical Modelling of Flow and Dispersion Phenomena.* Edited by Giampaolo Manfrida and Daniele Contini. Firenze University Press, 2003.

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ASTRONOMY

X-RAY VISION

After two decades in space, the world's leading x-ray telescope—the Chandra Observatory—is still revealing new secrets of the cosmos

By Belinda J. Wilkes

BLAST SCENE

DEEP IN THE HEART of the Crab Nebula lies a highly magnetized, rapidly rotating neutron star that was produced when a massive star exploded as a supernova in the year 1054. This multiwavelength image reveals the debris from the blast: x-rays are shown in purple, ultraviolet light in blue, visible in green, infrared in yellow and radio light in red. The x-ray emission, closest to the neutron star, is dominated by light released by charged particles that were accelerated to high energies by the star's rotation.

X-RAY: NASA, CXC AND SAO; OPTICAL: NASA AND STScI; INFRARED: NASA, JPL AND CALTECH; RADIO: NSF, NRAO AND VLA; ULTRAVIOLET: ESA AND XMM-NEWTON

Belinda J. Wilkes is a senior astrophysicist at the Smithsonian Astrophysical Observatory and director of the Chandra X-ray Center, both in Cambridge, Mass.

SINCE ITS LAUNCH IN 1999, NASA'S CHANDRA X-RAY OBSERVATORY has been studying the heavens through short-wavelength x-ray light, the best window for sighting colossal black holes, galaxy clusters and the remnants of violent supernovae. The telescope captures the position, energy and arrival time of each x-ray photon that reaches its detector. That ability, in combination with its uniquely sharp imaging quality and capacity to see x-ray light over a broad range of energies, has revolutionized our view of the x-ray universe. It has changed our understanding of big mysteries such as dark matter, the birth of stars and even the properties of the planets in our solar system.

Chandra was designed to solve a key question in x-ray astronomy: What is the makeup of the diffuse x-ray light that appears to be present in every direction of the cosmos—the so-called x-ray background? It was also designed to be a "general observatory," with most of the telescope time awarded to scientists around the world working on diverse projects, chosen after an annual call for proposals. Even after two decades of operation, Chandra receives around 500 to 650 proposals every year, which amounts to about 5.5 times more observing time requested than we have to grant—the process is highly competitive.

Chandra has been extraordinarily productive. It achieved its original goal by revealing that nearly all of the mysterious x-ray background light comes from thousands of individual supermassive black holes at the centers of other galaxies. It also revealed new secrets from a host of celestial objects: strong x-ray emission from jets of material flying out of supermassive black holes in the process of gobbling up matter; shining aurorae in the atmosphere around Jupiter; light from colliding neutron stars that were also detected through gravitational waves; and extremely bright star-sized black holes aptly named ultraluminous x-ray sources. Science papers based on Chandra observations number more than 8,000, and our user community numbers more than 4,000 scientists worldwide.

I joined the mission three years before launch as deputy group leader for user support. I was involved with building the Web site and documents to provide information for our scientist users, the first call for proposals and peer review, and the calibration of the telescope as it was prepared for launch at NASA's Marshall Space Flight Center in Alabama. Although this time was busy and stressful as we pulled everything together for liftoff, it was nothing compared with the first few months after launch.

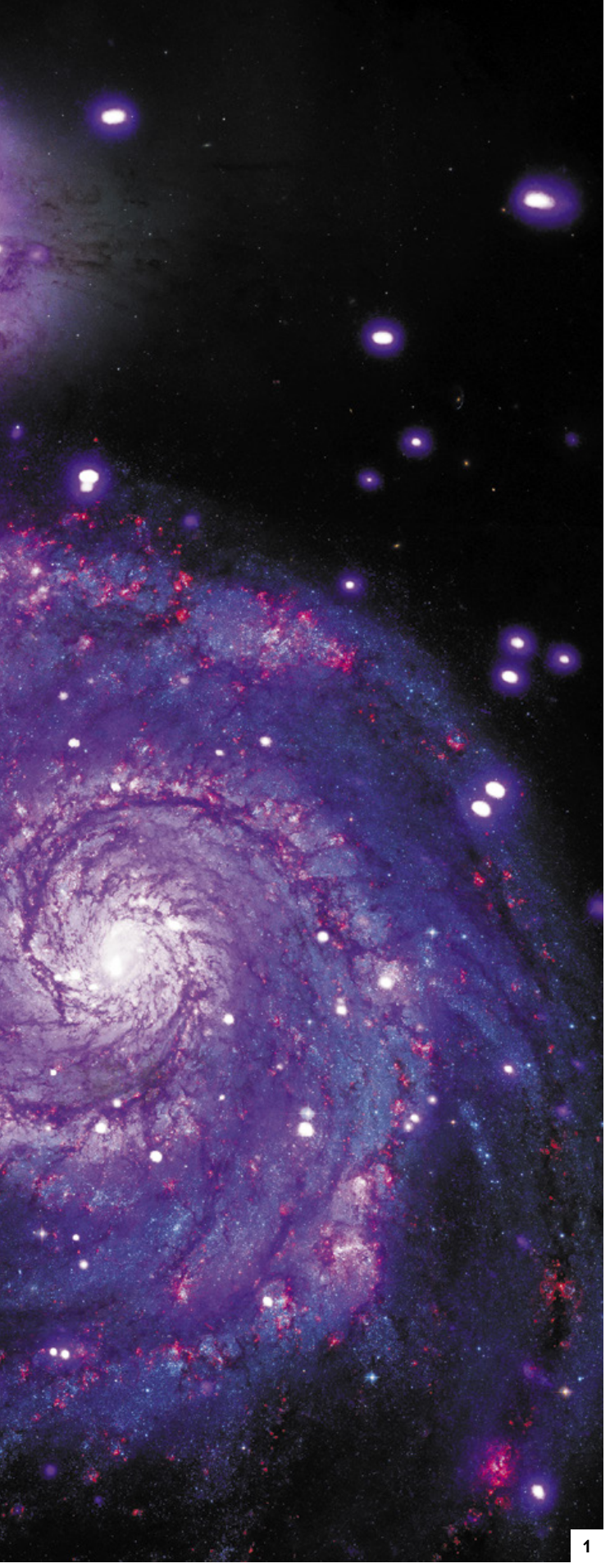
Chandra has reached its 20th anniversary year, and the observatory is still going strong. I serve as director of the Chandra X-ray Center in Cambridge, Mass., where we run the telescope's operations. With telescopes coming online now and in the future, such as the Event Horizon Telescope, the James Webb Space Telescope, and many more, we expect Chandra to continue to forge new ground and further expand our knowledge of the hottest and most violent places in the universe for years to come.

IN BRIEF

This year is the 20th anniversary of NASA's Chandra X-ray Observatory, which has been continually orbiting Earth since its 1999 launch.

The telescope has made major discoveries about supermassive black holes, the remnants of supernova explosions, and more.

As it begins its third decade, Chandra continues to be productive. Planned collaborations with new and existing observatories will further expand our knowledge of the universe.



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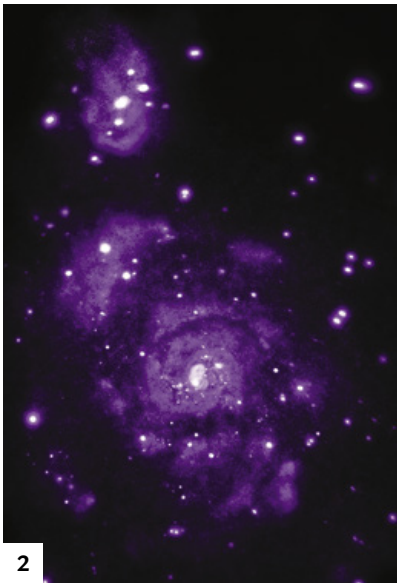

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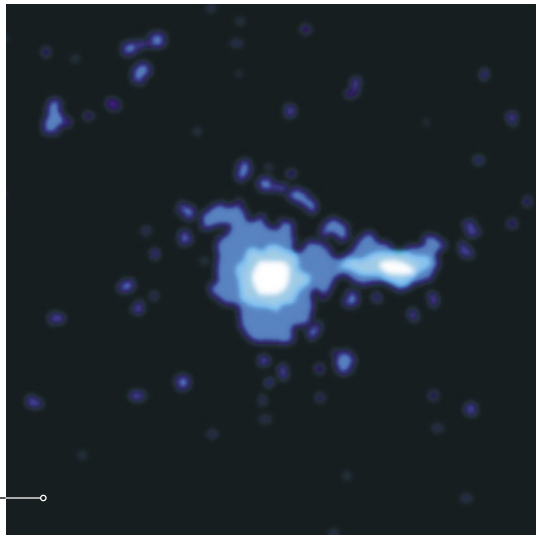
SWIRLING SPIRALS

TWO MERGING GALAXIES, collectively known as M51, or the Whirlpool, show the beautiful arms characteristic of spiral galaxies. About 400 x-ray sources, most of them binary stars, are visible here, primarily located near regions of star formation. Scientists speculate that the interaction between the two galaxies is triggering a wave of star formation that results in the large number of x-ray binaries in this system. Pulsations from one x-ray binary imply that the compact companion is a neutron star that must be accreting huge amounts of material from its companion to generate its unusually high luminosity.

The main image (*1*) is a composite of Chandra's x-ray data (*2*) and optical light (*3*) captured by the Hubble Space Telescope. Combining data from various telescopes allows astronomers to create fuller, multiwavelength pictures that reveal cosmic phenomena visible in different ranges of the electromagnetic spectrum.

X-RAY: NASA, CXC, WESLEYAN UNIV. AND R. KILGARD ET AL.; OPTICAL: NASA AND STScI



FLYING JET

EARLY IN ITS TENURE Chandra observed the quasar PKS 0637-752, a supermassive black hole in the nucleus of a distant galaxy and one that I had studied a decade before, using data from NASA's Einstein Observatory. The black hole is pulling in massive amounts of material from its host galaxy. As the material falls, it becomes so hot that it outshines the galaxy's 100 billion stars.

The extended light on the west (right-hand) side was a surprise and initially had the Chandra staff concerned that something had gone wrong with the telescope optics. Instead Chandra had discovered x-ray emission from a jet of plasma flying out of the infalling matter. This jet had previously been sighted in radio light, but the x-rays were unexpected. Chandra's ability to see the jet as well has resulted in major advances in our understanding of jets emanating from the poles of supermassive black holes.

NASA, CXC AND SAO

SMOKING GUN

AMONG CHANDRA'S most famous results is this composite image of the Bullet Cluster—a pileup of two galaxy clusters smashing together. The picture combines data from Chandra, Magellan and the Hubble Space Telescope. Here hot gas appears in x-ray light (*shown in pink*), whereas galaxies can be seen in visible light (*white*) from Magellan. From the visible-light image scientists infer the distribution of dark matter (*blue*) from the distortion of the galaxy images caused by gravity (a process called gravitational lensing).

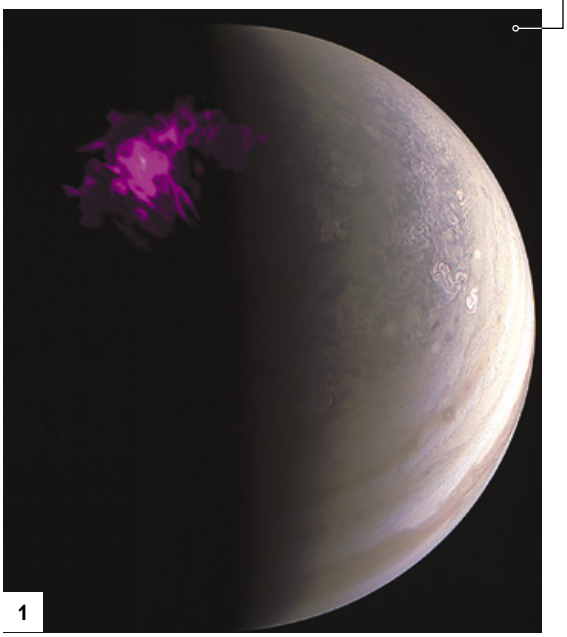
The separation between hot gas and dark matter provided the first direct evidence for the presence of dark matter. It demonstrates that this mysterious stuff does not interact with either itself or regular matter, because it moves with the galaxies, not "seeing" the other matter around it. In contrast, the hot gas interacts and slows down, forming the bullet shape that gives the combined clusters their name.

X-RAY: NASA, CXC, CFA AND M. MARKEVITCH ET AL.; OPTICAL: NASA, STScI, MAGELLAN, UNIV. ARIZONA AND D. CLOWE ET AL.; LENSING MAP: NASA, STScI, ESO WFI, MAGELLAN, UNIV. ARIZONA AND D. CLOWE ET AL.

CLOSER TO HOME

AS WELL AS FINDING distant supermassive black holes and clusters of galaxies, Chandra has made amazing discoveries within our solar system. These images of Jupiter show x-ray emission from the aurorae at both the north (*1*) and south (*2*) poles of the planet, a feature unique among the worlds in our solar system. The x-rays are thought to be generated when magnetic fields funnel particles from the equatorial ring around Jupiter. Chandra observations in 2019, coordinated with NASA's Juno satellite, which is currently orbiting Jupiter, are expected to provide detailed information on this process. As director, I have been able to facilitate some of these observations by allocating Director's Discretionary Time toward this study.

X-RAY: NASA, CXC, UCL AND W. DUNN ET AL.; OPTICAL: SOUTH POLE: NASA, JPL-CALTECH, SwRI, MSSS, GERALD EICHSTÄDT AND SEÁN DORAN; NORTH POLE: NASA, JPL-CALTECH, SwRI AND MSSS



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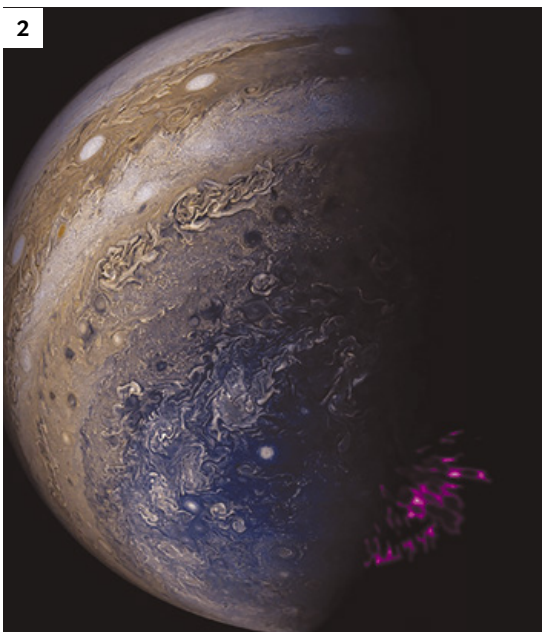

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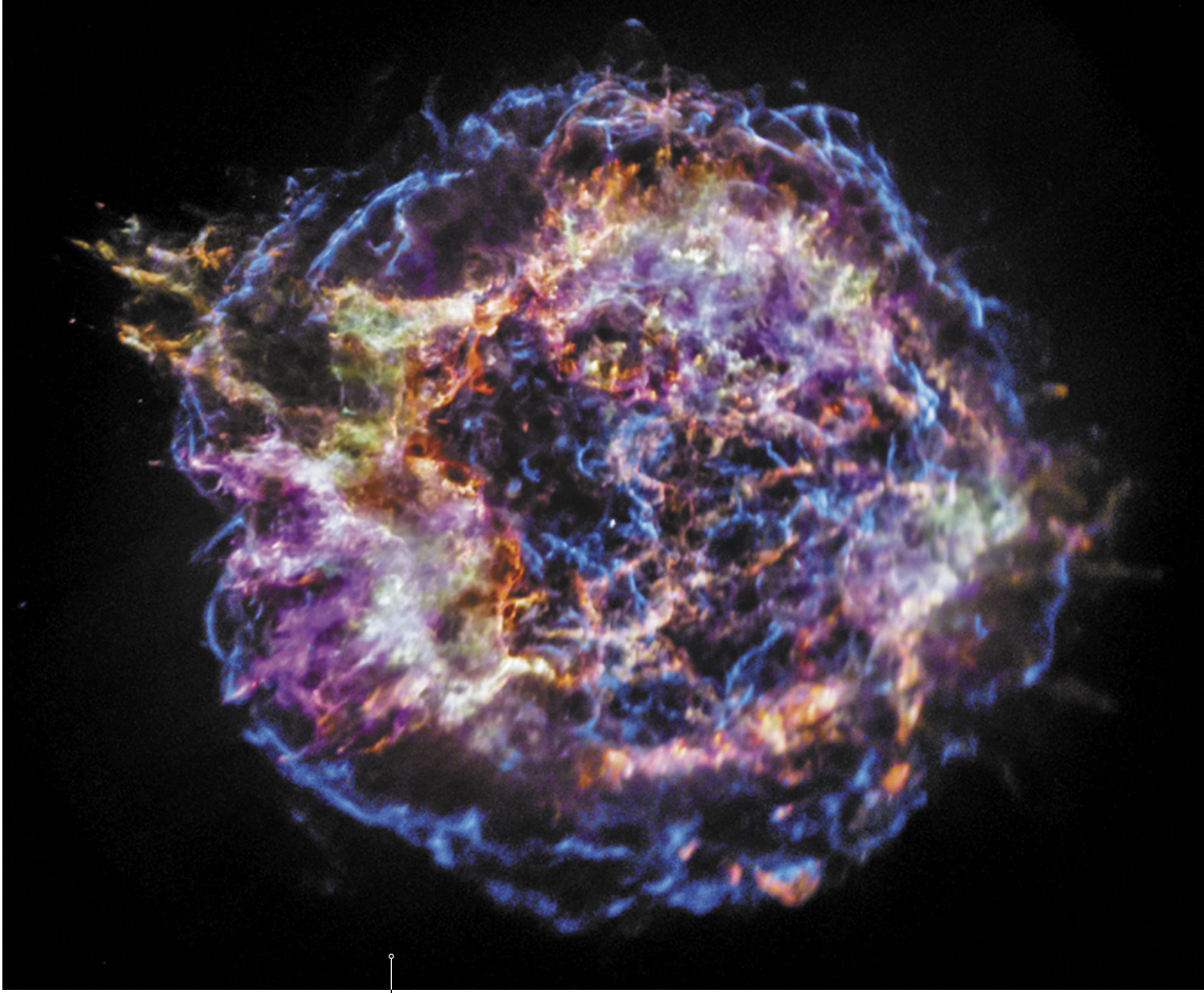
BABY STARS

MORE THAN 1,400 blue and orange points of light here are newly formed stars in this dense nebula, which is visible to the naked eye in the middle of the constellation Orion's sword. Chandra's sharp x-ray vision penetrates the dense gas and dust, revealing the new stars that are hidden from traditional visible-light telescopes. Young stars are hot and violent as gravity pulls in matter, magnetic fields accelerate it, and winds blow it out again as a star forms and begins to shine.

X-RAY: NASA, CXC, PENN STATE UNIV., AND E. FEIGELSON AND K. GETMAN ET AL.; OPTICAL: NASA, ESA, STScI AND M. ROBBERTO ET AL.



FIRST LIGHT

CHANDRA'S OFFICIAL first light image, of the iconic supernova remnant Cassiopeia A, immediately demonstrated the power of the telescope's high spatial resolution by discovering the long-sought neutron star at the center of this nebula. The dense neutron star, a remnant of the much larger star that exploded around 340 years ago as a supernova, had never been visible before. This image combines Chandra data taken over a period of several years, increasing the visible details of the complex structure. It also uses the observatory's energy resolution to reveal different chemical elements that were created within the star and blown out by the explosion: red color indicates silicon, yellow is sulfur, green shows calcium and purple displays iron. The bluish outer ring in the image is emission from high-energy particles accelerated in the forward shock wave of the explosion—another aspect first discovered by Chandra.

NASA, CXC AND SAO

MORE TO EXPLORE

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scientificamerican.com/magazine/sa

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Clarence Robinson Professor of Earth Sciences
George Mason University

Robert Hazen is also Senior Staff Scientist at the Carnegie Institution's Geophysical Laboratory and Executive Director of the Deep Carbon Observatory, where his recent research focuses on the role of minerals in the origin of life and the interactions between biomolecules and mineral surfaces.

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Cruiseimage/Trevor Adeline

Millie Hughes-Fulford, Ph.D.
Professor of Medicine
University of California Medical Center

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

Space: An Astronaut's Perspective

- Living and Working in Space
- ISS and Science
- The Right Stuff — Revised 2020 Edition
- The Future

Jill Tarter, Ph.D.
Emeritus Chair for SETI Research, SETI Institute

Jill Tarter achieved recognition for her work searching for evidence of extraterrestrial life, which entered public consciousness through the movie *Contact*, and has won several awards including the Lifetime Achievement Award from Women in Aerospace, two NASA Public Service Medals, *Time* Magazine's Top 100 Most Influential People in 2004 and many more for her dedication to communicating science to the public.

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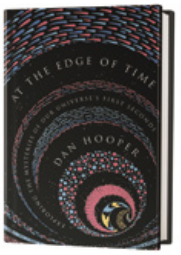
RECOMMENDED

By Andrea Gawrylewski

At the Edge of Time: Exploring the Mysteries of Our Universe's First Seconds

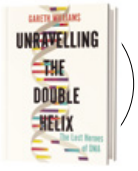
by Dan Hooper. Princeton University Press, 2019 ($24.95)



The first instants of the universe may seem like a blip on the cosmic time line, but this was probably the most important, formative era in history—and the most inscrutable. Scientists know precious little about what happened when the universe got its start: many cosmologists think space and time underwent an extremely rapid expansion called inflation, yet this theory raises as many questions as it answers. Learning more about this early epoch is the key to many of the most pressing conundrums in physics: What is dark matter? What drives dark energy? And why is the cosmos made of matter and not antimatter? Astrophysicist Hooper takes readers on a mind-bending expedition through these questions and shows how they all connect to the beginning. "Our universe's greatest mysteries," he writes, "are firmly tied to its first moments." *—Clara Moskowitz*

Unravelling the Double Helix: The Lost Heroes of DNA

by Gareth Williams. Pegasus, 2019 ($35)



The central code for all life on Earth has captivated and confounded scientists for nearly a century. In this expansive tome, writer Williams charts the first 100 years of DNA research—Nobel Prizes won and lost, intriguing discoveries, scientific betrayal and colorful lesser-known characters. For instance, at age 25 Lawrence Bragg, who had been a child prodigy, and his father, William, won the 1915 Nobel Prize in Physics for their work in crystallography. The son later became the director of the lab where Watson, Crick, Franklin and Wilkins made their DNA discovery. Also featured are Florence Bell and William Astbury, who first attempted to model the structure of DNA in three dimensions (although their results didn't quite hit the mark). Through these accounts Williams paints the story of one of science's greatest achievements—unraveling the four-letter code that launched thousands of discoveries. *—Jennifer Leman*

On Trial for Reason: Science, Religion, and Culture in the Galileo Affair

by Maurice A. Finocchiaro. Oxford University Press, 2019 ($32.95)

Italian scientist and inventor Galileo Galilei was a pioneer in the experimental investigation of motion, devising the law of falling bodies and an approximate law of inertia, among many other hypotheses. In 1632 he published his book *Dialogue on the Two Chief World Systems,* in which he supported Copernicus's idea that Earth in fact was not stationary but orbited the sun. The next year he was summoned to Rome to stand trial for "suspicion of heresy." Philosophy professor Finocchiaro presents a fascinating examination of these events and the ways Galileo's trial was essential in turning the Copernican hypothesis into accepted theory. It also birthed new strife between science and faith. The trial established how deeply skepticism of science was embedded in society. Galileo was convicted and sentenced to house arrest, where he continued his groundbreaking work until his death. He emerged from the affair as a cultural icon of reason and scientific thinking.

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

What's the Deal with Rich Men and Space?

Their obsession harks back to "classic" sci-fi—but there's a more socially conscious kind

By Zeynep Tufekci

Tech billionaire Elon Musk, who runs Tesla and SpaceX, is trying to buy up all the houses in Boca Chica, Tex.—a tiny community of just a few dozen people—so he can use the area to launch his Mars spaceship. He says he might have people on their way to the Red Planet within a decade.

Amazon CEO Jeff Bezos also has a spaceflight company, Blue Origin, and he sees the project as a stepping-stone to a future of space colonies. Bezos envisions that one day a trillion or more humans could be living somewhere else in the solar system, leaving Earth behind as a sort of park. The late Microsoft co-founder Paul Allen founded Stratolaunch, which similarly had space travel in its sights. (There's also Richard Branson's Virgin Galactic; he's not from the tech industry, but still….) These men aren't necessarily focused exclusively on space, but why do they put billions toward launching humans out there? One reason is that Earth is threatened with climate change and nuclear war; space is a kind of plan B. But a crewed flight to Mars is full of perils—most notably the fact that we don't currently have a way of protecting humans from the adverse effects of months and months of deep-space radiation. And once we get there, the planet's lack of a significant magnetic field or atmosphere means the threat will still be substantial. It's also not clear whether proposed plans for hauling the tons of supplies needed to make life there even barely possible could work as well as envisioned (or at all).

Still, what's wrong with dreaming, right? In one sense, nothing. But in another, it matters how people with a lot of money dream. Bezos, Allen and Musk all have talked about their love of science fiction as part of their inspiration for investing in space. Bezos spent his summers reading authors such as Isaac Asimov and Robert A. Heinlein. Allen so loved his boyhood science-fiction collection that when he discovered that his mother had sold his books, he had the entire collection re-created.

As a former science-fiction geek myself, I can only sympathize. At its best, though, science fiction is a brilliant vehicle for exploring not the far future or the scientifically implausible but the interactions among science, technology and society. The what-if scenarios it poses can allow us to understand our own societies better, and sometimes that's best done by dispensing with scientific plausibility. For example, Ursula K. Le Guin's brilliant book *The Left Hand of Darkness* imagines an envoy from Terra (our Earth) to Gethen, a planet without fixed boundaries between genders. Through the hero's encounter with an "ambisexual" species, we end up interrogating our own cultural norms around masculinity and femininity—groundbreaking for a book published in 1969.

Science fiction is sometimes denigrated as escapist literature, but the best examples of it are exactly the opposite. For me, it's not the scientifically implausible part of science fiction that is most interesting. It's what the expanded imagination allows us to discover about ourselves and our societies—and then to make them better.

Science and art have always been somewhat funded through the eccentric interests of the wealthy, and the combination has always been a mixed bag. One thing about being a billionaire is that it's probably not hard to find people who will encourage you to spend money chasing space operas that either will not happen because of scientific constraints or will end up in disaster.

But more important, tech billionaires can shape our lives today, through how their companies operate, by repaying their obligations to society through taxes on their enormous wealth (at the moment, fairly little), and through their investments in solving the problems that threaten us. Doing that requires imagination. It's just not the kind depicted on the covers of science-fiction books I, too, read as a child; it's the kind that takes us to expanded universes only to have us think harder about how to understand the one inhabitable place for us in this vast universe—our fragile, pale blue dot—and make it a better place to live. SA

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Illustration by Catarina Mouta

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.

Lunar Litter

People dump their junk everywhere, even the moon

By Steve Mirsky

One can learn a lot by browsing Twitter. In early October, for example, I found out that one way to tell if a particular lung cancer treatment (anti-PD-1/anti-PD-L1 therapy) is working is if the gray hair of patients returns to its youthful color; eight species of roundworms were discovered living in California's Mono Lake despite its high levels of arsenic; and, seriously, the president of the United States tweeted that Democrats "are continuing to interfere in the 2016 Election." Make that witch hunt a tachyon hunt.

I was also informed, via a tweet by Charles Fishman, author of *One Giant Leap: The Impossible Mission That Flew Us to the Moon,* that in 2012 NASA published "a comprehensive catalogue of human artifacts on the Moon": space waste.

The following quiz looks at the stuff left just by the Apollo moon landings. Of the hundreds of pieces of detritus, I chose four from each mission. I then added one item that is not actual lunar trash. Your job is to identify the object that was not in fact left on the moon. Answers follow. Correct responses win you deep personal satisfaction.

Apollo 11:
Defecation collection devices
Lunar overshoes
Hammer
Tongs
Buzz's buzzer

Apollo 12:
Defecation collection devices
TV zoom lens
Color TV camera
TV adapter cable
Copy of the 1953 classic sci-fi movie *Cat-Women of the Moon* (somehow featuring music by Oscar-winning composer Elmer Bernstein)

Apollo 14:
Defecation collection devices
Towels
Lunar module ascent stage
Gnomon
Yesmon

Apollo 15:
Passive seismic experiment leveling stool
Wet wipes
Lunar dust brush
Dune Buggy–style vehicle
Spray can of Vapoorize (as later seen in the 2004 movie *Envy*, with Ben Stiller, Jack Black, Amy Poehler, and Oscar winners Rachel Weisz and Christopher Walken)

Apollo 16:
Defecation collection device
Tissue dispenser
High-gain antenna assembly
Vise device
Rice spice

Apollo 17:
Defecation collection devices
Antibacterial-antifungal ointment
Wrist mirror
Nail clippers
Tardigrades able to survive on a diet exclusively of toenails

Bonus Question:
Why didn't the *Apollo 15* astronauts leave any defecation collection devices on the moon?

ANSWERS:

Apollo 11: Buzz's buzzer. I have shaken his hand and did not receive an electric shock. But if you annoy him enough with claims that the moon landing was faked, he will punch you in the face, as he did in 2002 to a particularly aggressive provocateur who called him a liar and coward.

Apollo 12: Copy of *Cat-Women of the Moon.* Videocassette technology was too primitive in 1969 to allow movies and a playback system to be sent to the moon without adding a great deal of additional mass that would require significant amounts of extra fuel.

Apollo 13: Read the book! (Did you know that Ron Howard's brother, parents, wife and oldest daughter were in the movie?)

Apollo 14: There's no such thing as a Yesmon, although many organizations, businesses and presidential cabinets are filled with yes-men.

Apollo 15: Vapoorize is a fictional feces-removal product and was in any case unnecessary for this mission (**Bonus Question answer**) because, according to a 1971 NASA press release, "solid body wastes are collected in plastic defecation bags … sealed after use and stowed in empty food containers for post-flight analysis." Probably back on Earth.

Apollo 16: Rice spice. Rice does not require a specific spice, although saffron and cardamon are popular spices for use with rice.

Apollo 17: Tardigrades. Although they can't be conclusively ruled out.

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Illustration by Matt Collins

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INNOVATION AND DISCOVERY AS CHRONICLED IN *SCIENTIFIC AMERICAN*

Compiled by Daniel C. Schlenoff

DECEMBER

1969 Attitudes to Pot

"The prevailing public attitude toward marihuana in the U.S. is charged with a hyperemotional bias. In part this is the product of an 'educational campaign' initiated in the 1930's by the Federal Bureau of Narcotics, a campaign that has disseminated much distortion and misinformation about the drug. The still powerful vestige of the Protestant ethic in this country condemns marihuana as an opiate used solely for the pursuit of pleasure (whereas alcohol is accepted because it lubricates the wheels of commerce and catalyzes social intercourse). Marihuana's effect in producing a state of introspection and bodily passivity is repellent to a cultural tradition that prizes activity, aggressiveness and achievement."

A New Year's Greeting

"The following verses were written after the poet W. H. Auden had read 'Life on the Human Skin,' by Mary J. Marples [SCIENTIFIC AMERICAN, January 1969]:

"On this day tradition allots
To taking stock of our lives,
My greetings to all of you, Yeasts,
Bacteria, Viruses,
Aerobics and Anaerobics:
A Very Happy New Year
To all for whom my ectoderm
Is as Middle-Earth to me.

I should like to think that I make
A not impossible world,
But an Eden it will not be:
My games, my purposive acts,
May become catastrophes there.
If you were religious folk,
How would your dramas justify
Unmerited suffering?"

1919 The Nature of Things

"Dr. Einstein tells us that when velocities are attained which have but just now come within the range of our close investigation, extraordinary things happen—things quite irreconcilable with our present concepts of time and space and mass and dimension. We are tempted to laugh at him, to tell him that the phenomena he suggests are absurd because they contradict these concepts. Nothing could be more rash than this. We must be quite as well prepared to have these conditions reveal some epoch-making fact as was Galileo when he turned the first telescope upon the skies. And if this fact requires that we discard present ideas of time and space and mass and dimension, we must do so quite as thoroughly as our mediaeval fathers had to discard their notions of celestial 'perfection.'"

1869 Flight Fail

"An exhibition of a flying machine, named by its inventor, Mr. Frederick Mariott, 'The Avitor,' took place in a room of the Avitor Works, at Shell Mound Lake, Calif. We give herewith an illustration of the machine. The hopes which were first raised by the success of the experiment as performed under cover, have been since dashed by unsuccessful attempts to navigate the machine against currents of wind. This was only a trial machine, the balloon being cigar-shaped, thirty-seven feet in length. The boiler and furnace are together only a little over a foot long and four inches wide."

1969

1919

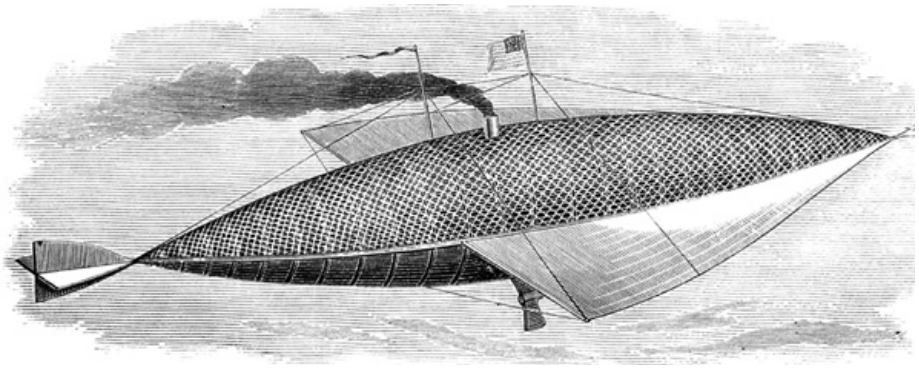
1869

Postcard Invention

"The Austrian Government has introduced a novelty in postage, which might be introduced with great benefit in all countries. The object is to enable persons to send off messages of small importance, without the trouble of obtaining paper, pens, and envelopes. Cards of a fixed size are sold at all the post offices for two kreutzers, one side being for the address and the other for the note. It is thrown into the box, and delivered without envelopes. A halfpenny post of this kind would certainly be very convenient, especially in large towns."

Maddening Thought

"Our brains are seventy-year clocks. The Angel of Life winds them up, then closes the case, and gives the key into the hand of the Angel of the Resurrection. Tic-tac! tic-tac! go the wheels of thought; our will cannot stop them; they cannot stop themselves; sleep cannot still them; madness only makes them go faster; death alone can break into the case, and seizing the ever-swinging pendulum, which we call the heart, silence at last the clicking of the terrible escapement we have carried so long beneath our wrinkled foreheads. If we could only get at them, as we lie on our pillows and count the dead beats of thought after thought and image after image jarring through the over-tired organ! —Oliver Wendell Holmes"



1869: The "Avitor" flew nicely as a model but failed against real-world conditions.

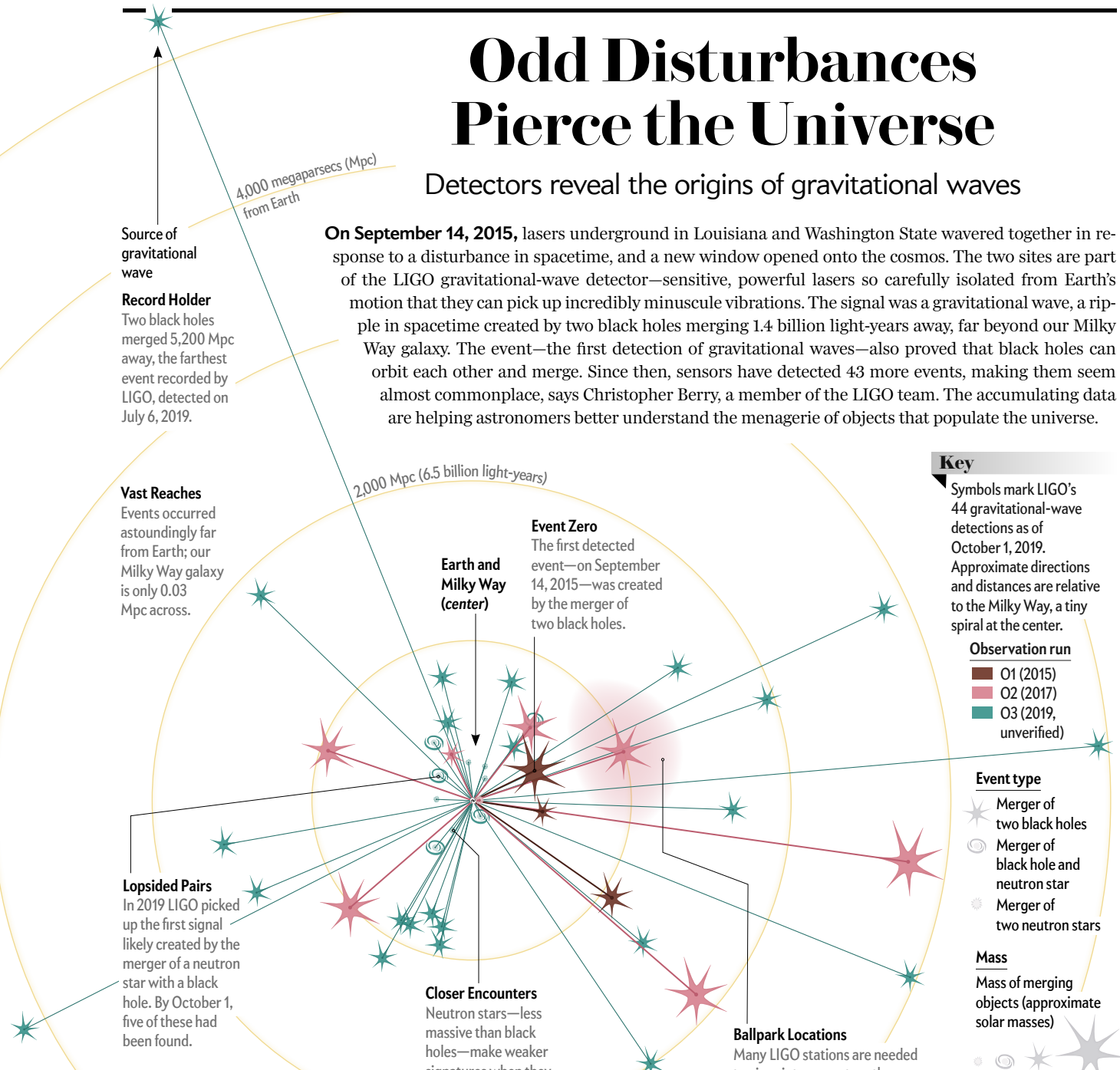
SCIENTIFIC AMERICAN, VOL. XXI, NO. 23, DECEMBER 4, 1869

Text and Graphic by Katie Peek

Odd Disturbances Pierce the Universe

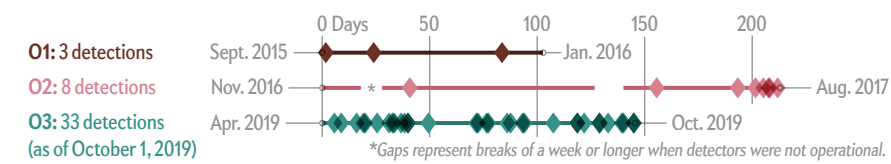
Detectors reveal the origins of gravitational waves

On September 14, 2015, lasers underground in Louisiana and Washington State wavered together in response to a disturbance in spacetime, and a new window opened onto the cosmos. The two sites are part of the LIGO gravitational-wave detector—sensitive, powerful lasers so carefully isolated from Earth's motion that they can pick up incredibly minuscule vibrations. The signal was a gravitational wave, a ripple in spacetime created by two black holes merging 1.4 billion light-years away, far beyond our Milky Way galaxy. The event—the first detection of gravitational waves—also proved that black holes can orbit each other and merge. Since then, sensors have detected 43 more events, making them seem almost commonplace, says Christopher Berry, a member of the LIGO team. The accumulating data are helping astronomers better understand the menagerie of objects that populate the universe.



Quickening Pace of Discovery

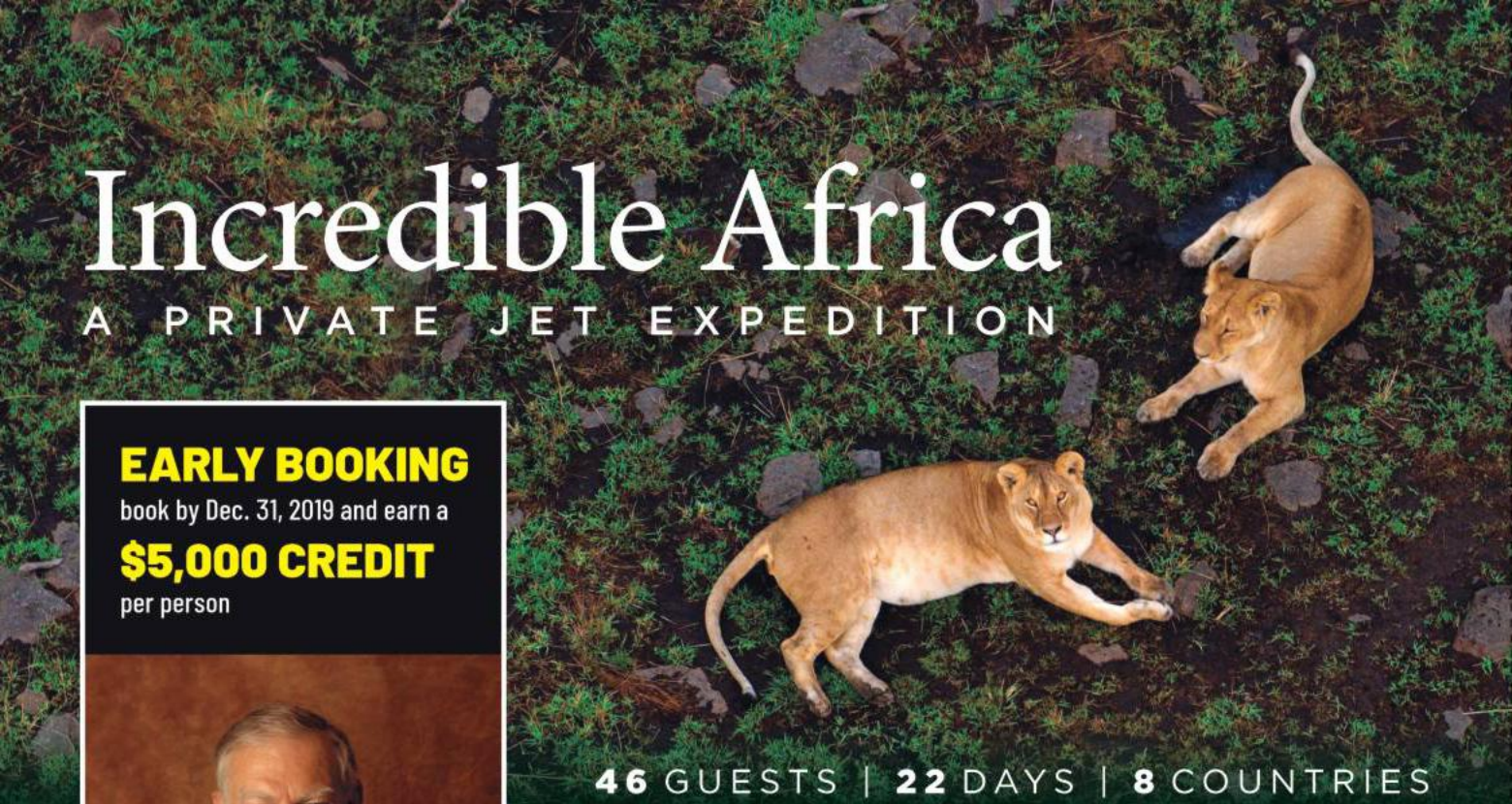
LIGO detected three confirmed events during its first run—dubbed "O1"—over four months in 2015. By run O3, detections were piling up five times as fast (although some may not withstand scientific scrutiny). Improvements in LIGO's physical setup have led to the increase.



SOURCES: GRACEDB—LIGO GRAVITATIONAL-WAVE CANDIDATE EVENT DATABASE; "GWTC-1: A GRAVITATIONAL-WAVE TRANSIENT CATALOG OF COMPACT BINARY MERGERS OBSERVED BY LIGO AND VIRGO DURING THE FIRST AND SECOND OBSERVING RUNS," BY B. P. ABBOTT ET AL. (LIGO SCIENTIFIC COLLABORATION AND VIRGO COLLABORATION), IN *PHYSICAL REVIEW X*, VOL. 9, ARTICLE 031040; JULY 2019

Incredible Africa

A PRIVATE JET EXPEDITION



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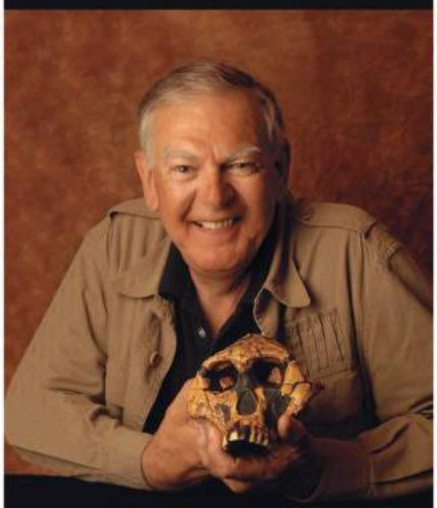

TRAVEL WITH EXPEDITION HOST

Donald Johanson

Best known for his 1974 discovery of **'Lucy,'** one of the most complete skeletons of *Australopithecus afarensis* known, Donald Johanson is one of the expedition hosts of Incredible Africa.

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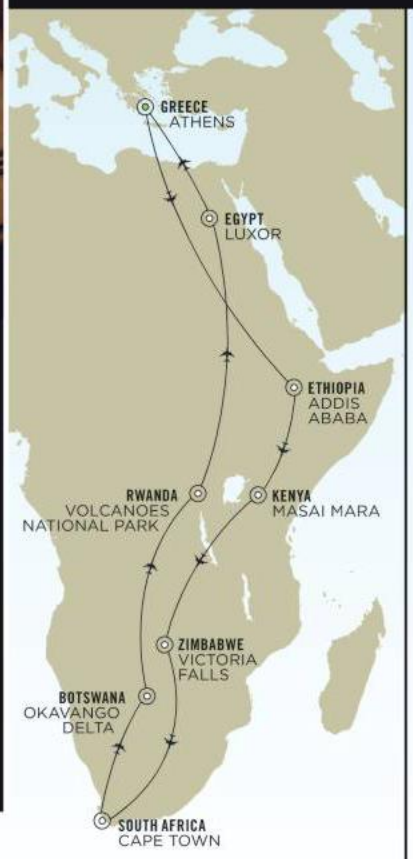

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