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SCIENTIFIC AMERICAN

World-changing ideas that are poised to transform society

DECEMBER 2017

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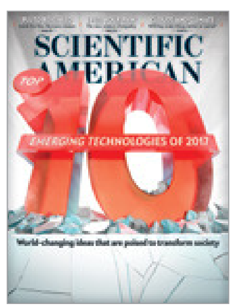
SCIENTIFIC AMERICAN

ANNIE GREEN-ARMYTAGE *Alamy*



ON THE COVER

This special report, compiled and produced by *Scientific American* and the World Economic Forum's Expert Network, highlights 10 emerging technologies with genuine momentum and the potential to create significant social and economic benefits.
Image by Mark Ross.

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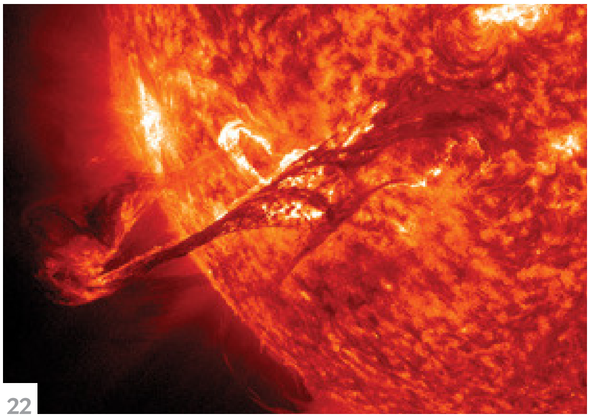
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ON THE WEB

Do-It-Yourself CRISPR
Scientific American examines how a new and easy-to-use D.I.Y. gene-editing tool will change science and society.
Go to www.ScientificAmerican.com/dec2017/crispr

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

Let's Science That

As an editor, I've never been a big fan of turning nouns into verbs when perfectly good options already exist. But I'd be happy to see us use "science" that way. It's a powerful, evidence-based process of conducting experiments, gathering data and performing analysis on the results. It's at once a methodical set of practices and a tool that inspires hope for a brighter future by advancing discovery and innovation.

That's why our cover story, "Top 10 Emerging Technologies of 2017," has a special resonance for me. It's about world-changing ideas coming out of the labs that are poised to help us lead better, healthier lives. *Scientific American* produced the section in collaboration with the World Economic Forum. The Forum annually brings together business and policy leaders—and, increasingly, scientists and their research—to discuss ways we can work together to tackle the world's greatest challenges. Turn to page 28.

The partnership that led to this special report began three years ago. I was invited to serve as vice chair of one of the Forum's past Global Agenda Councils, focused on identifying emerging technologies. Our chair was the irrepressible polymath Bernard S. Meyerson, chief innovation officer of IBM. With the help of knowledgeable council members, we produced terrific lists for two years.

After our council term ended, our Forum lead, Rigas Hadzilacos, asked me if *Scientific American* might like to continue to help develop the Top 10 Emerging Technologies list. He proposed that we could tap the knowledge of members of the Forum's Expert Network and Global Future Councils; we also planned to reach out to the ever savvy *Scientific American* board of advisers and other specialists who keenly observe developing innovations. Not least, Meyerson also smilingly told me he'd enjoy the chance to work for *me* this time around. How could I resist an opportunity like that? I'm grateful to all who generously helped to shape this collaboration and to the editorial team members who have now brought it to you in this edition.

Elsewhere in our pages, you'll find lots of other ways science is making a difference: changing everything we thought we knew about a "former" planet ("Pluto Revealed," page 40); helping us understand how the tragic history of stolen people has forged modern society ("How Captives Changed the World," page 78); illuminating the true population health of American burying beetles ("Beetle Resurrection," page 64); and exploring the implications of possibly using new gene-editing techniques to preserve ecosystems in the Galápagos (*page 48*). Have a question? Let's science that. SA

Illustration by Eric Petersen (eyepiece), Illustration by Nick Higgins (DiChristina)

August 2017

NUCLEAR MATTERS

In "Nuclear War Should Require a Second Opinion" [Science Agenda], the editors argue that the president of the U.S. should not be the only person to decide on whether or not to cause worldwide havoc by ordering a nuclear launch and that "we need to ensure at least some deliberation."

Alone or through informed advice and widespread consent, threatened by enemies or not, an American president (or any other president) should *never* have the power to destroy the world. The U.S. has countless other ways to make adversaries sorely regret threatening it.

Stelios Bakalis *Thessaloniki, Greece*

Your editorial's recommendation introduces ambiguity. Would it be desirable for the president to consult "high-ranking members of Congress" after a first strike, or the imminence of one, when these members might themselves be divided? And how many need to affirm? To minimize delay and the possibility of error, might not it be better to require the secretary of defense or the national security advisor, or both, to certify that there is unmistakable evidence that these weapons have been used?

What constitutes evidence would be clarified by a policy of "no first use" (NFU) of nuclear weapons. NFU draws a bright line between when the use of such weapons is justified—in particular, to retaliate against their first use by another country—and when it is not. If one side adopts it, it is in the interest of the other side to do so to prevent a nuclear Armageddon, at least given that both sides have second-strike capability (as the U.S. and Russia do).

For a state like North Korea, which does not have such capability, retaliation by the U.S. would almost certainly wipe out its future capability and annihilate its leadership. So even though North Korea may not agree to NFU, it would be foolhardy for it to seriously consider a first strike, which translates into its implicit adoption.

Steven J. Brams *Professor of politics, New York University*

"Before trying to increase crop yields, we must find ways to reduce inefficiencies in our food production and distribution."

OLGA SYRAYA *DÜSSELDORF, GERMANY*

CROP TALK

In "Building a Better Harvest," Marla Broadfoot reports on efforts to utilize the phytobiome—the web connecting crops with environmental factors such as microbial communities—to avoid famines. I appreciate that crop science aims to adopt a more holistic approach. But I am somewhat perplexed by Broadfoot's assertion that yields must increase by 70 percent, as concluded in a 2009 United Nations Food and Agriculture Organization (FAO) discussion paper, to satisfy population growth and increasing meat consumption.

Before trying to increase crop yields, we must find ways to reduce inefficiencies in our food production and distribution. About a third of edible food is wasted globally, and the FAO found that 6.7 percent of global greenhouse gases comes from food waste. Further, a June 2010 report by the United Nations Environment Program urged a global shift toward a plant-based diet to fight hunger, poverty and climate change. And adoption of such a diet would make people healthier. China has already recognized the environmental and health threat posed by growing meat consumption and has developed a campaign to reduce it by 50 percent by 2030.

Olga Syraya *Düsseldorf, Germany*

Broadfoot's article largely ignores an important consequence of crop yield increases: they can depress market prices for the crops. Unless they provide more income despite falling prices, higher yields may do the farmers more harm than good.

In addition, although Broadfoot concludes with a brief mention of the problems involved in getting food into the hands of the starving, that observation conceals an important point: if we stopped putting our crops into the bellies of cattle and ethanol fermenters and the hands of dictators, we could probably feed the world right now without having to increase yields, and doing so would also reduce pressure on the environment created by high-intensity agriculture. Sometimes human problems require human solutions.

Geoff Hart *via e-mail*

MENTAL MONOLOGUE

"Talking to Ourselves," by Charles Fernyhough, discusses studies on the neural bases of people talking to themselves in their mind. I wonder if any research has been done to determine if such "inner speech" is still present in people suffering from dementia or Alzheimer's disease—or if it is present but in a different form. My mother-in-law sat motionless for hours, unable to speak to us, and I always wondered if she still could speak to herself.

Sandra Robbins *Carlsbad, Calif.*

I would like to know if any of the brain pathways found in the research on self-talk could be similar to dreaming. It seems like dreaming might be an uncontrolled visual re-creation of the process.

Lanny Schroeder *via e-mail*

FERNYHOUGH REPLIES: Regarding Robbins's question: Inner speech is difficult to study. In the case of individuals with dementia, the problem of obtaining reliable reports on inner experience is even more acute. It appears likely to me that inner speech will continue in people who, for reasons including dementia, don't use much spoken language. One possibility for investigating such speech in dementia would be *to develop nonverbal measures, such as pictorial representations of aspects of inner speech, that could be used with individuals who express little external language.*

In answer to Schroeder: Dreaming occurs mainly (though not exclusively) during the rapid eye movement (REM) sleep stage, when activity in the brain's cerebral cortex is similar to that observed when people are awake. Methodologically, tying particular dreams involving speech to activation in language and other pathways would be extremely hard. One way forward might be through obtaining detailed self-reports on dreams by adapting existing techniques of experience sampling. But making such methods work with a sleeping participant—perhaps awoken by a prompt or beep and invited to report on the dream—would be challenging indeed.

STRATEGIC CHOICE?

"A Matter of Choice," by Peg Tyre, investigates the results of school vouchers and finds that they have led to lower scores in math and reading. I was dismayed that the article did not answer the question posed under its title: "So why has the Trump administration embraced them?"

The article discusses everything but the proverbial gorilla in the room, which is that public education is but another segment of the public trust that is being directly and systematically dismantled in the name of private profits.

Mohammad Babar *Jefferson City, Mo.*

INIMITABLE ALLUSION

In "Technology as Magic" [TechnoFiles], David Pogue invokes the name "Jeeves" in reference to instructing a hypothetical butler. Pogue must get these things right: the original Jeeves, created by British author P. G. Wodehouse, was not a butler. "If the call [came], he [could] buttle with the best of them," but he was, in fact, a "gentleman's personal gentleman"—a valet.

Charles Griffin *via e-mail*

ERRATUM

In "The Roots of Science Denial" [October 2017], an editors' note incorrectly states that a draft of the Climate Science Special Report was leaked to the press. The draft had been made available for public comment months earlier. We regret the error.

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Ice under Siege

We need a treaty to protect the warming Arctic from exploitation

By the Editors

Snow crabs have arrived off the Arctic coast of Norway, around the islands of Svalbard—foot soldiers in the world's newest territorial battle. The crabs were not seen there at the start of this century, but today multitudes have migrated to the chilly waters. Models project that the snow crab catch could soon reach 170,000 metric tons a year—potentially bringing in about $1 billion and making it, with Arctic cod, one of the region's most lucrative resources.

That kind of money is one reason Norway grabbed a Latvian fishing vessel pulling crabs from Svalbard waters this past winter. (The ship was held and later fined.) But there are many other reasons—including the race to pump undersea oil and to establish new military outposts—that have nations with Arctic coasts scrabbling, like aggressive crabs, to establish territorial rights. Ice loss caused by climate change is opening up the Arctic, and it looks like the competition to take advantage has the potential to destroy the region and affect the entire planet.

The ice data are unequivocal: NASA reports that the average area of Arctic sea ice that remains after the summer melting season has shrunk by 40 percent since 1980. Winter sea ice has been at record lows for the past three years, according to the U.S. National Snow and Ice Data Center.

The newly open area boasts many attractions for nations whose territories extend into the Arctic Circle (Russia, Canada, the U.S., Norway, and four more), as well as countries looking for more efficient shipping routes, such as China. As the ice retreats, financial and national security interests advance. Here is just some of what's at stake:

- **FISHERIES.** Open waters allow more fishing fleets. But a free-for-all could lead to drastic depletion of fish and crab stocks. Hence, Norway's claim that European Union countries have very limited rights, or no rights at all, in its northern grounds.
- **OIL.** This year Norway increased its estimate of the amount of oil in the Barents Sea, including areas north of the Arctic Circle, to 2.8 billion cubic meters. That's double previous estimates. The number of exploratory wells in the Barents is at a record high. The U.S. has announced plans to expand Arctic oil prospecting. Russia already has and asserts its continental shelf—and oil rights—extend even farther north.
- **MINING.** A Chinese firm has taken over a mine in Greenland. And on the seafloor, nodules of valuable metals such as manganese and iron have been discovered, and companies are looking for ways to recover them.
- **NAVIGATION.** Canada has mapped the newly widened Northwest Passage, noting that most of it sits over the country's continental shelf, giving it a claim of control that is challenged by the U.S. This shorter route between Asia and Europe will attract huge ships, and lack of safety and environmental regulations could lead to devastating accidents.
- **NATIONAL SECURITY.** Russia has established a new military base in the Arctic, a move that has made NATO uneasy. The Russians have 40 icebreakers, some of them nuclear-powered. The U.S. has but two conventionally powered vessels.

Clearly, the world needs a treaty that governs how we use this valuable region. It is a unique place: parts of the Arctic are national territories, but as a whole, it is a global commons. Oil spills, construction, overfishing, coastal degradation (which will affect the indigenous peoples who live there), and military confrontation could have far-reaching consequences.

Such an agreement can't be a mirror of the 1961 Antarctic Treaty, which set aside that entire continent as a research reserve. That one was easy because no country bordered Antarctica and no one lived there. The Arctic is entirely different. Eight nations claim parts of it, and it is home to groups such as the Sami that live in Scandinavian countries and Russia. We need a treaty that sets resource limits in different categories and gets nations to agree on shares. This is a feasible approach: The United Nations Convention on the Law of the Sea was negotiated between many nations with exactly these kinds of principles. (Only one major seafaring country, the U.S., has refused to sign.) The Arctic Council, made up of the eight Arctic states, is the group to spearhead this, and the time is now. Otherwise the ice will be only the first of many things to disappear.

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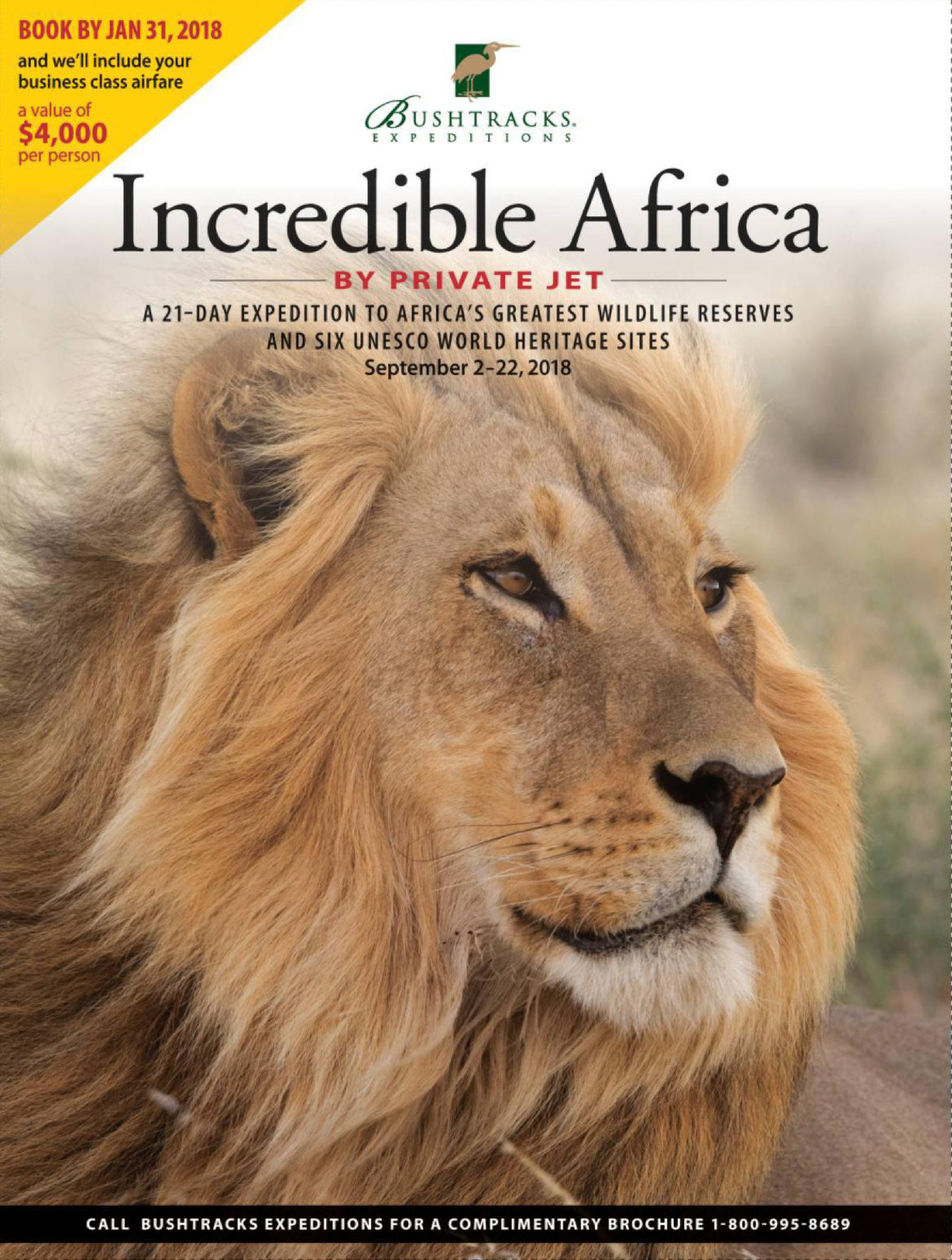
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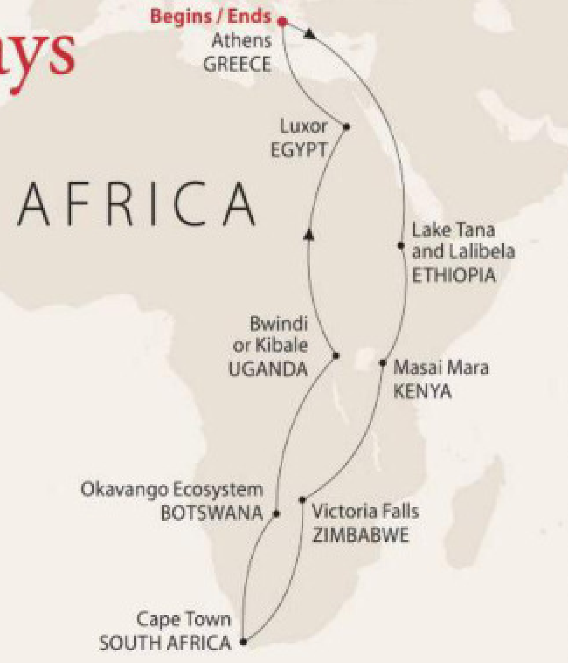


TRAVEL WITH

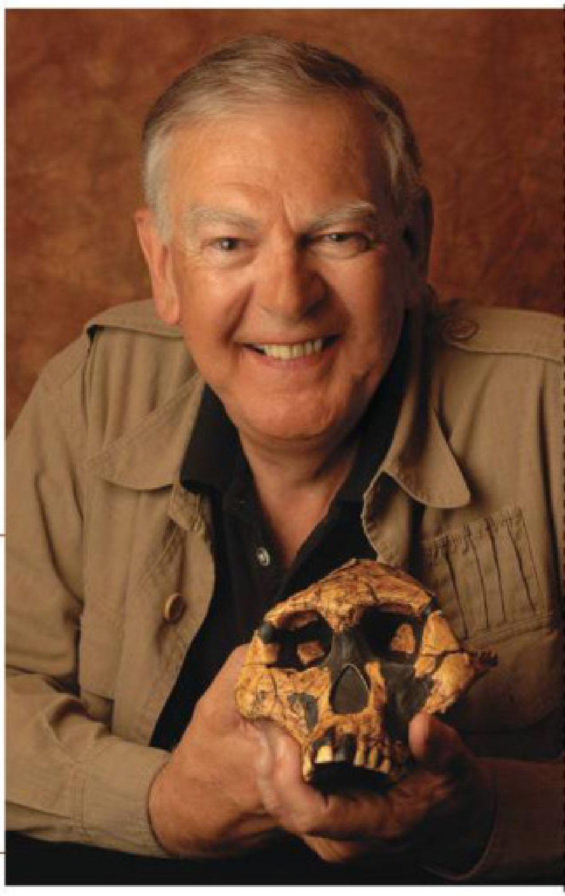
Donald Johanson

THE ANTHROPOLOGIST WHO DISCOVERED LUCY,

the world's most celebrated human ancestor

"Some 60,000 years ago, *Homo sapiens* ventured out of Africa for the first time, initiating what has become a favorite activity of our species: exploring the planet. I am thrilled and privileged to join you on this remarkable trip. As an anthropologist with a passion for studying the genesis and diversity of humanity over millions of years and more than 11 million square miles of African landscape, I have journeyed to this land many times over the past 50 years, and with each trip I am further enriched." — Donald Johanson

Anthropologist Donald Johanson is hosting this expedition throughout. He is the Virginia M. Ullman Chair in Human Origins, professor in the School of Human Evolution and Social Change, and the Founding Director of the Institute of Human Origins at Arizona State University. Since 1970 he has conducted field research in paleoanthropology in Eastern Africa and the Middle East. Most notably, **he discovered the 3.18 million year old hominid skeleton popularly known as 'Lucy.'** He is an Honorary Board Member of the Explorers Club, a Fellow of the Royal Geographical Society, and the recipient of several international awards. He has written, among other books, *Lucy: The Beginnings of Humankind.*



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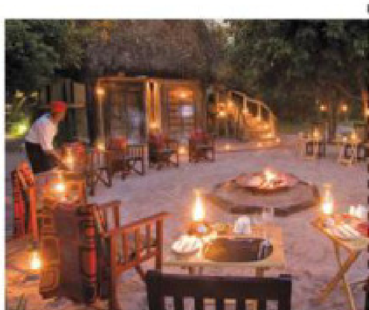

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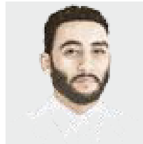

Sahand Ghodrati is president of the class of 2020 at the Loyola University Chicago Stritch School of Medicine.

DACA's Demise Is Bad for Our Health

Med school "Dreamers" will give more care to underserved communities

By Sahand Ghodrati

I watched news coverage of the 2016 presidential election results sitting beside my roommate, a medical student at the Loyola University Chicago Stritch School of Medicine. He has been in this country since he was a kid, but he is undocumented. Now, with the Deferred Action for Childhood Arrivals (DACA) program on life support, I have a much more intimate understanding of the fear on his face that evening in November.

Like many undocumented youth, my roommate learned of his immigration status only when it came time to apply for college. He grew up in our society, was educated by our public school system where he pledged allegiance to our flag, and cherishes American values as much as anyone I know. It occurs to me now, as he faces the threat of being sent "back" to Thailand, his country of birth but not his allegiance, that this scenario is especially ridiculous as he is preparing to dedicate a lifelong career to the betterment of our nation's health.

Stritch was the first U.S. medical school to openly accept applications from DACA recipients, and it is now home to more undocumented students than any other medical school in the country. Our DACA classmates are among the most resilient people I have ever met. They excel in a grueling medical curriculum despite the daily demonization of their status in our national political conversation.

Reminding folks that "Dreamers" stand for the same things native-born citizens do shouldn't be necessary. But just in case some readers are not convinced, I will make the case for undocumented physicians. One thing most Americans can agree on, even in 2017, is that our health care system has plenty of room for improvement. The dramatic shortage of providers in underserved communities is one area of focus.

To respond to this shortage and to tackle historic inequities that have led to underrepresentation of minority groups, medical schools have shifted toward mission-based admissions initiatives that weigh more than mere grades and standardized test scores. At Loyola, a Jesuit institution, this mission is grounded in the principles of social justice and service to others. The university decided to build its Loyola Center for Health on Roosevelt in the less affluent western suburbs of Chicago, less than a mile from our school's campus. The Access to Care program there provides free health care to individuals in the local uninsured population, including people who are undocumented.

Health equity is further promoted by recruiting medical students from diverse backgrounds. This initiative improves health access in underserved communities: data have shown repeatedly that underrepresented minorities in medicine go on to practice in underserved communities at higher rates. Undocumented immigrants, who live in society's shadows without access to health care, financial freedoms or the personal agency of having a driver's license, for example, are among the most disenfranchised groups in today's America.

Stritch began admitting undocumented students in 2014, in recognition of the medical profession's duty to benefit all people. Their presence not only will result in our graduates reaching a broader range of patients but also will guarantee they are a key component of our professional development. When we confront differing identities and perspectives, we actively build empathy—perhaps the most vital quality of any good doctor.

To be sure, we were not immune to the divisive forces unleashed during the 2016 presidential campaign. Our class's stark ideological divide has compromised personal relationships and introduced troubling fault lines in our community, just as it did for people across the country.

But despite our differences, we recognize the importance of supporting our undocumented colleagues. Even the majority of our most conservative classmates attended a rally for our DACA classmates and feel strongly about their right to realize their passion for treating the sick of this nation. For us, this is not a matter of politics—it's common sense. SA

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Illustration by James Olstein

ADVANCES

Before plate tectonics began, much of Earth was covered in rocks the color of this black sand beach in Vík, Iceland.

GEOLOGY

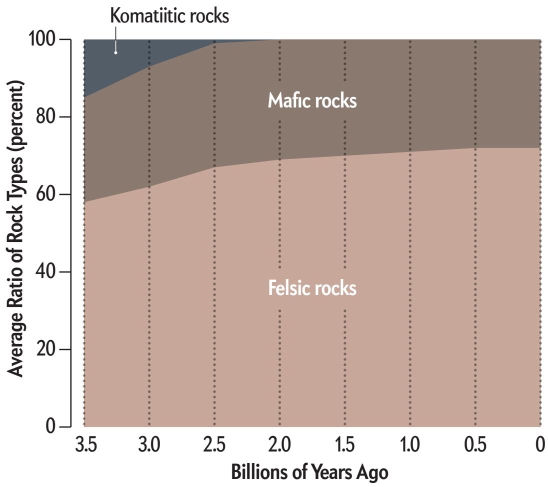
Dawn of Plate Tectonics

Recent findings heat up the debate over when these crust pieces started moving

The early Earth may have looked much like Iceland—where lava fields stretch as far as the eye can see, inky mountainsides tower above the clouds and stark black sand beaches outline the land. But the planet's color scheme gradually became less bleak. Today it also includes paler rocks, like the ash-colored granite of Half Dome in Yosemite National Park. Scientists remain uncertain as to when the world started this transition, but new evidence is narrowing the time frame.

A recent study suggests the shift had already transpired 3.5 billion years ago. The finding is hotly debated but may help scientists understand when tectonic plates—the interlocking slabs of crust that fit together like puzzle pieces far below our feet—started to wake up and shuffle around. The key to this idea is that light-colored rocks are actually dark ones "reincarnated." In short, light rocks form when dark ones are pushed deep inside Earth—possibly when one tectonic plate slips under another in a process called subduction. Given that light-colored rocks were abundant billions of years ago, plate tectonics had likely already kicked in by then, the study researchers conclude.

Nicolas D. Greber, a geologist now at the University of Geneva in Switzerland, and his colleagues analyzed 78 sediment layers from around the world to pin down



Researchers measured the ratio of different rock types in Earth's crust over time. The proportion of mafic rocks remained constant, but the amount of felsic rock started to increase around 3.5 billion years ago, coinciding with a decrease in another type of rock called komatiitic—suggesting plate tectonics had already begun by then.

the ratio of lighter (or felsic) rocks to darker (or mafic) rocks. But it was not as simple as counting light stones versus dark ones, because both had long since eroded into tiny particles. Instead Greber's team looked at titanium. Although the metallic element is present in both types of rock, the proportion of its isotopes (chemically identical atoms with the same number of protons but different numbers of neutrons) shifts as the rock changes from mafic to felsic. Suppose you mix something that turns out both salty and sweet, Greber explains. Performing an analysis like his team did would give you "an idea of how much salt you added and how much sugar you added." He had expected the earliest sediments in his sample, which dated back 3.5 billion years, to be composed mostly of mafic particles. To his surprise, roughly half the particles were felsic. His group reported the findings in September in *Science.*

This result goes against the predominant view in the field—that the early Earth was still cloaked in dark mafic rocks 3.5 billion years ago—says Jun Korenaga, a geophysicist at Yale University, who was not involved in the study. "It's very refreshing to see that a group is going in this direction," he says. "They tried to shake [up] the community, and this is a highly welcome input."

Scientists have long argued over how long ago these crustal plates began to stir, with estimates ranging from one billion to 4.2 billion years. Jonathan O'Neil, a geochemist at the University of Ottawa, who was not involved in the new work, points out that several recent studies peg the beginning of plate tectonics to around three billion years ago. He notes that there is no consensus yet, however. And that is a major problem, if scientists want to understand the evolution of early Earth. Shifting plates dramatically reshape the planet, not only by sculpting ocean basins and thrusting up mountain ranges but also by altering the composition of the atmosphere and oceans. This would have affected the supply of nutrients available to the fledgling life on our young planet. In fact, some scientists contend that plate tectonics was crucial to the origin of life.

With such high stakes, it is easy to see why scientists are cautious about settling on a firm origin date. For example, Paul Tackley, a geophysicist at the Swiss Federal Institute of Technology Zurich, disagrees with Greber's latest interpretation. He maintains that felsic rocks can form anytime mafic rocks sink deep within Earth—and not only along subduction zones. When a volcano erupts, for example, the newly released lava can push down mafic rocks until they become so deeply buried that they melt under the high subterranean pressures and temperatures, transforming into felsic rocks even without plate movements.

Although Greber agrees felsic rocks can form this way, he argues that such a high felsic-to-mafic ratio cannot be explained by Tackley's explanation alone. O'Neil and Korenaga agree with Greber that subduction is the most likely factor. But that would not necessarily mean that subduction—and therefore plate tectonics—was occurring on a global scale. Instead many experts speculate that early plate tectonics activity was probably more episodic, starting and stopping locally multiple times before it became a continuous and worldwide process. The only way to know for sure is to analyze more sediments—something Greber hopes to do in the future. *—Shannon Hall*

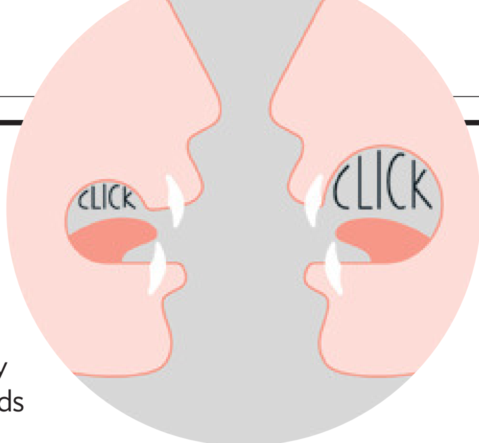
PRECEDING PAGES: LIZ TORMES; THIS PAGE: SOURCE: "TITANIUM ISOTOPIC EVIDENCE FOR FELSIC CRUST AND PLATE TECTONICS 3.5 BILLION YEARS AGO," BY NICOLAS D. GREBER ET AL., IN *SCIENCE*, VOL. 357; SEPTEMBER 22, 2017

Graphic by Amanda Montañez

LINGUISTICS

Speaking in Clicks

Mouth shape may explain why few languages use these sounds



Click sounds, such as those found in some languages in Africa, make perfectly good consonants. So why do they appear so rarely in most human speech? One culprit may be anatomy.

Previous studies have suggested that in some speakers of click languages, the alveolar ridge—the rounded bump between the upper teeth and the roof of the mouth—is small or even absent. In recent research, Scott Moisik of Nanyang Technological University in Singapore and Dan Dediu of the Max Planck Institute for Psycholinguistics in Nijmegen, the Netherlands, built biomechanical models that simulated clicks in vocal tracts with alveolar ridges of varying sizes. Their results, published in January in the *Journal of Language Evolution,* showed a clear disadvantage for tracts with large ridges. These allowed less air to be trapped in the mouth, requiring more muscular force to produce a click.

The authors interpret this finding as support for an anatomical bias against clicks. They believe the bias is probably weak at the individual level; people with large alveolar ridges can still learn click languages. Nevertheless, their models suggest that such individuals may find it difficult to learn click consonants or that their pronunciations may be wrong. Amplified over generations, this bias might explain why such consonants are so rarely found in languages worldwide.

These results are not the first to challenge the traditional premise among linguists that language evolution is largely immune to external factors. Several other researchers have recently argued that geographical context, environmental conditions and genetics could all play a role. But Moisik and Dediu's work goes a step further by singling out a single feature of human anatomy and quantifying its contribution to a particular type of speech sound.

Susanne Fuchs, senior researcher at the Leibniz Center of General Linguistics in Berlin, who was not involved in the work, says the study's conclusions are valid. But she cautions that they may present a chicken-and-egg problem: "The palate shape of an individual matures from early childhood to puberty and … may be affected by frequent productions of clicks," Fuchs says. "Therefore, over the course of history, it may well be possible that vocal tract properties and click productions developed in parallel." —*Anne Pycha*

Illustrations by Thomas Fuchs

COMPUTER ENGINEERING

Quantum Leaps

Advances in "qubit" design could lead to more powerful computers

Quantum computers can theoretically blow away conventional ones at solving important problems. But they face major hurdles: their basic computational units, called quantum bits or qubits, are difficult to control and are easily corrupted by heat or other environmental factors. Now researchers have designed two kinds of qubits that may help address these challenges.

Conventional computer bits represent either a one or a zero. But thanks to an eerie quantum effect known as superposition—which allows an atom, electron or other particle to exist in two or more states, such as "spinning" in opposite directions at once—a single qubit made of a particle in superposition can simultaneously encompass both digits. When multiple qubits become "entangled" (referring to a quantum property that links one particle's actions to those of its partners), computing capacity can rise exponentially with the number of qubits. In principle, a 300-qubit quantum computer could perform more calculations at once than there are atoms in the observable universe.

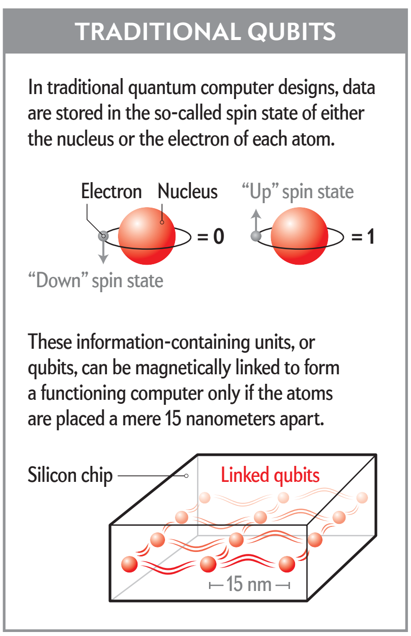
Currently qubits based on a particle's spin direction must be positioned about 15 nanometers apart—any more, and their entanglement fails. But quantum engineer Andrea Morello of the University of New South Wales in Australia and his colleagues now claim to have designed qubits that can be separated by up to 500 nanometers. This provides much more room for vital apparatus to control the qubits. To create one of these so-called flip-flop qubits (*graphic*), an electron is pulled some distance from an atom's nucleus. This causes the atom to exhibit positive and negative electric poles that can interact over relatively large distances, the researchers reported in September in *Nature Communications.*

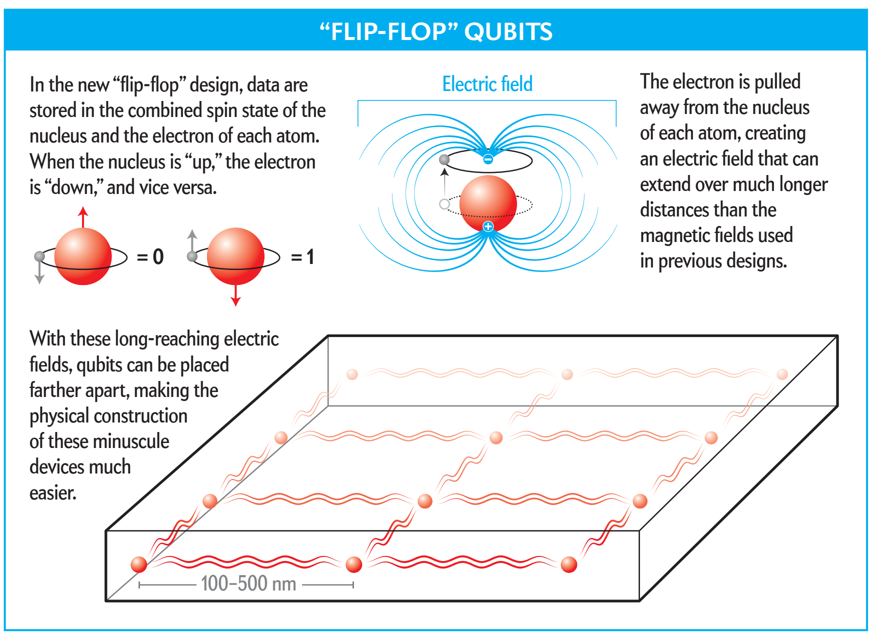
> "I think it's very exciting that scientists are still pursuing new roads to build large-scale quantum computers."
> —*Seth Lloyd, M.I.T.*

Another proposed qubit design is based on "quasiparticles," which are formed from negatively charged electrons interacting with positively charged "holes" in superconducting material. In work reported in August in *Nature,* scientists at the Delft University of Technology and Eindhoven University of Technology, both in the Netherlands, and their colleagues created structures in which a pair of separated quasiparticles can "braid," or exchange places, acting as a single qubit. The distance between them would decrease the chance that environmental effects could perturb both particles at once, which potentially makes such qubits highly stable, says study co-lead author Hao Zhang, a quantum physicist at Delft.

Both teams say they hope to create working versions of the new qubits soon. "I think it's very exciting that scientists are still pursuing new roads to build large-scale quantum computers," says quantum physicist Seth Lloyd of the Massachusetts Institute of Technology, who did not take part in either study.

—*Charles Q. Choi*





SOURCE: "SILICON QUANTUM PROCESSOR WITH ROBUST LONG-DISTANCE QUBIT COUPLINGS," BY GUILHERME TOSI ET AL., IN *NATURE COMMUNICATIONS*, VOL. 8, ARTICLE NO. 450; SEPTEMBER 6, 2017

Illustration by Brown Bird Design

ROB WHITE *Getty Images*

BIOCHEMISTRY

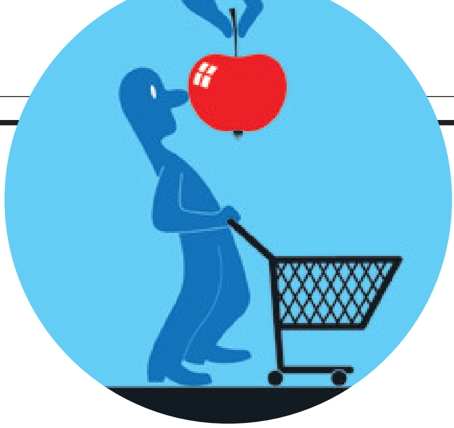
Smoky Wine

Wildfires can contaminate grapes and ruin the beverage's flavor

Some wines, like those aged in toasted oak barrels, taste great with a hint of smoke. But too much can spoil the flavor. As the climate warms and wildfires grow more frequent and intense, pollution from them can drift into vineyards and get absorbed by the plants—imparting a foul, ashy taste known in the industry as "smoke taint." Bushfires between 2006 and 2007 ruined around $60 million to $70 million worth of wine in the Australian state of Victoria alone. This year late summer wildfires damaged grapes in Oregon and Washington State and, in a tragedy that killed dozens, devastated parts of northern California.

Little is known about the biochemistry of how smoke contaminates wine. Adding to the mystery is that smoky notes cannot always be tasted in the grapes themselves—but they still sometimes find their way into the finished product. Recent research, however, helps explain what is going on. In a study published in July in the *Journal of Agricultural and Food Chemistry,* Wilfried Schwab, a food chemist at the Technical University of Munich, and his colleagues identified a type of grapevine enzyme called glycosyltransferases, which bind smoke molecules to sugars in the grapes. This creates chemicals called glucosides that are difficult to taste but can be broken down by yeast during fermentation, freeing the ashy notes and ruining the wine.

The discovery points to some possible fixes for the pungent problem. One option is to breed or isolate strains of yeast that leave the glucosides intact. Another strategy is to develop a chemical that deactivates glycosyltransferases and could be sprayed on vines. This would prevent sugars from binding to and locking up the acrid flavors within the plant, says Markus Herderich, a scientist at the Australian Wine Research Institute, who was not involved in the Munich work. Scientists might also be able to find grape strains with low natural levels of glycosyltransferases—or even to genetically engineer plants that lack such chemicals. The search for solutions, Schwab says, is on. —*Doug Main*



PSYCHOLOGY

Healthy See, Healthy Do

Nutritious supermarket displays can sway purchasing decisions

Visit the grocery store on an empty stomach, and you will probably come home with a few things you had not planned to buy. But hunger pangs are not the only culprit behind impulse purchases. The location of store displays also influences our shopping choices—and may make or break some healthy eating habits.

The checkout area is a particular hotspot for junk food. Studies have found that the products most commonly found there are sugary and salty snacks—and a few studies have suggested that simply swapping in healthier options can shift customer behavior. A 2012 study in the Netherlands found that hospital workers were more likely to forgo junk food for healthy snacks when the latter were more readily available on canteen shelves, for example. In 2014 Norwegian and Icelandic researchers likewise found that replacing unhealthy items with healthy ones in the checkout area significantly increased last-minute sales of healthier foods.

These findings caught the attention of the New York City Department of Health and Mental Hygiene, which has been working with more than 1,000 store owners to encourage them to stock and promote nutritious foods. "We know that the food retail environment is full of cues meant to encourage consumption," says Tamar Adjoian, a research scientist at the department. "Making healthy food more convenient or appealing can lead to increased sales of those products."

Adjoian and her colleagues wondered if such findings would apply to their city's dense urban checkout areas, so they recruited three Bronx supermarkets for their own study. They gave one checkout line in each store a healthy makeover, replacing candy, cookies and other processed snacks with fruit, nuts and similar items containing 200 or fewer calories per serving. Then they recorded purchases over six three-hour periods in each store for two weeks.

Of the more than 2,100 shoppers they observed, just 4 percent bought anything from the checkout area. Among those who did, however, customers in the healthy lines purchased nutritious items more than twice as often as those in the standard lines—and they bought unhealthy items 40 percent less often. The findings were reported in September in the *Journal of Nutrition Education and Behavior.*

The potential impact may seem small, but Adjoian believes that converting more checkout lines would open customers' eyes to nutritious, lower-calorie foods. Health department officials are now exploring ways to expand healthy options at checkout aisles throughout New York City.

—*Rachel Nuwer*

BIOMECHANICS

Wag the Lizard

How leopard geckos adapt to losing their tail

Somewhere in the highlands of Afghanistan, a hungry fox pounces on a tasty-looking leopard gecko. But the lizard has a get-out-of-jail-free card: a detachable tail. The dropped appendage flails around long enough to distract the fox, allowing the gecko itself to run off and hide.

Leopard geckos are one of a few lizard species that possess this self-amputation ability, known as autotomy. The technique is effective, but the tail can account for about a quarter of the lizard's body mass. So how do these animals adapt to losing so much of it that quickly?

When geckos lose their tail, they "take this more sprawled posture" and walk with their limbs splayed out farther from their body, says Chapman University biologist Kevin Jagnandan. Most researchers initially assumed this stance was a response to a suddenly shifted center of mass. But when Jagnandan observed leopard geckos with a tail in his laboratory, he realized that they wag it as they walk, suggesting that these movements may be key to the lizards' locomotion.

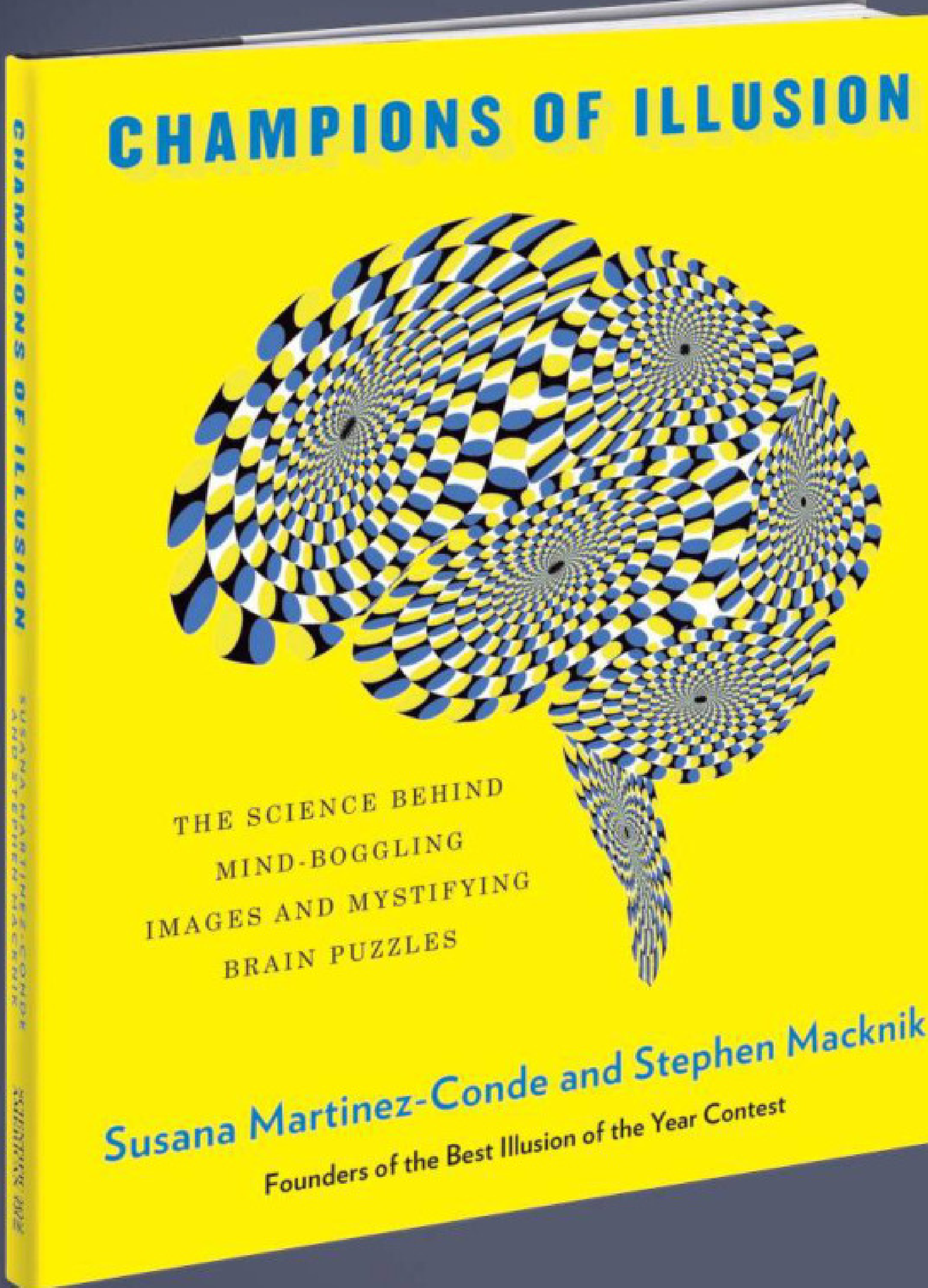
To test this hypothesis, Jagnandan and his team assessed the postures of 10 geckos walking in various conditions: with their tail intact; with their tail restrained by a small section of glued-on fishing rod (of negligible mass); and with their tail self-amputated. These comparisons allowed the researchers to distinguish the effects of lost mass from those of lost tail-wagging on the geckos' movements.

The lizards with an immobilized tail adopted stances similar to those with no tail, the researchers reported in a study published in September in *Scientific Reports.* This result suggests the sprawling walk they adopt after losing their tail is not compensating for the missing mass but rather for the lack of tail-wagging. Jagnandan thinks tail movements help the lizards maintain balance and stability as they walk. He suspects that the tails of arboreal mammals, such as cats and monkeys, serve a similar purpose.

Bill Ryerson, a biologist at Saint Anselm College, who was not involved in the study, was surprised by the findings. "We thought we had settled it—it seemed pretty open and shut" that mass was the main factor, he says. The new study challenges this earlier idea in a "beautifully simple" way, Ryerson adds.

Jagnandan hopes that understanding how animals react to missing body parts could ultimately help engineers design robots that can move more efficiently as heavy loads—or even entire limbs—are added and removed. —*Jason G. Goldman*

EVAN KAFKA *Getty Images*


CHAMPIONS OF ILLUSION
THE SCIENCE BEHIND MIND-BOGGLING IMAGES AND MYSTIFYING BRAIN PUZZLES
Susana Martinez-Conde and Stephen Macknik
Founders of the Best Illusion of the Year Contest
CHAMPIONS OF ILLUSION

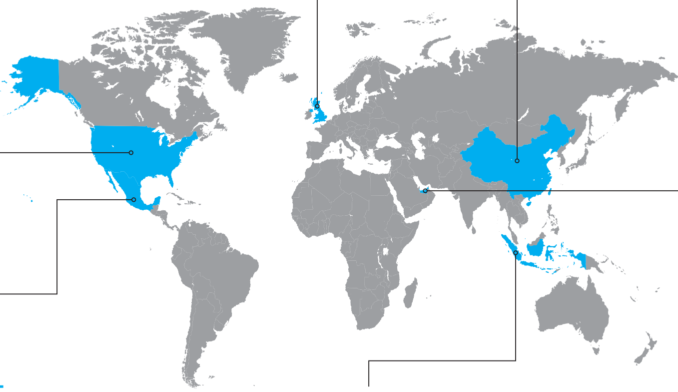
IN THE NEWS

Quick Hits

U.K.
A U.K.-based Formula One racing team has built the "Baby Pod 20"—a container inspired by racing car technology for transporting babies more safely in ambulances. A children's emergency service is already using the pods.

CHINA
Researchers found that giant panda habitats have declined significantly since the species was first listed as endangered nearly 30 years ago. Although the iconic animal is now designated as merely "vulnerable," scientists are concerned about the increasing fragmentation of its home territory.

U.S.
A staggering 88 percent of adults viewed the total solar eclipse that swept across the continental U.S. in August, a national study found. At least 20 million traveled to see it, and many others watched it online.



UNITED ARAB EMIRATES
Dubai conducted a test flight, sans passengers, of what it called the world's first drone taxi. The two-seater pilotless vehicle, developed by German company Volocopter, is hoisted by 18 propellers.

MEXICO
Seismologists say the soft soil under Mexico City, which was once the bottom of an ancient lake, exacerbated the effects of a magnitude 7.1 earthquake that killed hundreds of people in September.

INDONESIA
An animal-rights group settled a lawsuit with a British photographer over "selfies" supposedly taken with his camera by a crested macaque in Indonesia. The group claimed the copyrights belonged to the monkey.

—Yasemin Saplakoglu

For more details, visit www.ScientificAmerican.com/dec2017/advances

ADVANCES

NEUROSCIENCE

Food High

The brain releases feel-good chemicals after meals—even unappetizing ones


GETTY IMAGES

When we experience something painful, our brain produces natural painkillers that are chemically similar to potent drugs such as morphine. Now research suggests these endogenous opioids also play another role: helping regulate the body's energy balance.

Lauri Nummenmaa, a brain-imaging scientist at the University of Turku in Finland, and his colleagues measured endogenous opioid release in the brains of 10 healthy men. The subjects were injected with a radioactive substance that binds to opioid receptors, making it possible to visualize the receptors' activity using positron-emission tomography.

The study found evidence of natural painkillers in the men's brains after they ate a palatable meal of pizza. Surprisingly, their brains released even more of the endogenous opioids after they ate a far less enticing—but nutritionally similar—liquid meal of what Nummenmaa called “nutritional goo.” Although the subjects rated the pizza as tastier than the goo, opioid release did not appear to relate to their enjoyment of the meal, the researchers reported earlier this year in the *Journal of Neuroscience.*

“I would've expected the opposite result,” says Paul Burghardt, an investigator at Wayne State University, who was not involved in the work. After all, previous human and animal studies led researchers to believe that endogenous opioids helped to convey the *pleasure* of eating.

MEDICINE

Reprogram, Restore, Regenerate

A new technique repairs tissue by delivering infusions of DNA

The ability to convert, or “reprogram,” cells into other types has raised hopes for regenerating damaged limbs and organs. But existing methods are risky or inefficient and have been tried only on laboratory animals. A new technology could overcome these limitations, however. Researchers have used it to restore injured mouse legs and claim the technique is safe enough to test in humans.

Cells are typically reprogrammed using mixtures of DNA, RNA and proteins. The most popular method uses viruses as a delivery vehicle—although they can infect unintended cells, provoke immune responses and even turn cells cancerous. One alternative, called bulk electroporation, exposes entire cells to an electric field that pokes holes in their membranes to let in genetic material and proteins. Yet this method can stress or kill them, and only a small proportion is converted to the desired cell type.

Tissue nanotransfection, described in a study published in October in *Nature Nanotechnology,* involves a chip containing an array of tiny channels that apply electric fields to individual cells. “You affect only a small area of the cell surface, compared with the conventional method, which upsets the entire cell,” says study co-author L. James Lee, a chemical and biomolecular engineer at the Ohio State University. “Essentially we create a tiny hole and inject DNA right into the cell, so we can control the dosage.”

Chandan Sen, a physiologist at Ohio State, and his colleagues developed a genetic cocktail that rapidly converts skin cells into endothelial cells—the main component of blood vessels. They then used

Nummenmaa, too, was surprised. His group's earlier research showed that obese people's brains had fewer opioid receptors—but that receptor levels recover with weight loss. "Maybe when people overeat, endogenous opioids released in the brain constantly bombard the receptors, so they [decrease in number]," he says.

Why more opioids flooded the brain after the goo versus the pizza remains a mystery, but the researchers speculate that faster digestion of the liquid meal may have produced more of the chemicals at the time of the scan, 15 minutes after eating.

The new results may indicate that opioids play a wider role in energy metabolism than scientists previously thought. One possibility is that the opioid system is triggered by the satisfaction of a full stomach and replenished energy, Nummenmaa says.

"If you take a step back and look at conditions that activate opioid release—pain, feeding, pleasure—they are all related to homeostasis," or keeping the body's energy in balance, he explains. "The most interesting thing is that eating triggered the system even in the absence of sensory pleasure."

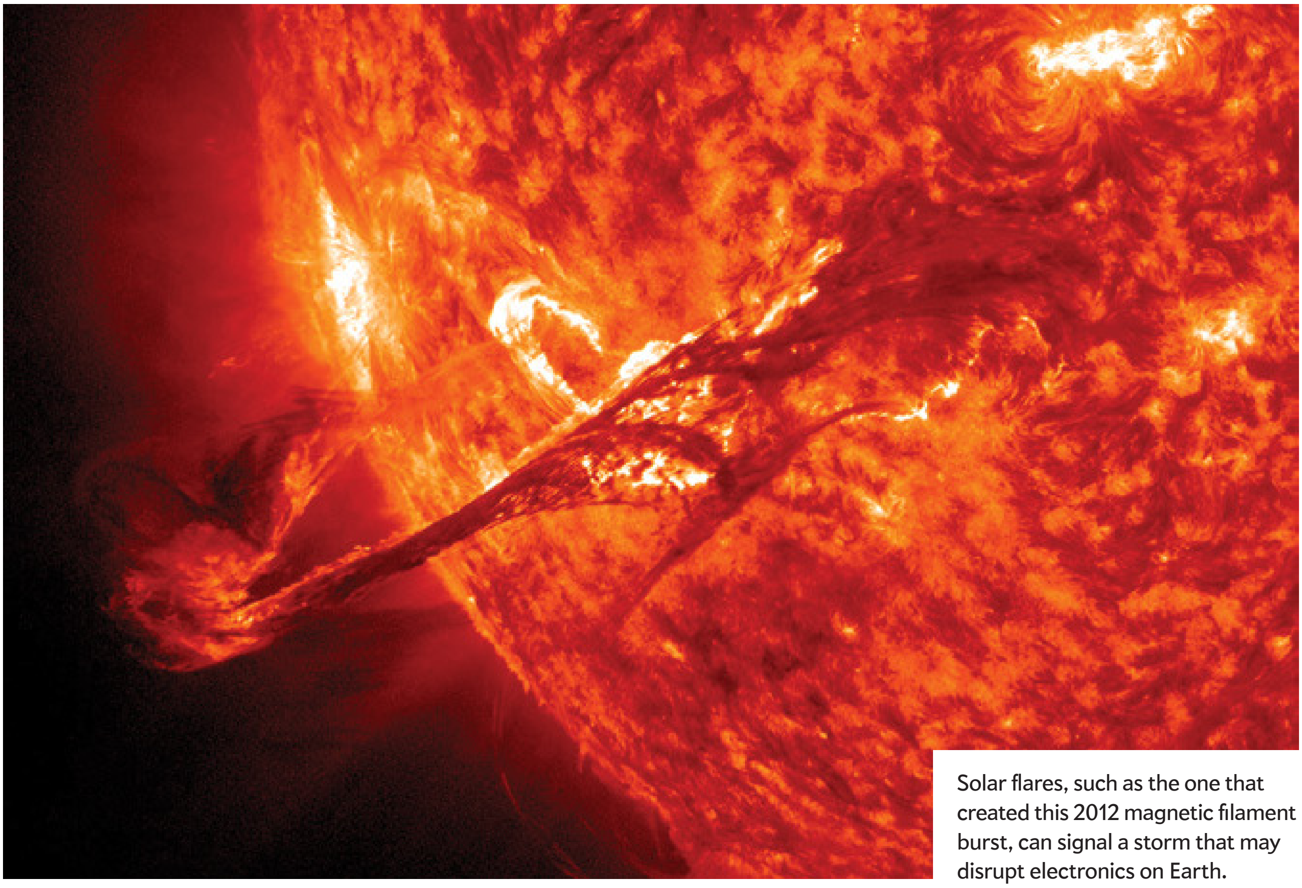
—Stephani Sutherland

their technique on mice whose legs had been damaged by a severed artery that cut off blood supply. New blood vessels formed, blood flow increased, and after three weeks the legs had completely healed.

Additionally, the transformed cells appeared to secrete reprogramming materials in extracellular vesicles (EVs) that targeted deeper tissue. Injecting mice with EVs harvested from the skin of other treated mice was as effective as using the chip itself. The researchers also converted skin cells from mice into neuronlike cells and transplanted them into mouse brains damaged by stroke, improving the animals' mental function. "As a proof of principle, this [approach] is very nice," says neurobiologist Benedikt Berninger of Johannes Gutenberg University Mainz in Germany, who was not involved in the study. "A big question would be: Can we get [EVs] to convert only specific cells?"

The team hopes to begin human trials within a year. "Considering what could be done," Sen says, "this could be transformative."

—Simon Makin



Solar flares, such as the one that created this 2012 magnetic filament burst, can signal a storm that may disrupt electronics on Earth.

SPACE

Solar Storm Doomsday?

"Space weather" events could cost trillions of dollars in damage

Humanity has begun collectively grappling with the dangers of global threats such as climate change. But few authorities are planning for catastrophic solar storms—gigantic eruptions of mass and energy from the sun that disrupt Earth's magnetic field. In a recent preprint paper, two Harvard University scientists estimate the potential economic damage from such an event will increase in the future and could equal the current U.S. GDP—about $20 trillion—150 years from now.

There are precedents for this kind of storm. The so-called Carrington Event of 1859 began with a bright solar flare and an ejection of magnetized, high-energy particles that produced the most intense magnetic storm ever recorded on Earth. It caused brilliant auroras in the atmosphere and even delivered electric shocks to telegraph operators. But a Carrington-scale storm today would cause far more harm because society now depends so heavily on electrical power grids, communications satellites and GPS.

In an effort to quantify that threat, astrophysicists Abraham Loeb and Manasvi Lingam of the Harvard-Smithsonian Center for Astrophysics developed a mathematical model that assumes society's vulnerability to solar burps will grow in tandem with technological advances. Under this model (described in the paper, which was submitted to arXiv.org), during the next 50 years the potential for economic damage will depend primarily on the rising odds of a strong solar storm over time. Beyond 50 years our vulnerability will increase exponentially with technological progress until the latter levels off.

Some scientists question the model's predictions. "Estimating the economic impact is challenging now, let alone in over a century," says Edward Oughton, a research associate at the University of Cambridge's Center for Risk Studies. Yet he warns that uncertainty should not deter us from practical preparations, such as making power grids more resilient and improving early-warning systems.

Loeb and Lingam envision a much wilder strategy: a $100-billion magnetic deflector shield, positioned between Earth and the sun. This idea seems "pretty preposterous," however, given that solar particles arrive at Earth from all directions, says Daniel Baker, director of the Laboratory for Atmospheric and Space Physics at the University of Colorado Boulder.

A better understanding of "space weather"—the changing conditions in Earth's outer space environment, including solar radiation and particles—could help find the best strategies for confronting a dangerous solar storm, says Stacey Worman, a senior analyst at consulting firm Abt Associates. "This is a challenging but important question," Worman says, "that we need more eyes on." *—Jeremy Hsu*

COURTESY OF NASA, SOLAR DYNAMICS OBSERVATORY, AND AIA, EVE AND HMI SCIENCE TEAMS

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

Marijuana and the Teen Brain

How much should we worry?

By Claudia Wallis

American parents have been warning teenagers about the dangers of marijuana for about 100 years. Teenagers have been ignoring them for just as long. As I write this, a couple of kids are smoking weed in the woods just yards from my office window and about a block and a half from the local high school. They started in around 9 A.M., just in time for class.

Exaggerating the perils of cannabis—the risks of brain damage, addiction, psychosis—has not helped. Any whiff of *Reefer Madness* hyperbole is perfectly calibrated to trigger an adolescent's instinctive skepticism for whatever an adult suggests. And the unvarnished facts are scary enough.

We know that being high impairs attention, memory and learning. Some of today's stronger varieties can make you physically ill and delusional. But whether marijuana can cause lasting damage to the brain is less clear.

A slew of studies in adults have found that nonusers beat chronic weed smokers on tests of attention, memory, motor skills and verbal abilities, but some of this might be the result of lingering traces of cannabis in the body of users or withdrawal effects from abstaining while taking part in a study. In one hopeful finding, a 2012 meta-analysis found that in 13 studies in which participants had laid off weed for 25 days or more, their performance on cognitive tests did not differ significantly from that of nonusers.

But scientists are less sanguine about teenage tokers. During adolescence the brain matures in several ways believed to make it more efficient and to strengthen executive functions such as emotional self-control. Various lines of research suggest that cannabis use could disrupt such processes.

For one thing, recent studies show that cannabinoids manufactured by our own nerve cells play a crucial role in wiring the brain, both prenatally and during adolescence. Throughout life they regulate appetite, sleep, emotion, memory and movement—which makes sense when you consider the effects of marijuana. There are "huge changes" in the concentration of these endocannabinoids during the teenage years, according to neurologist Yasmin Hurd of the Icahn School of Medicine at Mount Sinai, which is why she and others who study this system worry about the impact of casually dosing it with weed.

Brain-imaging studies reinforce this concern. A number of smallish studies have seen differences in the brains of habitual weed smokers, including altered connectivity between the hemispheres, inefficient cognitive processing in adolescent users, and a smaller amygdala and hippocampus—structures involved in emotional regulation and memory, respectively.

More evidence comes from research in animals. Rats given THC, the chemical that puts the high in marijuana, show persistent cognitive difficulties if exposed around the time of puberty—but not if they are exposed as adults.

But the case for permanent damage is not airtight. Studies in rats tend to use much higher doses of THC than even a committed pothead would absorb, and rodent adolescence is just a couple of weeks long—nothing like ours. With brain-imaging studies, the samples are small, and the causality is uncertain. It is particularly hard to untangle factors such as childhood poverty, abuse and neglect, which also make their mark on brain anatomy and which correlate with more substance abuse, notes Nora Volkow, director of the National Institute on Drug Abuse and lead author of a superb 2016 review of cannabis research in *JAMA Psychiatry*.

To really sort this out, we need to look at kids from childhood to early adulthood. The Adolescent Brain Cognitive Development study, now under way at the National Institutes of Health, should fill the gap. The 10-year project will follow 10,000 children from age nine or 10, soaking up information from brain scans, genetic and psychological tests, academic records and surveys. Among other things, it should help pin down the complex role marijuana seems to play in triggering schizophrenia in some people.

But even if it turns out that weed does not pose a direct danger for most teens, it's hardly benign. If, like those kids outside my window, you frequently show up high in class, you will likely miss the intellectual and social stimulation to which the adolescent brain is perfectly tuned. This is the period, Volkow notes, "for maximizing our capacity to navigate complex situations," literally building brainpower. On average, adolescents who partake heavily wind up achieving less in life and are unhappier. And those are things a teenager might care about.

Illustration by Celia Krampien

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

The Digital-Subscription Dilemma

In principle, you could share your password with anyone

By David Pogue

Decades ago a "subscription" generally referred to magazines or newspapers. Once you'd paid, the publisher didn't care how many times you read each article. You were even welcome to share an issue with family and friends. After all, a physical magazine has a built-in piracy limit: the number of people who can crowd around the pages simultaneously.

Digital subscriptions, though, are quite different. Companies care a *lot* about who uses them and how many are doing so at once. And no wonder: A digital subscription is really just a username and password. Without some software restrictions by Netflix, you could, in theory, share your password with everyone you know. And pretty soon Netflix would go out of business.

All right, so unlimited password sharing is unworkable. The question, though, is, What's the right approach to preventing it?

The world is still trying to figure that out.

Netflix introduced streaming movies in 2007. No more waiting for a DVD in the mail! Instead—get this—you paid for your movie watching *by the hour*. You could pay $6 a month to watch six hours of movies, $18 to watch 18 hours, and so on.

Until that moment, humanity had always paid for movies by the movie—in the theater, on DVD or on pay-per-view. Netflix introduced a concept we now take for granted: movie *surfing*. Start a movie; if it doesn't grab you, start a different one. No big whoop.

Eventually Netflix adopted a flat fee for unlimited streaming movies, and the world was changed forever.

I fly a lot, so I pay $60 a month for unlimited Gogo, an in-flight Wi-Fi service. On a recent flight, though, I couldn't sign on. A message told me that there was some account problem. (It wasn't a total loss: I got to reacquaint myself with the wonderful world of in-flight magazines and safety cards.)

My daughter had used my account on a flight *she* had taken a week earlier (with my okay), and it turns out that's a Gogo no-no. "Customers are not allowed to share their Gogo account with anyone," a rep told me—even if they're not using it simultaneously.

Wow. What powers Gogo, anyway—unicorn tears?

The *New York Times*'s policy is similarly stern. "You are not allowed to share your registration login credentials," its terms of service say. Violate that rule, and "we may refer you to appropriate law enforcement agencies."

Contrast those approaches with services such as Netflix, Hulu and Spotify: Your monthly fee allows a specified number of simultaneous streams, such as two or four. The companies don't have to sweat over how many people have your password. All they care is that only two of you are watching or listening *simultaneously*.

The genius of that system is that it leaves enforcement up to us. *We* yell at our kids to get off Netflix when we, the parents, are trying to watch something. The customers do the antipiracy work.

Maybe such services can afford those friendlier guidelines because they have technical ways to enforce them. If you're paying for two simultaneous Netflix watchers, a third one can't tune in. Sites such as that of the *Times,* on the other hand, must rely on the honor system. (Well, the honor system and the threaten system.)

The password-sharing conversation must have been very brief at MoviePass, which is like Netflix for the cineplex. For $10 a month, you can see all the movies you want in theaters. What's to stop you from lending out your "login"? A plastic MoviePass card.

The world has gone subscription mad. Everyone says we're in a new golden age of TV series—but to see them, you'll have to subscribe to Netflix, Hulu, Amazon Prime, HBO Go, CBS All Access, and on and on. Add that to your Spotify or Apple Music subscription, your one for Photoshop or Microsoft Office, your antivirus subscription and the identity-theft plan that we may all need soon.

There's still no single standard for metering all this stuff. Here's to the ongoing experiments—and to the industry finding the right balance between convenience and profit. SA

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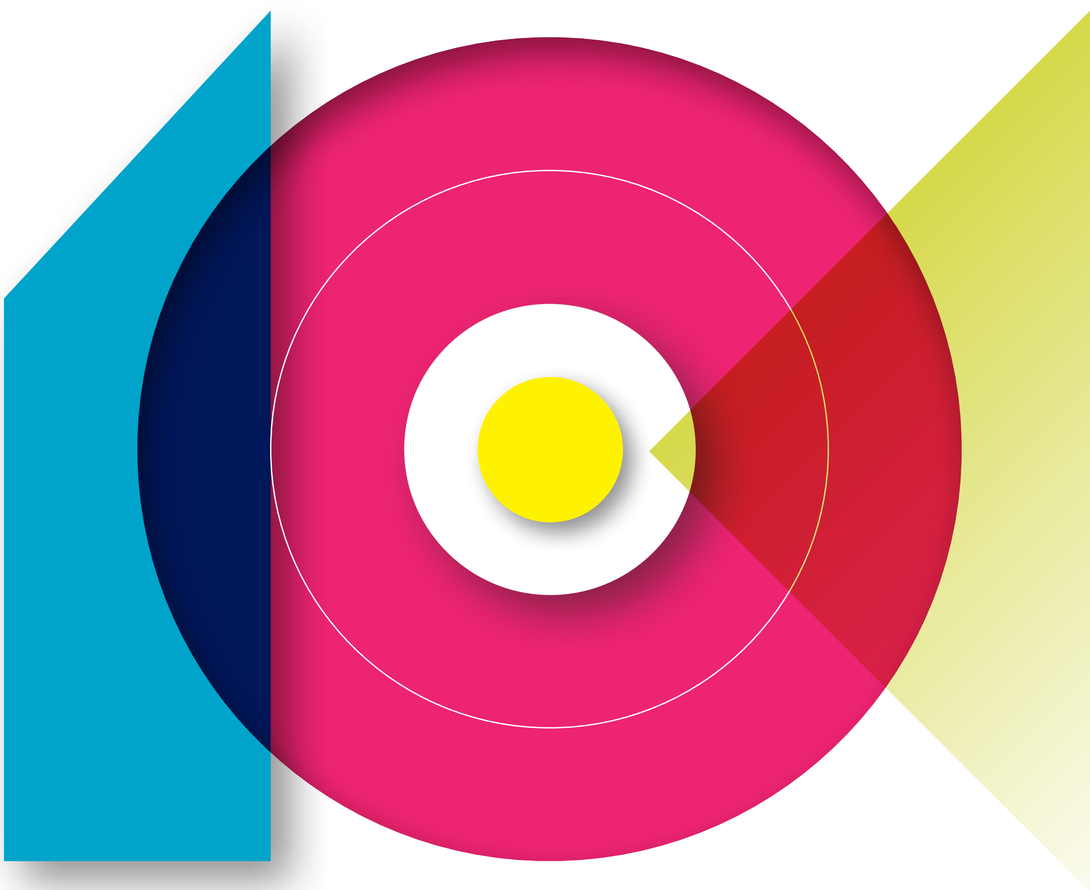
Illustration by Jay Bendt



SPECIAL REPORT

TOP 10 EMERGING TECHNOLOGIES *of* 2017

DISRUPTIVE SOLUTIONS THAT ARE POISED TO CHANGE THE WORLD

Illustrations by Eric Petersen

What if

drinking water could be drawn from desert air easily, without requiring enormous amounts of electricity from a grid? What if a doctor could do a biopsy for a suspected cancer without a blade of any sort? What if we didn't have to wait too long for the result? Technologies that make these visions a reality are expected to become increasingly commonplace in the next few years. This special report, compiled and produced in a collaboration between *Scientific American* and the World Economic Forum's Expert Network, highlights 10 such emerging technologies.

To choose the entrants in this year's emerging technologies report, we convened a steering group of world-renowned technology experts. The committee made recommendations and elicited suggestions from members of the Forum's Expert Network and Global Future Councils, *Scientific American*'s board of advisers and others who are tuned in to burgeoning research and development in academia, business and government. Then the group whittled down the choices by focusing on technologies that were not yet widespread but were attracting increased funding or showing other signs of being ready to move to the next level. The technologies also had to offer significant benefits to societies and economies and to have the power to alter established ways of doing things.

—Mariette DiChristina and Bernard S. Meyerson

IN BRIEF

When it comes to preventing and treating disease, better biopsy techniques, genomic vaccines and a massive global project to map every human cell are a boon to public health and personalized medicine.

Sustainably providing the resource needs of a growing population is becoming more possible thanks to advances in solar-powered water harvesting and artificial photosynthesis that produces renewable fuel. Real-time feedback is making precision farming an efficient way to feed more people.

Green tech is becoming more accessible to the masses. Entire blocks of homes can be transformed into zero-emissions communities. New approaches in hydrogen-fuel cells could mean cheaper gasoline-free cars.

Improvements in visual AI and quantum computing are leading to a future when machines interpret data and solve complex problems better than humans.

1

PUBLIC HEALTH

WATER MADE BY THE SUN

TECHNOLOGIES THAT PULL MOISTURE FROM THE AIR ARE NOW SOLAR-POWERED

By Donna J. Nelson and Jeffrey Carbeck

Billions of people lack access to clean water for all or part of the year or must travel far to collect it. Extracting water directly from the air would be an immeasurable boon for them. But existing technologies generally require a high-moisture climate and a lot of electricity, which is expensive and often unavailable. This problem is now becoming more tractable, thanks to robust systems in development that rely on readily available energy from the sun. They are scalable and work even in arid regions—where a third of the world's population lives, often in poverty.

Collaborators at the Massachusetts Institute of Technology and the University of California, Berkeley, have tested an approach that requires no electricity at all. The team intends for its technology to overcome a notable problem with most materials capable of absorbing water from the atmosphere (such as the zeolites in humidifiers): aside from needing high humidity, they give up the trapped water only when heated substantially, which takes energy.

The researchers designed their system around a class of porous crystals called metal-organic frameworks (MOFs), developed years ago by chemist Omar M. Yaghi, now in the U.C. Berkeley group. By choosing specific combinations of metals and organics, scientists can select the chemical properties of each MOF and thereby customize its uses. Beyond their versatility, MOFs' great promise lies with their phenomenally large pores: the surface area inside is almost 10 times that of porous zeolites. For context, one gram of an MOF crystal the size of a sugar cube has an internal surface area approximately equal to the area of a football field.

In April, Yaghi's group, along with that of M.I.T. mechanical engineer Evelyn Wang, reported on a prototype device incorporating MOF-801, or zirconium fumarate, which has a high affinity for water. It pulls moisture from the air into its large pores and readily

feeds the water into a collector in response to low-grade heat from natural sunlight. The device can harvest 2.8 liters of water daily per every kilogram of MOF even at relative humidity levels as low as 20 percent, similar to those of deserts. (According to Yaghi, a person needs at least a soda can's worth, or 355 milliliters, of drinking water a day.) Plus, it requires no additional input of energy. The investigators see more room for improvement. Further experimentation with MOF composition should make the technology less expensive (zirconium currently costs $150 per kilogram), increase the amount of water collected per unit of material and allow researchers to tailor MOFs to different microclimates.

Taking a different tack, a start-up called Zero Mass Water in Scottsdale, Ariz., has begun selling a solar-based system that does not have to be hooked up to an electric grid or an existing water system. A solar panel provides energy that both drives air through a proprietary water-absorbing material and powers condensation of the extracted moisture into fluid. A small lithium-ion battery operates the device when the sun is not shining. A unit with one solar panel, the company says, can produce two to five liters of liquid a day, which is stored in a 30-liter reservoir that adds calcium and magnesium for health and taste.

Cody Friesen, founder of Zero Mass Water and a materials scientist at Arizona State University, developed the system with the aim of having it work sustainably and easily anywhere in the world. An installed system with one solar panel sells in the U.S. for about $3,700. That price tag includes a required 10 percent donation toward reducing costs for installations in parts of the globe lacking water infrastructure. The same unit that reduces the need for bottled water in the U.S., Friesen notes, can also provide clean water to a school that lacks it so that children "are able to get educated and not get sick."

Over the past year, he says, systems have been placed in the southwestern U.S. and several other countries—among them, Mexico, Jordan and the United Arab Emirates—and the company has recently shipped panels to Lebanon, with funding from the U.S. Agency for International Development, to provide water to Syrian refugees. When most people think about solar, Friesen adds, "they think about electricity. In the future, people will think about water abundance."

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ENERGY

FUEL FROM AN ARTIFICIAL LEAF

TECHNOLOGY THAT MIMICS PHOTOSYNTHESIS CONVERTS CARBON DIOXIDE TO FUELS IN A SUSTAINABLE WAY

By Javier Garcia Martinez

The notion of an artificial leaf makes so much sense. Leaves, of course, harness energy from the sun to turn carbon dioxide into the carbohydrates that power a plant's cellular activities. For decades scientists have been working to devise a process similar to photosynthesis to generate a fuel that could be stored for later use. This could solve a major challenge of solar and wind power—providing a way to stow the energy when the sun is not shining and the air is still.

Many, many investigators have contributed over the years to the development of a form of artificial photosynthesis in which sunlight-activated catalysts split water molecules to yield oxygen and hydrogen—the latter being a valuable chemical for a wide range of sustainable technologies. A step closer to actual photosynthesis would be to employ this hydrogen in a reduction reaction that converts CO_2 into hydrocarbons. Like a real leaf, this system would use only CO_2, water and sunlight to produce fuels. The achievement could be revolutionary, enabling creation of a closed system in which carbon dioxide emitted by combustion was transformed back into fuel instead of adding to the greenhouse gases in the atmosphere.

Several researchers are pursuing this goal. Recently one group has demonstrated that it is possible to combine water splitting and CO_2 conversion into fuels in one system with high efficiency. In a June 2016 issue of *Science,* Daniel G. Nocera and Pamela A. Silver, both at Harvard University, and their colleagues reported on an approach to making liquid fuel (specifically fusel alcohols) that far exceeds a natural leaf's conversion of carbon dioxide to carbohydrates. A plant uses just 1 percent of the energy it receives from the sun to make glucose, whereas the artificial system achieved roughly 10 percent efficiency in converting carbon dioxide to fuel, the equivalent of pulling 180 grams of carbon dioxide from the air per kilowatt-hour of electricity generated.

The investigators paired inorganic, solar water-splitting technology (designed to use only biocompatible materials and to avoid creating toxic compounds) with microbes specially engineered to produce fuel, all in a single container. Remarkably, these metabolically engineered bacteria generated a wide variety of fuels and other chemical products even at low CO_2 concentrations. The approach is ready for scaling up to the extent that the catalysts already contain cheap, readily obtainable metals. But investigators still need to greatly increase fuel production. Nocera says the team is working on prototyping the technology and is in partnership discussions with several companies.

Nocera has an even bigger vision for the basic technology. Beyond producing hydrogen- and carbon-rich fuels in a sustainable way, he has demonstrated that equipping the system with a different metabolically altered bacterium can produce nitrogen-based fertilizer right in the soil, an approach that would increase crop yields in areas where conventional fertilizers are not readily available. The bacterium uses the hydrogen and CO_2 to form a biological plastic that serves as a fuel supply. Once the microbe contains enough plastic, it no longer needs sunshine, so it can be buried in the soil. After drawing nitrogen from the air, it exploits the energy and hydrogen in the plastic to make the fertilizer. Radishes grown in soil containing the microbes ended up weighing 150 percent more than control radishes.

The achievement could enable creation of a closed system in which CO_2 emitted by combustion was transformed back into fuel instead of adding to greenhouse gases.

Nocera admits that he initially ran the fertilizer test just to see if the idea would work. He envisions a time, however, when bacteria will "breathe in hydrogen" produced by water splitting and ultimately use the hydrogen to produce products ranging from fuels to fertilizers, plastics and drugs, depending on the specific metabolic alterations designed for the bugs.

3

COMPUTING

AI THAT SEES LIKE HUMANS

A DEEP-LEARNING TOOL FOR VISUAL TASKS IS CHANGING MEDICINE, SECURITY AND MORE

By Apurv Mishra

For most of the past 30 years computer-vision technologies have struggled to perform well, even in tasks as mundane as accurately recognizing faces in photographs. Recently, though, breakthroughs in deep learning—an emerging field of artificial intelligence—have finally enabled computers to interpret many kinds of images as successfully as, or better than, people do. Companies are already selling products that exploit the technology, which is likely to take over or assist in a wide range of jobs that people now perform, from driving trucks to interpreting scans for diagnosing medical disorders.

Recent progress in a deep-learning approach known as a convolutional neural network (CNN) is key to the latest strides. To give a simple example of its prowess, consider images of animals. Whereas humans can easily distinguish between a cat and a dog, CNNs allow machines to categorize specific breeds more successfully than people can. It excels because it is better able to learn, and draw inferences from, subtle, telling patterns in the images.

CNNs do not need to be programmed to recognize specific features in images—for example, the shape and size of an animal's ears. Instead they are taught to spot features such as these on their own. To train a CNN to separate an English springer spaniel from a Welsh one, for instance, you start with thousands of images of animals, including examples of both breeds. Like most deep-learning networks, CNNs are organized in layers. In the lower layers, they learn simple shapes and edges from the images. In the higher layers, they learn complex and abstract concepts—in this case, the more detailed aspects of ears, tails, tongues, fur textures, and so on. Once trained, a CNN can easily decide whether a new image of an animal shows a breed of interest.

CNNs were made possible by the tremendous progress in graphics processing units and parallel processing in the past decade. But the Internet has made a profound difference as well by feeding CNNs' insatiable appetite for digitized images.

Computer-vision systems powered by deep learning are being developed for a range of applications. The technology is making self-driving cars safer by enhancing the ability to recognize pedestrians. Insurers are starting to apply these tools to assess damage to cars. In the security camera industry, CNNs are making it possible to understanding crowd behavior, which will make public places and airports safer. In agriculture, deep-learning applications can be used to predict crop yields, monitor water levels and help detect crop diseases before they spread.

Deep learning for visual tasks is making some of its broadest inroads in medicine, where it can speed experts' interpretation of scans and pathology slides and provide critical information in places that lack professionals trained to read the images—be it for screening, diagnosis, monitoring of disease progression or response to therapy. This year, for instance, the U.S. Food and Drug Administration approved a deep-learning approach from the start-up Arterys for visualizing blood flow in the heart; the purpose is to help diagnose heart disease. Also this year Sebastian Thrun of Stanford University and his colleagues described a system in *Nature* that classified skin cancer as well as human dermatologists did. The researchers noted that such a program installed on smartphones, which are ubiquitous around the world, could provide "low-cost universal access to vital diagnostic care." Systems are also being developed to assess diabetic retinopathy (a cause of blindness), stroke, bone fractures, Alzheimer's disease and other maladies.

4

ENGINEERING

PRECISION FARMING

SENSORS, IMAGING AND REAL-TIME DATA ANALYTICS IMPROVE FARM OUTPUTS AND REDUCE WASTE

By Geoffrey Ling and Blake Bextine

As the world's population grows, farmers will need to produce more and more food. Yet arable acreage cannot keep pace, and the looming food security threat could easily devolve into regional or even global instability. To adapt, large farms are increasingly exploiting precision farming to increase yields, reduce waste, and mitigate the economic and security risks that inevitably accompany agricultural uncertainty.

Traditional farming relies on managing entire fields—making decisions related to planting, harvesting, irrigating, and applying pesticides and fertilizer—based on regional conditions and historical data. Precision farming, in contrast, combines sensors, robots, GPS, mapping tools and data-analytics software to customize the care that plants receive, all without increasing labor. Stationary or robot-mounted sensors and camera-equipped drones wirelessly send images and data on individual plants—information, say, about stem size, leaf shape and the moisture of the soil around a plant—to a computer, which looks for signs of health and stress. Farmers receive the feedback in real time and then deliver water, pesticide or fertilizer in calibrated doses to only the areas that need it. The technology can also help farmers decide when to plant and harvest crops.

As a result, precision farming can improve time management, reduce water and chemical use, and produce healthier crops and higher yields—all of which benefit farmers' bottom lines and conserve resources while reducing chemical runoff.

Many start-ups are developing new software, sensors, aerial-based data and other tools for precision farming, as are large companies such as Monsanto, John Deere, Dow and DuPont. The U.S. Department of Agriculture, NASA and the National Oceanic and Atmospheric Administration all support precision farming, and many colleges now offer course work on the topic.

In a related development, seed producers are applying technology to improve plant "phenotyping." By following individual plants over time and analyzing which ones flourish in different conditions, companies can correlate the plants' response to their environ-

ments with their genomics. That information, in turn, allows the companies to produce seed varieties that will thrive in specific soil and weather conditions. Advanced phenotyping may also help generate crops with enhanced nutrition.

Growers are not universally embracing precision agriculture for various reasons. The up-front equipment costs—especially the expense of scaling the technology to large row-crop production systems—pose a barrier. Lack of broadband can be an obstacle in some places, although the USDA is trying to ameliorate that problem. Seasoned producers who are less computer-literate may be wary of the technology. And large systems will be beyond the reach of many small farming operations in developing nations. But less expensive, simpler systems could potentially be applied. Salah Sukkarieh of the University of Sydney, for instance, has demonstrated a streamlined, low-cost monitoring system in Indonesia that relies on solar power and cell phones. For others, though, cost savings down the road may offset the financial concerns. And however reticent some veteran farmers may be to adopt new technology, the next generation of tech-savvy farmers are likely to warm to the approach.

The views, opinions and findings contained in this article are those of the authors and should not be interpreted as representing the official views or policies, either expressed or implied, of the Defense Advanced Research Projects Agency or the Department of Defense.

5

MEDICINE AND BIOTECH

MAPPING EVERY CELL

A GLOBAL PROJECT AIMS TO UNDERSTAND HOW ALL HUMAN CELL TYPES FUNCTION

By Sang Yup Lee

To truly, deeply understand how the human body works—and how diseases arise—you would need an extraordinary amount of information. You would have to know the identity of every cell type in every tissue; exactly which genes, proteins and other molecules are active in each type; what processes control that activity; where the cells are located exactly; how the cells normally interact with one another; and what happens to the body's functioning when genetic or other aspects of a cell undergo change, among other details. Building such a rich, complex knowledge base may seem impossible. And yet a broad international consortium of research groups has taken the first steps toward creating exactly that. They call it the Human Cell Atlas.

The consortium had its inaugural planning meeting in October 2016 and continues to organize. The Chan Zuckerberg Initiative is onboard as well. In June 2017 it announced that it was providing financial and engineering support to build an open data-coordination platform to organize the findings, so they will be readily sharable by researchers in the project and beyond.

The atlas, which will combine information from existing and future research projects, has been made feasible by a host of technological achievements. Those include advances in tools for isolating individual cells, for profiling the proteins in a single cell at any given time (proteins are the major workhorses in the body), and for quickly and inexpensively sequencing DNA and RNA. It will integrate research exploring all the "omes": the genome (the full set of genes), the transcriptome (the RNA made from the genes), the proteome (the proteins), the metabolome (small molecules, such as sugars, fatty acids and amino acids, involved or generated by cellular processes), and the fluxome (metabolic reactions whose rates can vary under different conditions). Then these findings will be mapped to different subregions of cells. The integrated results should lead to a tool that will simulate all the types and states of cells in our body and provide new understandings of disease processes and ways to intervene in them.

One of the most advanced pieces underlying the cell atlas is the continually updated Human Protein Atlas. It offers a glimpse of the kind of comprehensive work that goes into building the umbrella project, as well as the value it will ultimately bring.

Participants in the Human Protein Atlas have classified a large majority of the protein-coding genes in humans using a combination of genomics, transcriptomics, proteomics and antibody-based profiling, which identifies location. Since the program's inception in 2003, approximately 100 person-years of software development have gone into keeping track of and organizing the data for systems-level analyses. More than 10 million images have been generated and annotated by pathologists. The atlas includes a high-resolution map of the locations of more than 12,000 proteins in 30 subcellular compartments, or organelles, of various cells.

All the findings are available to the research community without restriction. Users can query the database to explore the proteins in any major organ or tissue, or they can focus on proteins with specific properties, such as those that participate in basic cell maintenance or that occur only in specific tissues. The data can also help model the plethora of dynamic, interacting components that enable life and can be used to explore ideas for new therapies.

Completing the Human Cell Atlas will not be easy, but it will be an immeasurably valuable tool for improving and personalizing health care.

6

MEDICINE AND BIOTECH

LIQUID BIOPSIES

ULTRASENSITIVE BLOOD TESTS PROMISE TO IMPROVE CANCER DIAGNOSIS AND CARE

By Apurv Mishra

A patient suspected of having cancer usually undergoes imaging and a biopsy. Samples of the tumor are excised, examined under a microscope and, often, analyzed to pinpoint the genetic mutations responsible for the malignancy. Together this information helps to determine the type of cancer, how advanced it is and how best to treat it. Yet sometimes biopsies cannot be done, such as when a tumor is hard to reach. Obtaining and analyzing the tissue can also be expensive and slow. And because biopsies are invasive, they may cause infections or other complications.

A tool known as a liquid biopsy—which finds signs of cancer in a simple blood sample—promises to solve those problems and more. A few dozen companies are developing their own technologies. Observers predict that the market for the tests could be worth billions.

The technique typically homes in on circulating-tumor DNA (ctDNA), genetic material that routinely finds its way from cancer cells into the bloodstream. Only recently have advanced technologies made it possible to find, amplify and sequence the DNA rapidly and inexpensively.

Right now the tests, which are available from several companies, mostly aid in treatment decisions for people already diagnosed with a particular form of cancer, such as prostate or lung. But the liquid tests can provide additional services that tissue biopsies cannot. Repeated tests could potentially detect disease progression or resistance to treatment long before it would trigger symptoms or appear on imaging. Tissue biopsies examine only selected bits of tumors and can thus miss cells that have turned more dangerous than their neighbors; in principle, the liquid biopsy can detect the full spectrum of mutations in a mass, indicating when more aggressive treatment is needed. Crucially, liquid biopsies may one day provide a fast, easy screening test for detecting a cancer and determining its type in people who seem perfectly healthy.

In a sign of the growing enthusiasm for the field, GRAIL, a company spun off from Illumina, raised $900 million in funding this past March from investors, including Amazon and several major pharmaceutical companies. GRAIL plans to use the money to further develop the technology and to run the large clinical trials (involving hundreds of thousands of subjects) needed to see if screening will be feasible. Also in March the California-based company Freenome received $65 million for clinical trials, expected to be carried out with multiple research partners, to determine whether the testing improves how cancer patients fare. And this past May Guardant Health announced it had raised $360 million from investors, on top of earlier funding, with the goal of deploying its liquid-biopsy test to one million people over the next five years.

For the tests to enter wide usage, clinical trials must prove that the approach detects cancer accurately and that by aiding in treatment decisions, it improves progression and survival rates.

7

AUTOMOTIVE

HYDROGEN CARS FOR THE MASSES

REDUCING PRECIOUS METALS MAKES FUEL-CELL CATALYSTS AFFORDABLE

By Donna J. Nelson

Battery-powered electric vehicles that give off no carbon dioxide are about to become mainstream. Today they constitute less than 1 percent of all rolling stock on the road globally, but multiple innovations in features such as the battery's cost and lifetime have made prices so competitive that Tesla has more than 400,000 advance orders for its $35,000 Model 3, which is slated to hit the road in the middle of 2018.

Unfortunately, the other great hope for vehicles that exhaust no carbon—those powered by hydrogen-fed fuel cells—remains too pricey for broad sales. (The manufacturer's price tag for the Toyota Mirai is $57,500.) A raft of laboratories and businesses, however, are determined to cut costs by replacing one of the most expensive components in the fuel cells: the catalyst. Many commercial versions contain the precious metal platinum, which aside from being pricey, is too rare to support ubiquitous use in vehicles.

Investigators are pursuing several lines of attack to shrink the platinum content: using it more efficiently, replacing some or all of it with palladium (which performs similarly and is somewhat less expensive), replacing either of those precious metals with inexpensive metals, such as nickel or copper, and forgoing metals altogether. Commercial catalysts tend to consist of thin layers of platinum nanoparticles deposited on a carbon film; researchers are also testing alternative substrates.

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MEDICINE AND BIOTECH

GENOMIC VACCINES

VACCINES COMPOSED OF DNA OR RNA COULD ENABLE RAPID DEVELOPMENT OF PREVENTIVES FOR INFECTIOUS DISEASES

By Geoffrey Ling

Standard vaccines to prevent infectious diseases consist of killed or weakened pathogens or proteins from those microorganisms. They work by teaching the immune system to recognize certain bits of protein—called antigens—on the surface of the pathogen as a foe. The immune system is then prepared to pounce the next time it encounters those foreign antigens. (Many modern vaccines deliver only the antigens, leaving out the pathogens.) Vaccines that treat cancer also rely on proteins, which doctors may deliver to patients to enhance immune responses. These proteins can include the immune system's own guided missiles: antibodies.

In contrast, a new kind of vaccine, which is poised to make major inroads in medicine, consists of genes. Genomic vaccines promise to offer many advantages, including faster manufacture when a virus, such as Zika or Ebola, suddenly becomes more virulent or widespread. They have been decades in the making, but dozens have now entered clinical trials.

Genomic vaccines take the form of DNA or RNA that encodes desired proteins. On injection, the genes enter cells, which then churn out the selected proteins.

Compared with manufacturing proteins in cell cultures or eggs, producing the genetic material should be simpler and less expensive. Further, a single vaccine can include the coding sequences for multiple proteins, and it can be changed readily if a pathogen mutates or properties need to be added. Public health experts, for instance, revise the flu vaccine annually, but sometimes the vaccine they choose does not match the strains that circulate when flu season arrives. In the future, investigators could sequence the genomes of the circulating strains and produce a better-matched vaccine in mere weeks.

Genomics also enables a new twist on a vaccination approach known as passive immune transfer, in which antibodies are delivered instead of antigens. Scientists can now identify people who are resistant to a certain pathogen, isolate the antibodies that provide that protection and design a gene sequence that will induce a person's cells to produce those antibodies.

With such goals in mind, the U.S. government, academic laboratories and companies large and small are pursuing the technology. A range of clinical trials to test safety and immunogenicity are under way, including for avian influenza, Ebola, hepatitis C, HIV, and breast, lung, prostate, pancreatic and other cancers. And at least one trial is looking at efficacy: the National Institutes of Health has begun a multisite clinical trial to see if a DNA vaccine can protect against Zika.

Meanwhile researchers are working to improve the technology—for example, by finding more efficient ways to get the genes into cells and by improving the stability of the vaccines in heat. Oral delivery, which would be valuable where medical personnel are scarce, is not likely to be feasible anytime soon, but nasal administration is being studied as an alternative. Optimism is high that any remaining obstacles such as these can be resolved.

Stanislaus S. Wong of Stony Brook University, who works closely with Radoslav R. Adzic of Brookhaven National Laboratory, is among those leading the charge. He and his colleagues have, for instance, combined relatively small amounts of platinum or palladium with cheaper metals such as iron, nickel or copper, producing many alloyed varieties that are far more active than commercial catalysts. Wong's group has fashioned the metals into ultrathin one-dimensional nanowires (roughly two nanometers in diameter). These nanowires have a high surface-area-to-volume ratio, which enhances the number of active sites for catalytic reactions.

Naturally, platinum-free catalysts would be ideal. Work on them is newer but bustling. In late 2016 Sang Hoon Joo of Ulsan National Institute of Science and Technology (UNIST) in South Korea reported that an iron- and nitrogen-doped carbon nanotube catalyst has activity comparable to commercial catalysts. Also, Liming Dai of Case Western Reserve University and his colleagues have invented a catalyst using no metal at all; it is a nitrogen- and phosphorus-doped carbon foam that is as active as standard catalysts.

Inventing and preparing a material that has excellent catalytic activity is just part of the challenge, Wong notes. Researchers are also working to scale up existing lab production methods to ensure consistency in the activity and durability of the best candidates. In all phases of their efforts, experimentalists are getting help from theorists who apply sophisticated computer models to figure out how all kinds of variables affect performance—from the chemical compositions, sizes and shapes of metal nanoparticles to the architectures of the support structures. Such collaborations, Wong says, should one day make it possible to rationally design superior catalysts for affordable fuel-cell vehicles.

Of course, the goal of a sustainable transport system demands not only zero carbon emissions during driving but also during the production and distribution of the fuel, be it electricity or hydrogen. That larger challenge remains.

9

ENERGY

SUSTAINABLE COMMUNITIES

INSTEAD OF "GREENING" INDIVIDUAL HOUSES, ENTIRE BLOCKS OF HOMES ARE RETROFIT INTO A SINGLE EFFICIENT UNIT

By Daniel M. Kammen

In the past decade the construction and retrofitting of individual homes to reduce energy and water use has grown explosively. Yet applying green construction to multiple buildings at once may be an even better idea. Sharing resources and infrastructure could reduce waste, and retrofitting impoverished or moderate-income neighborhoods could also bring cost savings and modern technology to people who would typically lack such opportunities. Working at the neighborhood level does add complexity to planning, but these neighborhood efforts offer rewards that even green single-family homes cannot offer.

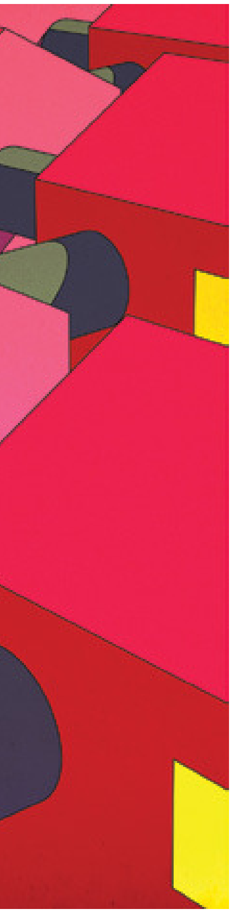
One such example is the Oakland EcoBlock project, which I lead at the University of California, Berkeley, with my colleague Harrison Fraker, a professor of architecture and urban design. It is a multidisciplinary endeavor involving urban designers, engineers, social scientists and policy experts from city, state and federal governments, academia, private industry, nonprofits and grassroots organizations.

The program, which has been planned in great detail but has not yet begun construction, will retrofit 30 to 40 contiguous old homes in a lower- to middle-income neighborhood near California's famous Golden Gate Bridge. It aims to apply existing technology to dramatically reduce fossil-fuel and water consumption and greenhouse gas emissions. We expect to rapidly recoup the money spent on infrastructure with savings from operating expenses while ensuring residents' long-term comfort and security.

To bring in renewable power, we will install solar panels on buildings throughout the area and send the energy to a smart microgrid. Excess solar energy will be stored via flywheels housed in a communal building. The residents will also share electric cars, which will have access to more than two dozen local charging stations. These measures should reduce annual electricity consumption by more than half and bring carbon emissions to zero—a valuable feat, considering that more than a quarter of U.S. greenhouse gas emissions emanate from residences.

The Environmental Protection Agency estimates that as much as 50 percent of California's home water consumption goes to lawns and gardens. We will treat and reuse wastewater from toilets as well as gray water sent down drains and released by washing machines. The recycled fluid will go toward gardening and irrigation. We will collect rainwater and deliver it to toilets and washers and install efficient fixtures and taps. Treated solid wastes, meanwhile, will be incorporated into compost. Our estimates suggest that the EcoBlock's system-level redesign will cut demand for potable water by up to 70 percent.

The Oakland EcoBlock project will provide local construction jobs and help revitalize a community. If it is as successful as we predict, it could serve as a model of sustainability that can be replicated elsewhere in the U.S. and beyond. To date, we have received inquiries from Europe, North Africa and Asia, confirming widespread interest in targeting and redesigning whole communities, not just individual homes.



10

COMPUTING

QUANTUM COMPUTING

NEW ALGORITHMS AND TECHNIQUES OPEN THE DOOR TO INNOVATIVE APPLICATIONS

By Dario Gil

Quantum computing has captured imaginations for almost 50 years. The reason is simple: it offers a path to solving problems that could never be answered with classical machines. Examples include simulating chemistry exactly to develop new molecules and materials, as well as solving complex optimization problems, which seek the best solution from among many possible alternatives. Every industry has a need for optimization, which is one reason this technology has so much disruptive potential.

Quantum computers tackle problems by harnessing the power of quantum mechanics. Rather than considering each possible solution one at a time, as a classical machine would, they behave in ways that cannot be explained with classical analogies. They start out in a quantum superposition of all possible solutions, and then they use entanglement and quantum interference to home in on the correct answer—processes that we do not observe in our everyday lives.

Every industry has a need for optimization, which is one reason this technology has so much disruptive potential.

The promise they offer comes at the cost of them being difficult to build. A popular design requires superconducting materials that must be kept 100 times colder than outer space, exquisite control over delicate quantum states, and proper shielding so not a single stray ray of light reaches the processor. Until recently, access to nascent quantum computers was restricted to specialists in a few facilities around the world. But progress over the past several years has enabled the construction of the world's first prototype systems that can finally test out ideas, algorithms and other techniques that until now were strictly theoretical.

Existing machines are still too small to fully solve problems more complex than supercomputers can handle today. Nevertheless, tremendous progress has been made. Algorithms have been developed that will run faster on a quantum machine. Techniques now exist that prolong coherence (the lifetime of quantum information) in superconducting quantum bits by a factor of more than 100 compared with 10 years ago. We can now measure the most important kinds of quantum errors. And in 2016 IBM provided the public access to the first quantum computer in the cloud—the IBM Q experience—with a graphical interface for programming it and now an interface based on the popular programming language Python. Opening this system has fueled innovations that are vital for this technology to progress, and more than 20 academic papers have been published using this tool. The field is expanding dramatically. Academic research groups and more than 50 start-ups and large corporations worldwide are focused on making quantum computing a reality.

With these technological advancements and a machine at anyone's fingertips, now is the time for getting "quantum ready." People can begin to figure out what they would do if machines existed today that could solve complex problems. Many quantum computing guides are available online to help them get started.

There are still many obstacles. Coherence times must improve; quantum error rates must decrease, and eventually we must mitigate or correct the errors that do occur. Researchers will continue to drive innovations in both the hardware and software. Investigators disagree, however, over which criteria should determine when quantum computing has achieved technological maturity. Some have proposed a standard defined by the ability to perform a scientific measurement so obscure that it is not easily explained to a general audience. I and others disagree, arguing that quantum computing will not have truly emerged as a technology until it can solve problems that have commercial, intellectual and societal importance. The good news is, that day is finally within our sights.

MORE TO EXPLORE

The Top 10 Emerging Technologies of 2016. Scientific American and World Economic Forum, June 23, 2016. www.scientificamerican.com/report/the-top-10-emerging-technologies-of-2016

FROM OUR ARCHIVES

High Hopes for Hydrogen. Joan Ogden; September 2006.
Robot Pills. Paolo Dario and Arianna Menciassi; August 2010.
Reinventing the Leaf. Antonio Regalado; October 2010.
More Food, Less Energy. Michael E. Webber; January 2012.
Quantum Connections. Christopher R. Monroe et al.; May 2016.
Machines Who Learn. Yoshua Bengio; June 2016.

scientificamerican.com/magazine/sa

PLUTO displays a huge variety of surface shades and features in this enhanced color view captured in 2015 by New Horizons.

PLANETARY SCIENCE

NASA'S **NEW HORIZONS** CHANGED EVERYTHING WE THOUGHT WE KNEW ABOUT THIS DISTANT PLANET

PLUTO REVEALED

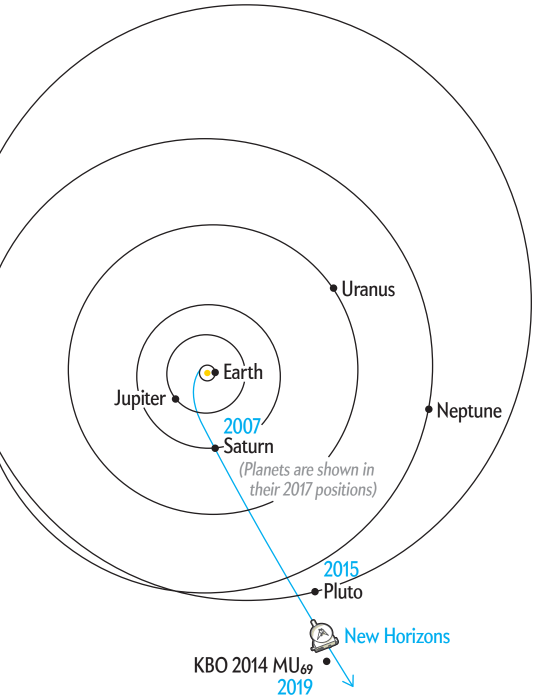
By S. Alan Stern

IN BRIEF

After a long and rocky process to get the mission off the ground, NASA's New Horizons spacecraft launched in 2006 to explore the Pluto system close-up.

During a flyby of the planet in the summer of 2015, the probe discovered that Pluto and its moons are far more complex and dynamic than expected.

Instead of a static and featureless body, Pluto displayed towering mountains, vast glaciers and a surprisingly substantial atmosphere. Even on its moons, New Horizons found stunning features such as a red polar cap and canyons. Scientists are still analyzing the spacecraft's horde of data and expect many more discoveries soon.



S. Alan Stern is a planetary scientist and associate vice president of the space science and engineering division at the Southwest Research Institute. He is principal investigator of the New Horizons mission and a former director of NASA's Science Mission Directorate.

AS THE CLOCK NEARED 9 P.M. ON JULY 14, 2015, I STOOD with then NASA administrator Charles Bolden and others in our mission control at the Johns Hopkins University Applied Physics Laboratory in Maryland. Within about a minute we were due to receive the first signals from the New Horizons spacecraft, some three billion miles away, after its daring, one-shot flyby of Pluto and its system of five moons.

That signal, racing at the speed of light to giant NASA antennas on Earth, would tell us whether or not the flyby had worked. Would it reveal that our mission had gone haywire or succeeded—or would there simply be silence? Anything was possible.

Nearby almost 2,000 invited guests also waited to hear the news. Across the world, so did countless others watching on television and online. It had taken more than 26 years to make this happen—14 years to "sell" the project, four more to build and launch it, and then more than nine years to fly it across the solar system. For myself as the project leader and for our mission and science teams, everything we had worked to achieve rode on what we were about to learn from the incoming signal.

Suddenly, communications arrived. Seconds later huge computer displays in mission control started decoding them into a spacecraft health report. One by one our flight engineers evaluated their data and reported in, every one of them confirming working spacecraft systems. New Horizons had survived its historic flyby and was operating perfectly. Cheers erupted across mission control, hands shot into the air to wave flags and hugs spread across the room. Our nearly three-decade quest to explore the farthest world ever reconnoitered—the Everest of planetary exploration—had succeeded!

By the next morning, New Horizons had already sent its first high-resolution images back to Earth, revealing Pluto as a stunningly complex world. Over the days and months that followed, the spacecraft's data continued to come in, and it kept coming until late 2016. All told, New Horizons made more than 400 separate observations using seven scientific instruments—a haul that produced about 5,000 times as much data as had the first mission to Mars, NASA's Mariner 4.

The scientific bonanza of that data set has revolutionized our knowledge of the Pluto system and upended common thinking about how complex and energetic small planets can be. And the viral public reaction to the mission—including more than two billion page views on our mission Web site, almost 500 newspaper front-page stories during the week of the flyby, along with dozens of magazine features, the Google doodle, and more—also came as a welcome surprise.

In hindsight, it is easy to see how valuable the exploration of Pluto has been—both for research and for the public's appreciation of planetary science. But truth be told, the mission almost never got off the ground.

2001: A SPACE ODYSSEY

NASA FIRST ANNOUNCED solid intentions to fly a mission to Pluto in 1999, when it invited teams around the country to propose instruments to fly on its Pluto Kuiper Express (PKE) mission. I led a team that submitted a main camera and spectrometer instrument suite proposal, but by September 2000 PKE's estimated cost had grown so high that before NASA could even select instruments to fly on it, the agency canceled the mission.

The planetary science community immediately swung into action, decrying the cancellation and asking NASA to reverse itself. The public also protested, inundating NASA with phone calls and more than 10,000 letters of protest. And one teenager even drove cross-country to appeal to NASA in person to resurrect the exploration of the ninth planet. (Despite common misconceptions, I, along with most other planetary scientists I know, refer to Pluto as a planet and do not use the International Astronomical Union planet definition, which excludes Pluto, in speech or research papers.) Finally, in December 2000, NASA announced that it would conduct a competition for new Pluto flyby mission concepts. Proposals would still have to meet the objectives set out for the PKE mission and must have a plan to reach Pluto by 2020, but they had to come in under roughly half of PKE's cost. Ultimately NASA received five phone-book-thick proposals from various teams, each offering detailed plans for such a mission. I led one of those teams. We called our mission New Horizons because we were proposing what would be NASA's first exploration of a new planet since the Voyager missions of the 1970s.

Our team, based at the Southwest Research Institute where I work and the Johns Hopkins University Applied Physics Lab where our spacecraft would be built and controlled, had much less experience with planetary missions than our main competitors, but we made up for that with ingenuity. To control costs, we suggested sending one, not two, spacecraft on the journey—something so risky it was almost unparalleled in first-time planetary exploration. We also proposed hibernating the spacecraft during the almost 10-year trip to Pluto to reduce staffing costs and concentrating on scientific capabilities at the expense of the ability to return data quickly after the flyby. We doggedly perfected our proposal and put it through countless reviews to ensure it was flawless in every respect—from technical implementation to science team composition to management plans, education and public outreach, cost controls and even contingency plans. In late November 2001 NASA announced that it had selected New Horizons over all our competitors. We had won! But little did we know what we were in for next.

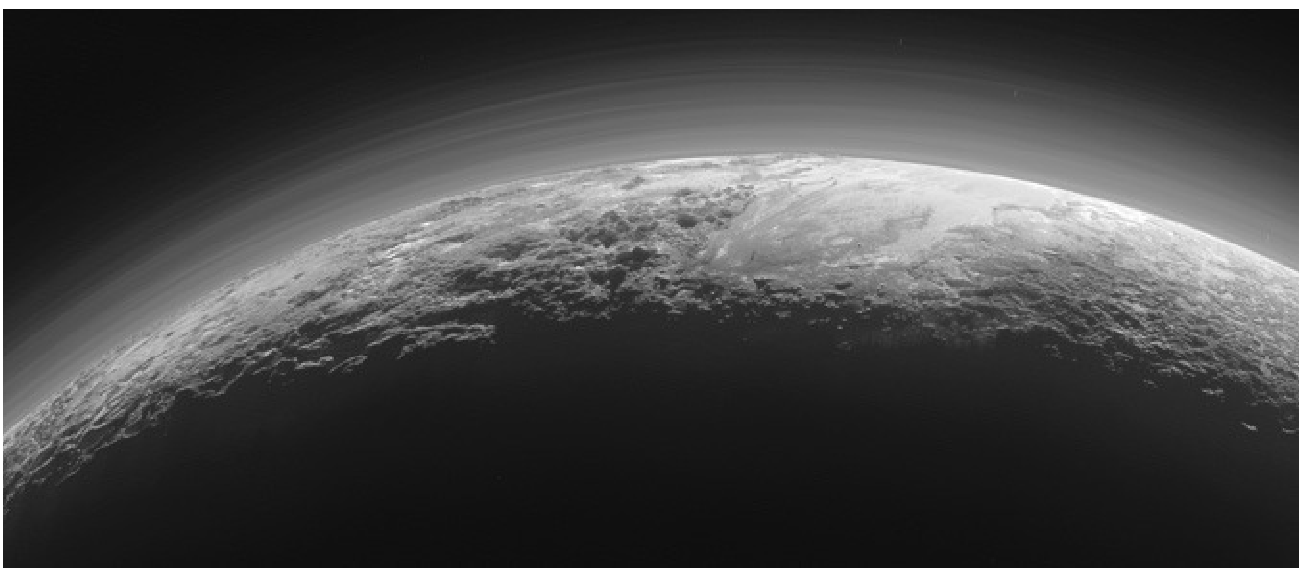
To be ready to make our scheduled launch window in January 2006, we would have to design, build and test our spacecraft in just four years and two months—a process that had taken past NASA missions such as Voyager, Galileo and Cassini eight to 12 years to do. We would also have only 20 percent of Voyager's budget. But just as we were preparing to grapple with those challenges, less than three months after our selection, the Bush administration proposed canceling New Horizons altogether by writing it out of the federal budget released in early 2002. This move launched a protracted funding battle between Congress and the White House that was resolved only when the National Academy of Sciences rated Pluto exploration as a top "Decadal Survey" priority in summer of 2002, convincing enough lawmakers that the mission was worthy. Then, just as we thought we might be out of the woods, two multimonth shutdowns of Los Alamos National Laboratory jeopardized our ability to acquire enough plutonium to fuel our spacecraft's nuclear power generator.

Many people in NASA and the scientific community did not think the New Horizons team could survive so many setbacks. But we literally worked nights and weekends, 52 weeks a year, for four years, to overcome these hurdles. As a result, we made it to the launchpad on time, ready to fly to Pluto.

PLANNING A LONG-DISTANCE HOLE IN ONE

NEW HORIZONS WAS OUTFITTED with everything it would need to learn as much as it could during its brief flyby of the Pluto system. The business end of New Horizons is its seven-instrument payload. Included are black-and-white and color cameras, two spectrometers (which separate light into its various wavelengths to map the atmospheric and surface composition), and a detector to study the dust that impacts the spacecraft. Also onboard are two space plasma sensors used to measure how fast Pluto's atmosphere escapes and the composition of those escaping gases, as well as a radio science package capable of measuring surface temperatures and profiling atmospheric temperature and pressure with altitude.

This instrument payload brought more scientific firepower to bear on a first flyby of a new planet than ever before, primarily because we were using 2000s-era technology, compared with earlier first-flyby missions built in the 1960s and 1970s, such as the twin Voyager spacecraft. For example, whereas the Voyager 1 surface composition mapping spectrometer had just one pixel, the composition mapper on New Horizons has 64,000 pixels. These advances in capability, combined with a spacecraft memory that can store more than 100 times as much data as Voyager's tape recorders, meant that New Horizons could be much more effective than previous first-flyby missions.

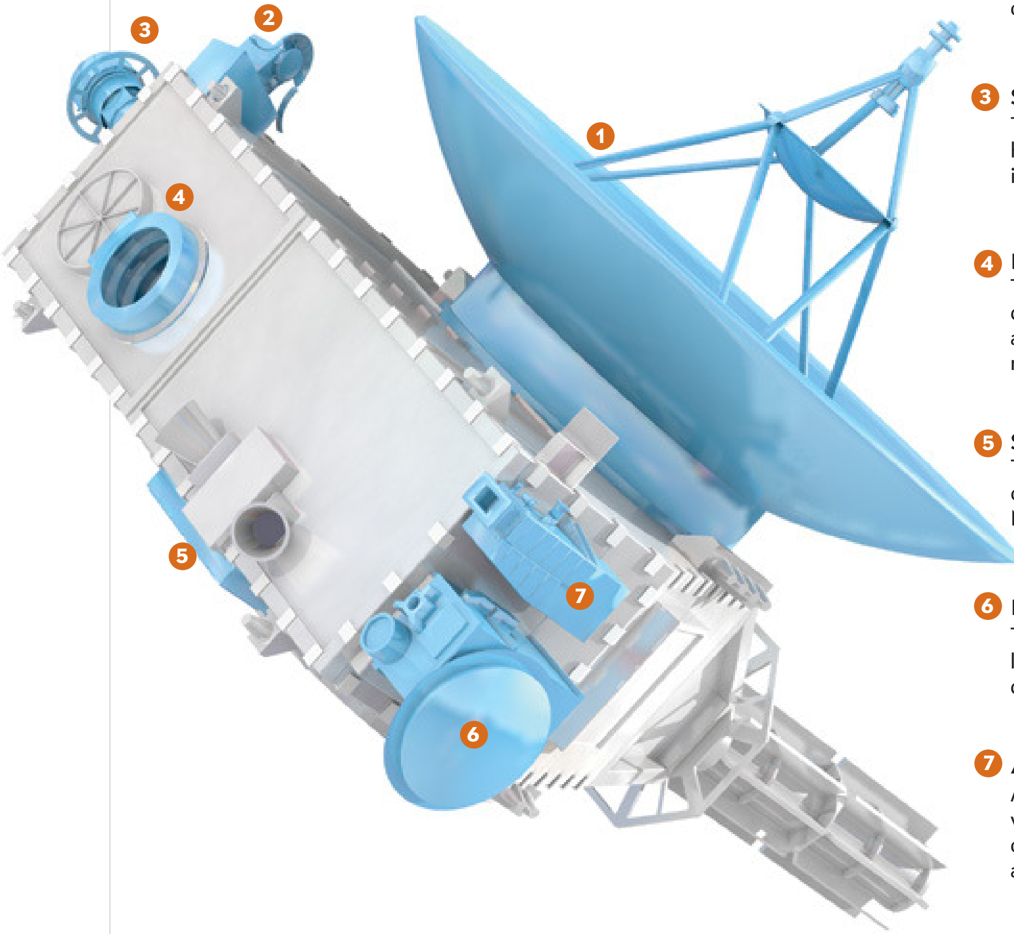


COURTESY OF NASA, JOHNS HOPKINS UNIVERSITY APPLIED PHYSICS LAB AND SOUTHWEST RESEARCH INSTITUTE

ATMOSPHERIC HAZE is suspended above Pluto in this view from New Horizons. Mountains rising 15,000 feet are visible on the left, and glaciers cut the terrain on the right. At the top is the smooth expanse of the icy nitrogen plain called Sputnik Planitia.

Eyes on the Horizon

New Horizons carried seven scientific instruments to collect as much information as it could about Pluto and its five moons during its brief flyby of the system. The suite of instruments allowed it to take color and black-and-white photographs, spectroscopic measurements and temperature readings, as well as detect the dust and space plasma the spacecraft encountered.



1 REX
The Radio Science Experiment uses the spacecraft's radio communications equipment to measure the temperature and pressure of Pluto's atmosphere.

2 PEPSSI
The Pluto Energetic Particle Spectrometer Science Investigation analyzes the density and composition of ions of plasma from Pluto's atmosphere.

3 SWAP
The Solar Wind Around Pluto instrument measures how fast Pluto's atmosphere is escaping and observes its interactions with the solar wind.

4 LORRI
The Long Range Reconnaissance Imager is a telescopic camera that can take high-resolution photographs at a distance. The data it collected helped scientists map Pluto and study the planet's geology.

5 SDC
The Student Dust Counter, an instrument built and operated by students, analyzes the space dust that hits New Horizons as it voyages across the solar system.

6 RALPH
This camera and spectrometer measures the wavelengths of incoming visible and infrared light to make color, composition and thermal maps of Pluto's surface.

7 ALICE
Alice makes spectroscopic measurements of ultraviolet light to enable astronomers to study the makeup of Pluto's atmosphere and search for atmospheres around Charon and Kuiper Belt Objects.

Although our spacecraft was "asleep" for much of its flight out to Pluto, planning for the flyby occupied our team for most of the journey. To accomplish its flyby objectives, New Horizons would need to arrive within a precise nine-minute window in time after its 9.5-year flight from Earth. It would also need to fly through a window in space that measured only around 35 by 60 miles. That might sound like a big target, but aiming to hit that window from three billion miles away at launch was the equivalent of hitting a golf ball from Los Angeles to New York City and landing a hole in one.

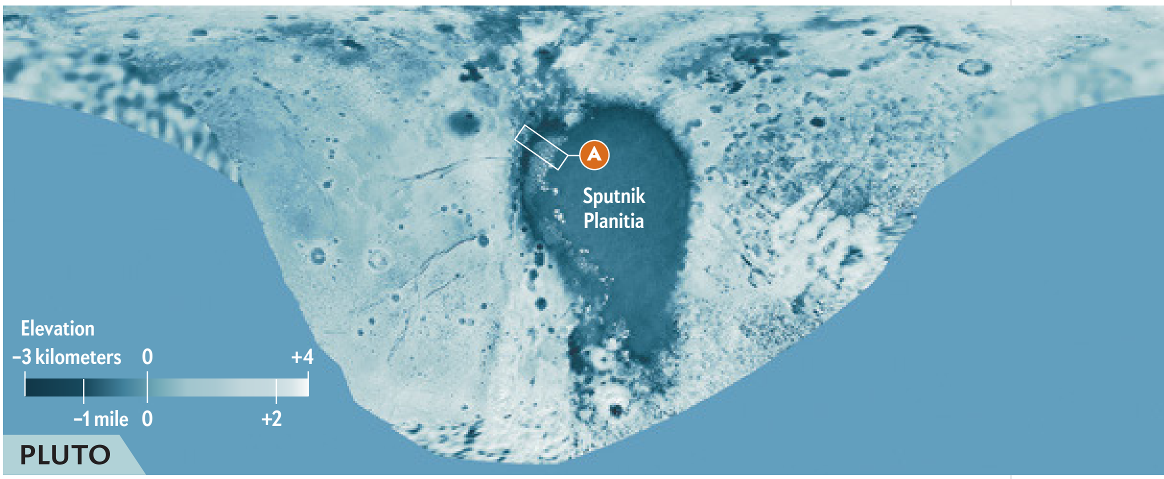
We also had to design, test and program every activity that we wanted New Horizons to carry out for the entire six-month-long flyby, which would run from mid-January through mid-July 2015. Those activities included more than 400 observations studying Pluto and all five of its moons by each of our seven scientific instruments; searches on approach for hazards and debris that could have harmed New Horizons; searches for new moons and rings; observations to triangulate on Pluto's position to help us home in on it; firings of our engines to ensure precise targeting of the flyby; and transmission of all the data recorded during the approach. We also had to plan not just one but three Pluto flybys, each along a separate trajectory, in case we found hazardous debris and needed to divert the spacecraft. Finally, we needed to write onboard intelligent software to handle more than 150 possible faults with the spacecraft or its instruments, and we had to create mission-control procedures for dozens of potential malfunctions too complex for the probe's software to deal with.

A NEW PLANET

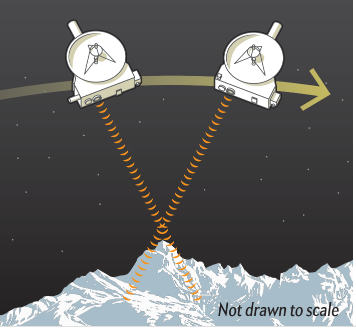
BECAUSE OF ITS SMALL SIZE and distant orbit, Pluto was largely unknown to scientists before the New Horizons flyby. Even the Hubble Space Telescope could barely resolve its disk. About all

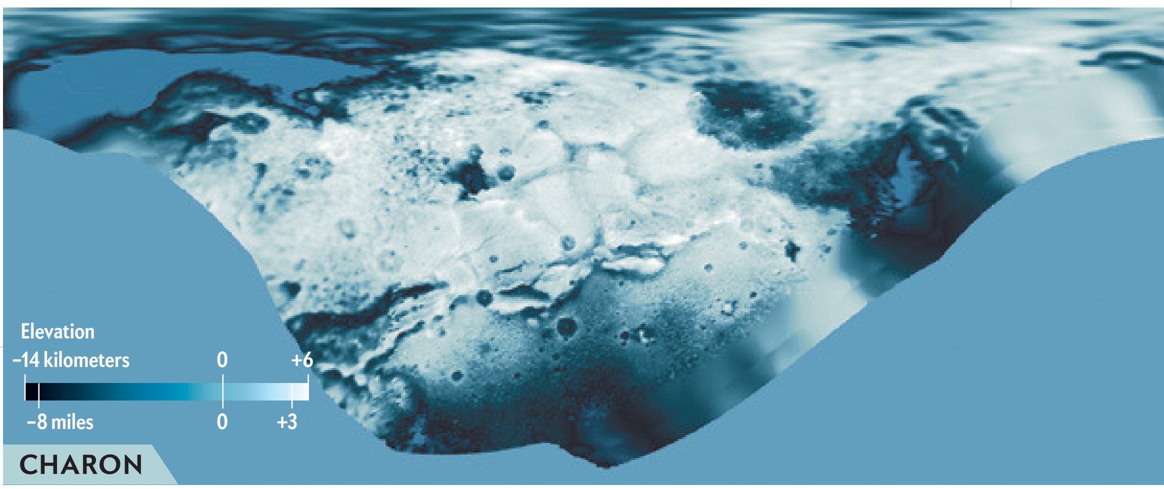
UNKNOWN TERRITORY

These global topographic maps of Pluto and Charon, made from New Horizons stereoscopic data, show the range of terrain on these worlds. Darker areas, such as Pluto's central Sputnik Planitia ice plain, represent lower elevations, and lighter regions are raised features such as mountains. Missing terrain in the bottom corners was either covered in darkness during New Horizons' flyby or was not resolved stereoscopically. The top photograph shows a 50-mile-wide strip on Pluto that displays rocky "badlands" (*on left*), rugged mountains (*center*) and the edge of the Sputnik Planitia glacier.



New Horizons was able to observe terrain from two different angles, much as our eyes do, to measure the "parallax" of the tops of mountains and other elevated features, or how much they appeared to move compared with lower terrain, to estimate their heights.





COURTESY OF NASA, JOHNS HOPKINS UNIVERSITY APPLIED PHYSICS LAB AND SOUTHWEST RESEARCH INSTITUTE (*Pluto terrain*); NASA, JOHNS HOPKINS UNIVERSITY APPLIED PHYSICS LAB, SOUTHWEST RESEARCH INSTITUTE, AND LUNAR AND PLANETARY INSTITUTE (*elevation data*)

that was clear was that it was roughly 1,400 miles in diameter, had at least five moons, a tenuous atmosphere, a reddish surface that contains ices of methane, nitrogen and carbon monoxide, and evidence of a polar ice cap and other large-scale surface markings. Those facts hinted it was likely to be more interesting and complicated than most of the frozen worlds in our outer solar system. But New Horizons revealed a planet that was far more complex, geologically diverse and active than most scientists anticipated.

Among our discoveries, we found that Pluto's atmosphere reaches hundreds of miles in altitude and has dozens of concentric haze layers but few, if any, clouds. New Horizons measured the atmospheric pressure at Pluto's surface for the first time, finding it is just 11 microbars—about the same pressure as at the top of Earth's mesosphere, some 50 miles overhead at the edge of space. We also found that Pluto's atmosphere is escaping 500 to 1,000 times less rapidly than expected, much more akin to the escape rates on Mars and Earth than the cometlike escape rates that preflyby models had predicted. And surprisingly, we found that Pluto's hazes tint its atmosphere blue, giving its skies a color distinctly reminiscent of Earth's.

New Horizons also revealed that Pluto is larger than most

Illustration by Bryan Christie Design

preflyby estimates had indicated, with a true diameter of 1,476 miles. This measurement definitively established Pluto as the largest of the small planets in the Kuiper Belt. Its larger size, when combined with Pluto's already known mass, lowered its density, meaning that while it is still a primarily rocky world with an icy exterior, the rock fraction is closer to 66 percent than the 70-plus percent we expected before the flyby. Of Pluto's remaining (nonrocky) mass, most is water ice, with just traces of more exotic ices on its surface. Models of Pluto's interior based on flyby measurements of its size, mass and shape now provide strong circumstantial evidence that Pluto hides a liquid-water ocean layer hundreds of miles down, where temperatures and pressures reach the water melting point.

For many years planetary scientists had debated whether Pluto's surface would contain steep topography. The answer depended on how deep its top layer of nitrogen ice was. This ice, which makes up most of Pluto's surface, is weak and slumps under its own weight, even in Pluto's reduced gravity, so a thick layer of it would prevent tall geologic features from forming. When New Horizons arrived at Pluto, though, some of its very first high-resolution images revealed mountains towering as high as 15,000 feet, suggesting that Pluto's surface nitrogen might be just a thin veneer over what we later identified as a water-ice crust.

New Horizons also revealed a stunning diversity of other geology on Pluto. We saw vast glaciers, fault systems running for hundreds of miles, chaotic and mountainous terrain caused by the breakup of gargantuan ice blocks, retreating methane scarps, methane snow caps on some mountain ranges, and thousands of one- to six-mile-wide pits presumably created by sublimating nitrogen ice across Pluto's equatorial plains.

Pluto's largest glacier, a nitrogen-ice feature named Sputnik Planitia (in honor of Sputnik, the first space mission), covers an area of more than 308,000 square miles—larger than the states of Texas and Oklahoma combined. No feature like it is known anywhere else in the solar system. Moreover, Sputnik Planitia is apparently geologically alive, as revealed by ice flows within it, as well as patterns across it that indicate that a heat source lies below. We also saw clear signs that its ices are being replenished by glaciers or avalanches from the surrounding mountain ranges that tower above it.

But Pluto's geologic surprises do not stop there. By counting its craters, we can estimate how long ago its terrain formed (the younger the surface, the less time there would have been for craters to build up). After doing this, we found a wide range of surface ages across the planet—from ancient, heavily battered ground more than four billion years old to middle-aged areas 100 million to a billion years old, to Sputnik itself, which has no identifiable craters and must be less—perhaps much less—than 30 million years old. This range of ages was unexpected because scientists widely predicted that Pluto's relatively small size would have caused it to cool early in its history and thus lose its ability to form new ground cover. As it turns out, that conventional wisdom was wrong. Pluto is still geologically alive today, although the sources of energy that power all this change are not yet clear.

Yet there was still more. Geologists on our team found methane-ice towers that climb more than 1,000 feet into Pluto's sky and stretch in an organized system over hundreds of miles. And if all that was not enough for one world, we also observed what appear to be large ice volcanoes only 100 million to 300 million years old, suggesting they operated in Pluto's recent past. Some on our team, myself included, see evidence for networks of drainage channels and a frozen lake that may indicate past epochs when Pluto's atmospheric pressure was much higher—higher even than Mars's today—allowing liquids to flow and even pool on the surface.

Simply put, Pluto's stunning range of atmospheric and surface features left the scientific community floored, suggesting that small planets can rival Earth and Mars in their complexity.

EXPLORING PLUTO'S SATELLITES

LIKE PLUTO ITSELF, Pluto's five satellites were largely unknown before New Horizons explored them. Charon, by far the largest of these worlds (at almost precisely half Pluto's diameter), was discovered by planetary astronomers Jim Christy and Robert Harrington using ground-based telescopes in 1978. Before New Horizons, it was known to be covered in inert water ice, to have little if any atmosphere, and to be much less colorful and reflective than Pluto. The four smaller moons—Styx, Nix, Kerberos and Hydra—were each discovered by members of the New Horizons team using the Hubble Space Telescope between 2005 and 2012. Scientists knew little about them before the Pluto flyby except their orbital properties, and they knew their colors were relatively neutral like Charon's. Even their sizes were only crudely estimated. None had ever been resolved by any telescope—they were simply points of light orbiting Pluto.

New Horizons allowed us to create detailed geologic, color, composition and topographic relief maps of Charon, to search much more sensitively for an atmosphere there, to measure its ultraviolet reflectivity, and to precisely determine its size and shape. The spacecraft was not able to fly as close to any of the four small satellites as it did to Charon, so what we could learn about them was necessarily less. But even so, New Horizons revealed their sizes, rotation periods and shapes and produced crude black-and-white maps of each. In the case of Nix and Hydra, New Horizons generated color maps, composition measurements and surface age estimates as well.

As a result of these discoveries, we now have a basic picture of Charon that rivals knowledge about the large icy satellites of the giant planets gathered by NASA's Voyager, Galileo and Cassini missions. Charon has no atmosphere at all and no surface volatiles, although we did find exotic ammonia- or ammonium-ice outcrops there. Based on crater counts, its surface looks to be more than four billion years old, with little variation in age, meaning that its geologic engine ran only briefly before exhausting itself. In that short time, however, Charon created vast, ice-flooded plains in its southern hemisphere, a vast belt of canyons up to five times deeper than the Grand Canyon, mountains and a red northern "polar cap" that is unlike any feature elsewhere in the solar system. That red pole seems to be made of methane and nitrogen that escaped from Pluto's atmosphere over time and was then redeposited at Charon's cold poles, where ultraviolet radiation chemically transformed these species into red hydrocarbon by-products. Charon's canyon belt appears to be the result of titanic stresses created by the freezing and expansion of water in Charon's interior as it cooled after the moon formed.

We found that Pluto's four small satellites are all about as reflective as Pluto, which is roughly twice as reflective as Charon; it is a mystery why they are so reflective when their surfaces seem to be made of the same material as Charon. None is large enough to retain an atmosphere. And although they each have some craters, which most likely created temporary rings around Pluto when material from the craters was ejected as they formed, we found that no such rings are present around Pluto today.

The orbits of Nix and Hydra suggest that they formed as a result of the same massive impact on Pluto that created Charon. Our maps of these moons have sufficient resolution to spot a variety of craters. Age dating of those craters reveals that their surfaces are about four billion years old—the same as Charon's. This finding proves that the impact that formed them occurred very early in the history of the solar system and cannot be the present-day energy source powering Pluto's current geologic activity. We also learned that the rotation periods of all four of Pluto's small moons are fast compared with their orbital periods—a surprising result that shows none of them has settled into the kind of tidal equilibrium of spin and orbit that is so common among the satellites of giant planets. Something, probably gravitational tugs from the binary system of Pluto and Charon orbiting each other, is affecting their rotation.

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2

CHARON, Pluto's largest moon, has deep canyons and vast ice plains (*1*). Crowds cheer New Horizons' flyby at the Johns Hopkins University Applied Physics Lab in 2015 (*2*).

COURTESY OF NASA, JOHNS HOPKINS UNIVERSITY APPLIED PHYSICS LAB AND SOUTHWEST RESEARCH INSTITUTE (1); COURTESY OF BILL INGALLS NASA (2)

Although New Horizons has now transmitted all the data from its flyby of the Pluto system to Earth, we have still barely examined many aspects of its measurements. I expect many more scientific discoveries about Pluto's surface, interior, origin and atmosphere, as well as about its moons, as our science team and others begin the multiyear process of digesting this incredible data set.

NEXT: THE KUIPER BELT

NEW HORIZONS' EXPLORATION of the Pluto system is complete, but the spacecraft's mission continues. In 2016 NASA approved a five-year extension, running through mid-2021, in which the spacecraft will further explore the Kuiper Belt—the extended ring of small bodies and small planets that orbits the sun far beyond Neptune. The highlight of this exploration will be a close flyby of the small Kuiper Belt Object (KBO) 2014 MU_{69} on January 1, 2019. This ancient, reddish rock, preserved in a cosmic deep freeze far from the sun for more than four billion years, will be the most pristine leftover from the formation of the solar system ever to be explored. It is only about 19 miles across, yet it could have its own moons, and it is believed to be typical of the building blocks from which Pluto and other small bodies in the Kuiper Belt were formed.

New Horizons will encounter MU_{69} when its distance from the sun is about 44 times that of Earth. The spacecraft will use its full battery of instruments to study the object's composition and geology during the flyby. It will look for evidence of activity and an atmosphere, search for moons and rings, and take its temperature.

In addition to the close flyby of MU_{69}, New Horizons will study at least two dozen more KBOs between 2016 and 2021 from close range. These observations will allow us to place our MU_{69} results in context and search for satellites of these objects, study their surface properties and determine their shapes. New Horizons will also measure the properties of the space environment at the far reaches of the Kuiper Belt—studying the helium gas, solar wind and charged particles in this distant region of the sun's sphere of influence. We will also trace the density of dust in the Kuiper Belt out to a distance of 50 times the Earth-sun separation, just beyond the most extreme reaches of Pluto's elliptical orbit.

After 2021, we are optimistic that NASA will choose to extend New Horizons' mission even further. The spacecraft is healthy and has the fuel and power to continue operating and communicating with Earth into the mid-2030s or longer. During that period New Horizons can study many more KBOs and may even be able to make another close flyby of one.

FUTURE HORIZONS

AFTER A ROCKY DEVELOPMENT PERIOD and a long flight across the solar system, New Horizons completed the reconnaissance of the last of the planets known at the dawn of the space age and became the first mission to explore small bodies in the Kuiper Belt.

For 15 years as we planned and flew the mission, I challenged our science team to use all of the perspective and knowledge gained in the exploration of the other planets to predict what we would find at Pluto. As it turns out, nature surprised us, revealing a much more diverse and active planet than even we expected.

In fact, Pluto is so complex and so dynamic that many of us on New Horizons, and many more in the scientific community, would like to see another mission be sent to further explore it and its moons from orbit. We would also like to see more flyby reconnaissance missions such as New Horizons explore more of the bodies in the Kuiper Belt to study their diversity, just as spacecraft have done for the inner planets and the giant planets. We hope that the mission's stunning success is not the end but rather the beginning of exploring the planets and smaller bodies of the Kuiper Belt. SA

MORE TO EXPLORE

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GENETICS

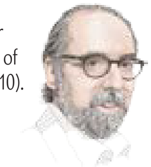
COULD GENETIC ENGINEERING SAVE THE GALÁPAGOS?

In the Galápagos, invasive species are driving native animals to extinction. Some conservationists are asking whether genetic manipulation is the solution

By Stephen S. Hall

MARINE IGUANAS of the Galápagos are vulnerable to feral cats and other invasive predators.

Stephen S. Hall is an award-winning science writer and regular contributor. He is author, most recently, of *Wisdom: From Philosophy to Neuroscience* (Knopf, 2010).



ON SEPTEMBER 25, 1835, DURING THE HMS *BEAGLE*'S SOJOURN TO THE GALÁPAGOS archipelago, Charles Darwin first set foot on what was then known as Charles Island. He found a colony of 200 to 300 inhabitants, nearly all political exiles sent there by Ecuador, aka the "Republic of the Equator," after a failed coup attempt. The lowlands did not much impress Darwin, with their "leafless thickets," but after trudging four miles inland and upward to a small, impoverished settlement in the highlands, he found "a green and thriving vegetation," cultivated with bananas and sweet potatoes, along with a group of islanders who, "although complaining of poverty, obtain, without much trouble, the means of subsistence." That was mainly because of the tens of thousands of giant tortoises that once prowled these islands. "In the woods," Darwin noted, almost as an afterthought, "there are many wild pigs and goats."

On the morning of August 25, 2017, Karl Campbell bounded off a twin-engine motorboat and onto the dock of that same humble island. Now known as Floreana, the island has 144 residents, half as many as in Darwin's time, and Campbell seemed to know them all. Dressed down in a baseball cap, blue jeans and gray T-shirt that read "Island Conservation," he ambled up to Claudio Cruz, at the wheel of a local bus (a converted truck with benches in the back), and exchanged some banter. He waved hello to Juanita and Joselito, who manned the Ecuadorian government's biosecurity checkpoint on the dock. He shouted out another "*Hola*" to the postmaster, popped his head into the community center to greet Myra and Holger, a farmer, and paused to catch up with Carmen, the woman who monitors the public bathrooms near the landing. His path up Floreana's one paved road was interrupted by salutations, chitchat, short jokes and the one-cheek kisses that are the custom in Ecuador.

Campbell, a 42-year-old Australian who has lived in the Galápagos Islands for 20 years, is a gregarious and outgoing fellow, with a tendency to begin conversations with "All good, mate?" But the cheery demeanor and bonhomie he displayed that morning is an essential part of a massive scientific undertaking. Campbell has a Ph.D. in vertebrate pest management from the University of Queensland in Australia, and in 2006 he began working as an animal removal specialist for Island Conservation, an organization based in Santa Cruz, Calif., that is devoted to preserving biodiversity and preventing extinctions by removing invasive species from islands throughout the world. Campbell has been working on eradications in the Galápagos since 1997, including a 2006 campaign to remove all the feral goats and donkeys from Floreana. A decade later he's a project manager with Island Conservation, and the most ambitious project on its agenda is once again on Floreana: to eradicate every single rat and mouse on the island.

There are hundreds of thousands of islands in the world. "You can't work on all of them," Campbell says. Conservationists, according to Campbell, "are currently able to do 10 to 20 islands a year to rid them of mice. So which are the ones you should be working on most urgently? We basically draw up a list of places where we should be working to prevent extinctions." Topping that list, he says, is Floreana.

"Floreana has one of the highest endemicity rates in the Galápagos, the highest rate of extinctions due to the invasive species here and the highest rate—by far—of critically endangered species, which makes it one of the highest-priority targets not just in the Galápagos but in the world," Campbell says, in a spiel that has the polish and urgency of countless recitations to funders, journalists and probably every one of Floreana's residents.

Floreana is at the limit of feasible projects using current eradication tools. The island is large (17,253 hectares, or about 46,600 acres), and it is inhabited, which complicates the task enormously. It means having to explain the logistics and consequences of the entire project—not least of which is a plan to dump 400 tons of rodent poison all over the island. That is why,

IN BRIEF

Invasive species have been a problem in the Galápagos Islands since mariners first arrived there. Hundreds of introduced species of plants, insects, reptiles, birds and mammals live in the archipelago, displacing and in some cases preying on native species.

Eradicating invasive species can be a brutal job. On the island of Floreana, a plan to eliminate the rodents that raid the nests of native birds and reptiles calls for 400 tons of rat poison, requiring weeks of dislocation for pets, livestock and perhaps children.

Genetic manipulation—for example, tweaking sex inheritance in rodents to produce an all-male, and thus reproductively doomed, population—is being discussed as a safer alternative to poison and bullets. But what are the risks? And would it even work?

PRECEDING PAGES: TUI DE ROY

BROWN RATS (*1*) are a primary target of a massive invasive-species eradication effort planned for the island of Floreana, where donkeys (*2*), cattle (*3*) and many other nonnative species have been introduced over the centuries. On neighboring Isabela Island, feral goats denuded the landscape of a giant Galápagos tortoise stronghold (*4*).

KRYSTYNA SZULECKA *Alamy* (1 and 3); WOLFGANG KAEHLER *Getty Images* (2); TUI DE ROY (4)

since 2012, Campbell and his colleagues, such as Carolina Torres and Gloria Salvador, have been visiting Floreana almost once a month, enduring the bumpy two-hour boat ride from the main island of Santa Cruz to meet with residents, describe their proposed project, and figure out the massively complicated steps needed to protect adults, children, livestock, water and endangered species from the effects of the poison.

Such eradications require almost military-scale logistics and precision, which is why Campbell has been desperately seeking an alternative to the blunt-force tools of current techniques. One of the most appealing, to his mind, is a controversial new form of genetic manipulation known as gene drive. Compared with the frustrations he endures every day on the Floreana project, he likens the technology to a magic wand out of *Harry Potter*.

The basic strategy of using gene drive in the conservation setting would be to tinker with the DNA of mice, using either the new gene-editing tool CRISPR or other tools of genetic manipulation, in such a way as to tilt the odds of sex inheritance; one example would be to produce offspring that would be exclusively male, eventually producing a daughterless population of mice. The elimination of females, of course, would create a reproductive dead end for that invasive species. Gene drive is far from a practical technology at this point, but Island Conservation has been working with molecular biologists in the U.S. and Australia to create these genetically modified mice, and Campbell has made no secret of his enthusiasm for the approach at recent scientific meetings.

And that, in turn, may be why the National Academies of Sciences, Engineering, and Medicine, in a 2016 analysis on the potential benefits and risks of gene drive, included the example of daughterless mice among a series of potential scenarios where the technology might be applied. As the report noted, "Perspectives on the place of human beings in ecosystems and their larger relationship to nature—and their impact on and manipulation of ecosystems—have an important role in the emerging debate about gene drives." That debate, in a sense, has already begun on Floreana, where residents have been weighing the benefits and risks of a massive, albeit nongenetic manipulation of their precious ecosystem for the past five years.

Campbell is the first to acknowledge that the Galápagos will not be the first or best place to test gene drive in the field. But it may be the best place to think about the implications, good and bad, of gene drive in the context of species preservation. If, as a global community, we value the preservation and protection of biodiversity in the Galápagos (a value ratified by its selection as among the first World Heritage sites by the United Nations agency UNESCO), we also have to come to terms with the complexities and paradoxes of invasive species eradication, which legitimizes the local elimination of certain animals for the benefit of other species—not least humans. As Campbell likes to point out, "No one comes to the Galápagos to see rats and goats and cats."

I. "RED IN TOOTH AND CLAW"

IF THE GALÁPAGOS ISLANDS have become synonymous in the public imagination with ecological harmony and thrillingly pristine biodiversity, the reality is somewhat different. Yes, the massive tortoises are stunning, but where thousands of them once bulldozed the highlands of Floreana, there are now about two dozen—all imported from other islands because the local species went extinct. Yes, the fearless finches are charming and beautiful, but the Floreana mockingbird disappeared from the island around 1880, one of 13 species that have gone locally extinct. Yes, the sea turtles languorously swimming off La Lobería Beach are magnificent, but their eggs have been relentlessly poached by indifferent predators. All those iconic Galápagos species have been ruthlessly threatened by invasive species.

There is a darkness to the Galápagos paradise, and it has been there a long time, perhaps since Tomás de Berlanga, then the bishop of Panama, went off course and discovered the islands in 1535. The first true invasive mammals on the islands were the pirates who frequented them in the 17th century, followed by sailors from whaling ships in the 18th century. These mariners brought in tow a malign ark of mammalian deplorables they introduced to islands that had been largely unperturbed for millions of years. If you want to be provocatively precise about it, the very first documented resident invasive species on Floreana was an Irish sailor named Patrick Watkins, marooned around 1805. He reportedly grew vegetables, which he bartered to visiting ships in exchange for rum (he was the model for a story by Herman Melville).

Three years before Darwin's arrival, a zoo's worth of invasive species had become entrenched on Floreana. It is no accident that in the scientific literature, the earliest date for many invasive species is 1832. That's when General José de Villamil, the first governor of the Galápagos Islands, arrived on Floreana to organize the penal colony. As Cruz—farmer, amateur historian, sometime bus driver and the largest landowner on Floreana—puts it, "He brought everything—goats, donkeys, cows, mules, horses, dogs, pigs, rats, everything." Similar animal importations occurred on other islands in the Galápagos during the 19th century, with devastating consequences on the local flora and fauna. Villamil brought the mules and donkeys to haul tortoises down from the highlands. At the time of his visit, Darwin reported that a previous ship visiting Floreana had loaded up on 200 tortoises in a single day (other ships reportedly collected as many as 700 apiece, according to Darwin).

Invasive mammals have wrought havoc on the ecosystem, in direct and indirect ways. Donkeys destroy tortoise eggs when they roll on the ground to cleanse themselves. Feral cats devour seabird chicks and snack on baby lava lizards, as do mice. Feral goats, in buzz cut fashion, chew through the native vegetation, removing the food that sustained the tortoise population for centuries and clearing the way for invasive plants such as guava, which has spread throughout the highlands. The Galápagos racer, once a common snake? Gone. More than 750 alien plant species and almost 500 alien insects have taken root in the Galápagos. As much as the islands have been a global classroom on evolution, they are also a reminder that nature is not static and that conservation sometimes alters nature to preserve it.

It has been the same story throughout the archipelago, though with some very odd chapters. In a 2012 compendium of "alien vertebrates" on the Galápagos, R. Brand Phillips, David A. Wiedenfeld and Howard L. Snell, all then affiliated with the Charles Darwin Research Station in Puerto Ayora on Santa Cruz, catalogued a rogue's gallery of 44 uninvited guest species, nearly half of them establishing feral populations. They ranged from obvious interlopers (goats, pigs, cattle, black rats) to an unwelcome menagerie of exotic animals. The Nile tilapia, a freshwater fish, turned up on the island of San Cristóbal in 2006; tree frogs have been spotted on two islands. Over the years nonnative visitors have included the mourning gecko, domestic ducks, cattle egrets, parakeets, peafowls and grackles. Three monkeys, of uncertain species, turned up on Floreana in the 1930s, and in 1937 one local entrepreneur tried to establish an ocelot colony on the island of Santiago. Ocelots!

Humans don't get a waiver from these waves of invasion, and their impact is increasing, too. In 1984 only 6,000 people total lived on five of the 129 islands and islets; more than 30,000 do today. And tourists? Three decades ago there were 20,000 a year; in 2016 there were 218,000. Just as more people began to come to the Galápagos to marvel at the local

Unnatural Selection

Island Conservation, a California-based organization, is helping Ecuadorian authorities plan the eradication of every rat and mouse on Floreana, a large, inhabited island in the Galápagos archipelago.

Map by Mapping Specialists

BLACK RATS (*1*), which came to the Galápagos on ships as early as the 17th century, devour eggs laid by native reptiles and birds. To fight back, biologists have resorted to baiting the nesting areas of the Galápagos storm petrel (*2*) and other species with rat poison.

biodiversity, that biodiversity became increasingly threatened by the invasive species.

The Galápagos National Park Service, which controls 97 percent of the land in the archipelago, first attempted to eradicate goats on Pinta Island in 1971—an undermanned campaign that proved the adage in the eradication business that "a 99 percent success is a 100 percent failure." Only 10 goats remained on the island after the eradication program, recalls Victor Carrion, a former national park service official who participated in many eradication efforts. Within 10 years the number had climbed back up to 2,000. "The problem," Carrion says with a shrug, "was the final stage."

The Galápagos National Park Service began to develop more effective eradication plans in the late 1990s. Around this time, Campbell, then 22 years old and trying to decide what to do with his life, turned up in the archipelago. He had no particular affinity for the Galápagos—except, perhaps, that as a teenager back in Brisbane, he kept hundreds of pet birds in aviaries he built himself. In August 1997 he served as a volunteer on a goat-eradication project on the island of Isabela. Within a decade he would play a leading role in some of the most ambitious—and controversial—island eradication projects in the world.

II. THE DEVIL WE KNOW

ERADICATION IS AN UGLY, EUPHEMISTIC BUSINESS. In 2004 the national park service and the Charles Darwin Foundation initiated a more systematic campaign to eradicate goats from the northern, uninhabited part of Isabela, the largest island in the archipelago. Two helicopters were used for aerial hunting; two or three hunters in each helicopter shot goats from the air, using semiautomatic 12-gauge shotguns and semiautomatic .223-caliber AR15 rifles. After the first aerial sweep, ground hunters with specialized dogs went into heavily vegetated parts of the island to flush out goats that had survived the initial onslaught. In the final phase, beginning in March 2005, the eradication team deployed some 700 "Mata Hari goats" and "Judas goats."

Campbell's Ph.D. project was the development of the Mata Hari goat—a variation on the Judas goat, which was developed in the 1980s. Judas goats are outfitted with radiotelemetric collars. The animals are very gregarious, so hunters use goats wearing a wire, if you will, to find other goats. Mata Hari goats take the gambit one step further—they are female goats outfitted with hormonal implants that induce a permanent state of estrus, so that they seek and attract male goats. Mata Hari goats, needless to say, were not cooked up in the evolutionary hot pot of the Galápagos. Indeed, Campbell trained local hunters to perform field surgery on female goats—tying their fallopian tubes, terminating any pregnancies and inserting hormonal packs so that they were in constant heat, after which they were outfitted with radiotelemetry transmitters on collars so they could be traced. Once released, the Judas and Mata Hari goats tracked down the last holdouts. When all was said and done, Project Isabela killed 62,818 goats, at a cost of about $4.1 million. To hear Carrion tell it, the main complaint of the locals was that they didn't get any of the meat. "They said, 'We're hungry, and we need the food!'" he recalls. Even 100 percent success, in this case, wasn't enough—on at least nine occasions, according to Carrion, disgruntled locals deliberately reintroduced eradicated species, in part to protest local fishing regulations.

But the magnitude of the eradication campaigns in the Galá-

TUI DE ROY (1); PETE OXFORD *Getty Images* (2)

FLOREANA GIANT TORTOISES were once thought extinct, but recent genetic research identified related species living on nearby Isabela. Biologists are breeding the tortoises and reintroducing them to Floreana.

pagos is staggering: 79,579 goats "removed" from Santiago, 41,683 from Pinta, 7,726 in San Cristóbal—in all, 201,285 goats have been "removed" from 13 islands (and you know it's a grisly business when euphemisms such as "removed" are used instead of "killed"). It's a pretty good bet that the tourists who flock to the Galápagos to swim with the sea turtles and follow the graceful arc of its storied birds are unaware that the islands have been turned into killing fields over the past two decades to preserve their famous biodiversity.

Even a modest rodent-eradication campaign illustrates just how tricky the traditional approaches can be. In 2012 the Galápagos National Park Service and collaborators began applying the rodent poison brodifacoum on the small, uninhabited island of Pinzón to eliminate rats, which had ravaged the eggs and hatchlings of giant tortoises for decades. The eradication was successful, and substantial numbers of tortoise hatchlings were reported on the island for the first time in a century. But the poison made its way into lava lizards, which in turn were eaten by endangered Galápagos hawks, resulting in at least 22 deaths because of brodifacoum poisoning (even though many of the hawks had been protected by "captive holding" for two weeks). In one instance, researchers found extremely high levels of rat poison in an owl carcass more than two years after the baiting.

And that brings us to the most ambitious island eradication in the Galápagos and perhaps anywhere in the world, an endeavor that everyone on Floreana refers to simply as the "*Proyecto*"—the Project.

III. THE DEVIL IS IN THE DETAILS

THERE IS ONE STORE in Floreana and one main road. As elsewhere in the Galápagos, the houses are simple cinder block constructions with corrugated metal roofs. If you go to one of the few restaurants in the island's single town, you better tell them ahead of time that you are coming: otherwise, they won't have enough food for you. The residents of Floreana are quiet-spoken, generous, subtly good-humored and deeply principled. Several years ago, when an entrepreneur from another island stiffed local workers out of their pay, no one on the island would serve him food, no one would rent him a room to sleep in and no one would speak to him. The entrepreneur's project collapsed. The island's quirky politics and fierce independence make such an endeavor socially daunting. As Campbell says, "It gets complicated real fast."

A recurring mantra in the recent National Academies report on gene drive—and, indeed, in almost every official white paper about genetic engineering in the past four decades—is the need for "public engagement." But that bloodless phrase does not begin to capture the passion and complexity of real projects in real circumstances. If eradications in general are hard, eradications on inhabited islands are *really* hard. That became clear to Campbell several years ago, during a small meeting with members of the Floreana community to discuss the *Proyecto*. One resident, adamantly opposed to the idea of having to remove livestock from the island, looked straight at Campbell and said, in unprintable language, "If you do this, I'm going to kill you." Campbell recalls the moment as "very conflictive."

The intensity of emotion does not seem entirely inappropri-

TUI DE ROY

ate, given the magnitude of the disruption. Since 2012 authorities in the Galápagos, with Island Conservation, have been formulating what they consider to be the most complex eradication plan of an inhabited island to date. It's not just the contentious adults on Floreana who make it complicated. It's children, pets and livestock, in addition to endangered birds and lava lizards.

Consider the staggering environmental risks of a "traditional," nongenetic eradication. To eliminate every rat and mouse from Floreana, the project calls for helicopters to drop some 360 million one-gram (0.035-ounce) pellets of brodifacoum—in Campbell's words, "Basically, systematically paint the whole island"—not just once but two times in the lowlands and three in the highlands, over a period of two months. To minimize potential health and environmental risks, the plan calls for extreme precautions. Water resources must be protected. Children may have to be removed from the island for up to six weeks. Pets will either need to be removed or restricted to domiciles or cages. Large agricultural livestock, such as cattle, pigs and horses, will have to be restricted in corrals (after the farmers of Floreana made clear that sending animals off the island for six months was not an acceptable option). Chickens will have to be housed in new covered coops built specifically for the project. Giant Galápagos tortoises in the Asilo de la Paz refuge will have to be temporarily restricted. Endangered birds will be trapped and held in specially built aviaries during the aerial baiting. In places off-limits to aerial baiting, such as buildings, homes or other structures, the eradication team will deploy traps and bait stations (the location of each bait station, in each home, has to be specified, and Carolina Torres, the lawyer for Island Conservation, is now drawing up a written agreement for each and every household). "A single pregnant female, or a single area missed, is a failure," Campbell says. "You need to get into every building, in every house, in every crawl space, in every closet, under every fridge to get every mouse."

The people from Island Conservation have taken the idea of "public engagement" to a new level. On a recent trip, Torres brought chocolates for Ericka Wittmer, a matriarch of one of the island's oldest families, and paid house calls to several island farmers to explain a legal issue involving contracts with the tenants who worked on parcels of their land. The organization recently provided paint for local homeowners to beautify their cinder block houses. When one resident expressed interest in starting a restaurant, Campbell and Torres encouraged her and promised to be customers. The organization has enlisted architects to design new chicken coops for the island's farmers; each unit will cost about $22,000. Campbell has learned the hard way that one-on-one relationship building is the best way to involve people in the decision-making process on such a delicate project. "If you do a town hall type of thing, they'll absolutely butcher you," he says. "Two or three people dominate the conversation, you don't know what other people think, and then afterwards, you have to spend a lot time dealing with the misinformation."

Despite initial reservations, Campbell says, most residents on Floreana support the eradication plan. In the highlands, Holger Vera, the farmer, stands amid a grove of orange trees, pineapple plants and other crops, lamenting the rapaciousness of the local rodents. They eat fledgling corn plants, he says; they devour pineapples; they eat the tubers of yucca. "Now they are even eating the sugarcane," he complains. "They are eating everything. But if we get rid of them, we can grow everything." Vera was initially skeptical about the *Proyecto,* Torres says, but he now sounds enthusiastic. Even if he has to board his seven dogs? "Yes, yes," he replies. Similarly, Cruz—who owns 80 cows, 130 pigs, more than 200 chickens, 10 horses and two dogs—agrees with the plan and the way it has been discussed with residents of Floreana. "We feel we are on the same page in terms of what's going on," he says.

"Essentially we have verbal agreements" from nearly all the residents, Campbell says. The plan still awaits final approval from Galápagos authorities. He believes the project could have been launched this year if funding had been secured in a timely fashion. (Costs are expected to be $20 million overall, but funding hiccups have now delayed it until at least 2020; Campbell estimates that each year of delay costs $1 million.) Despite funding uncertainty, the reality of the *Proyecto* recently sunk in when seven orange, 20-foot shipping containers arrived in Floreana in mid-July. They are intended to store uncontaminated livestock feed, or silage, for use during the rodent eradication; some farmers have already begun to store animal feed in the containers.

Pulling off a project this complicated is like managing a bureaucratic ecosystem—balancing the regulatory piece, the public engagement piece, the logistical piece, the funding piece, the poison mitigation piece. That's why Campbell thinks the Floreana project is "maxing out" the capability of traditional eradication tools. And that is why, not infrequently, he will say, "If we engaged the gene-drive technology, the conversations would be simpler, and the answers would be much more pragmatic."

IV. THE DEVIL WE DON'T KNOW

CAMPBELL FIRST became intrigued by the possibilities of gene drive in 2011, when he sat in on a conference call between biologists at North Carolina State University and officials of the U.S. Fish and Wildlife Service to discuss a possible genetic approach to control a runaway mouse problem on Southeast Farallon Island, about 20 miles west of the California coast, near San Francisco. John Godwin, a North Carolina State neurobiologist who studies animal behavior, had learned of the Farallon issue while skimming the Internet in 2011. He happened to be at a university with an established infrastructure dedicated to experimenting with—and considering the ethical implications of—genetic manipulation. Two of his colleagues, Fred Gould and David Threadgill, were already discussing the possibility of tinkering with the mouse genome in an attempt to create mice incapable of producing female offspring. Two other colleagues, Jennifer Kuzma and Jason Delborne, became deeply involved in how to engage the larger world of stakeholders—government regulatory agencies, animal management officials, bioethicists and, of course, the general public—in considering the prospect of releasing genetically altered animals into the wild. Kuzma and Gould serve as co-directors of the Genetic Engineering and Society Center at North Carolina State.

To make a long story short, Island Conservation joined forces in 2016 with other international groups to launch the GBIRd—Genetic Biocontrol of Invasive Rodents—program. GBIRd scientists are "cautiously investigating" genetic tools to preserve island ecosystems. The advent of the gene-editing tool CRISPR boosted efforts to develop an alternative approach to eradication. Those efforts gained traction in July, when the Defense Advanced Research Projects Agency gave the North Carolina State group $3.2 million to pursue gene drives for mouse eradication on islands.

FLOREANA LAVA LIZARDS are easy prey for the feral cats that stalk the island.

The basic idea of gene drive seems counterintuitive to anyone raised on the notion of Gregor Mendel's pea plants and the random inheritance of genes from parents. You usually have a 50–50 chance of inheriting a gene from one parent or the other. In rare instances, however, certain genes are favored, or "selfish"—they are inherited at much higher rates than random sorting would suggest. One such gene (technically, a region of the genome) exists in mice on chromosome 17; it is called the T-complex, and it is inherited at a rate of 95 percent. It might theoretically serve as a smuggler's bible, allowing a second gene to be quickly introduced in a population.

In an eradication scenario, researchers could theoretically attach a second piggybacking gene to the T-complex and essentially drive that second trait into the majority of offspring. One such mouse gene, known as *SRY,* determines male gender, so stitching it to a selfish gene would create more and more males (and fewer and fewer females) in each generation, until a mouse population would be daughterless. One of the basic requirements of gene drive is that the time between generations in the target animal is short; mice certainly qualify because their time between birth and reproductive maturity is 10 weeks. If the mice in the lab can be manipulated to pass along a desired gene, such as one to produce a single gender, and if those mice are reproductively successful in the wild, that gene could be rapidly driven into a population.

That's a lot of "ifs," but Threadgill, now at Texas A&M University, has been pursuing precisely that strategy in mice. This so-called daughterless breed could eliminate a native mouse population without environmental poison, without offshore animal relocations, without all the logistical nightmares entailed by the Floreana project. Paul Thomas, a biologist at the University of Adelaide in Australia, has been exploring the use of CRISPR to inactivate genes related to female fertility in mice, an approach that could be adopted to produce a population of entirely infertile females. In addition, Godwin, the neurobiologist, is testing whether an engineered mouse will pass sexual muster with wild mice (he is currently working with a batch transplanted from Southeast Farallon).

Species eradication is by no means the only application of gene drive. Target Malaria is an attempt to engineer mosquitoes so that they are incapable of transmitting malaria; the group, with funding from the Bill & Melinda Gates Foundation, has already begun community outreach efforts in Africa in anticipation of a field test. Kevin Esvelt, a biologist at the Massachusetts Institute of Technology, is pursuing a project to engineer white-footed mice on Nantucket to make them immune to the bacteria that cause Lyme disease. In the gene drive game, the rule of thumb is that islands are the best place for a field test; smaller islands are better than larger ones, and uninhabited islands are better than inhabited ones. Campbell suspects the first field test of gene drive will involve mosquitoes and adds that the U.S., Australia or New Zealand would probably be the most appropriate venue because their regulatory infrastructures are sophisticated enough to assess new hot-button genetic technologies.

Eradications are controversial, genetic modification even more so. "There is no safe way to experiment with these technologies in the wild," says Dana Perls, senior food and technology campaigner at Friends of the Earth. Jane Goodall, Fritjof Capra and other conservationists called for a moratorium on the research in an open letter published last September. Firing a shot across the bow of Island Conservation, the signatories said they were "alarmed that some conservation organizations have accepted funding for and are promoting the release of engineered gene-drive organisms into the wild."

The great fear is "unintended consequences"—that something unexpected and bad will happen. There is no question that gene drive, as the National Academies put it, "may have harmful effects for other species or ecosystems," and that alone warrants cautious and prudent development. But in previous public debates over genetic technologies, such as the battle over recombinant DNA in the 1970s, it was often difficult to separate legitimate concerns from exaggerated fears.

Back in the real world, during an excursion into the highlands of Floreana, Campbell and Torres led me to a freshwater

TUI DE ROY

spring—not far from the cave where the island's first settler, the drunkard Watkins, allegedly slept off his hangovers. As part of the project, the entire area surrounding the spring, which is already fenced off, will be covered with a tent, and special filters will be placed on the pipes to make sure no rodent bait gets into the system—even though brodifacoum is not water-soluble. Part of public engagement, Campbell said, is dealing with perceptions as well as legitimate fears. "You're working with people's perception of toxicants," he explained. "It's challenging to change people's perceptions of this, because they don't." One more reason, Campbell continued, that the genetic approach was more appealing. Then suddenly he changed the subject.

"Here we are," he said quickly, pointing to a rustle of vegetation inside the chain-link fence. "You see it? A rat!"

A pair of shiny, dark eyes briefly appeared amid the leaves. Campbell identified it as *Rattus rattus*—the black rat, which is known to eat the eggs and hatchlings of Galápagos petrels and giant tortoises. Like rats everywhere, it disappeared quickly—a sentinel of an inevitably larger population and a larger covert threat to what Campbell calls "species on the brink."

V. "THE STRANGER'S CRAFT OR POWER"

EVERY STROLL IN THE GALÁPAGOS is a nature walk, and each living creature tells a conservation story—some with happy endings, some not. During our last day on Floreana, a number of these stories began when Campbell's keen eye alighted on the animals that make this landscape so beloved—and beleaguered.

During breakfast, a cactus finch stalked our table. Its strong black and yellow beak had evolved to be larger and stronger, Campbell explained, to crack the unusually large and hard seeds of the local *Opuntia* cactus on Floreana; the cactus, in turn, is evolving even larger and tougher seeds to thwart this poaching—a reminder that evolution is not a textbook concept but an ongoing process. Moments later Campbell spotted a mouse darting behind a hunk of lava. As we finished our meal, another invasive species made an appearance—the sleek, black, smooth-billed ani (pronounced "Annie"). An example of old-school unintended consequences, farmers introduced the bird to the Galápagos in the 1960s in the belief that it could control ticks that afflicted cattle; it did not live up to its billing, so to speak, but it has exploded in numbers as an invasive species.

Later, on a walk to La Lobería Beach, Campbell pointed out fresh tracks of feral cats in the sand; they devour juvenile marine iguanas and lava lizards. ("The small ones have zero chance of getting away," he said.) Near the head of the beach, he indicated the gnawed-off limb of one of the *Opuntia* cacti. When rodents chew down the cacti, he explained, the plants fail to flower or bear fruit—eliminating a crucial source of sustenance for tortoises and mockingbirds, especially in the dry season, and depriving finches of nesting sites. And we paused to admire several magnificent sea turtles temporarily trapped in a lagoon during low tide. Their eggs and hatchlings, too, provide tasty meals for rats and cats.

It was Darwin's 20th-century bulldog, Richard Dawkins, who revived poet Alfred, Lord Tennyson's phrase "Nature, red in tooth and claw" to describe the noir side of natural selection—nature's game is not always pretty, and the postcard-perfect ecology of a place like the Galápagos often conceals a darker, more unsentimental interaction of predator and prey—an interaction whose delicate balance humans have repeatedly perturbed, whether by introducing invasive species or by attempting to atone for those ill-conceived introductions with literally toxic remedies. And now, on the horizon, we may have to decide whether to use futuristic techniques of genetic modification to restore the islands to an earlier, more pristine state.

For what it is worth, a small sampling of opinion on Floreana did not betray much local concern about the potential applications of gene drive, although it is not clear how well understood these technologies (and their potential risks) are. Vera shrugged off any worries and said he would have no problem with a genetic solution to the rodent problem. Ingrid Wittmer, another descendant of one of the earliest families on Floreana, shook her head no when asked, instead expressing concern about the fate of the short-eared owl once its main food source, mice, was eliminated during the *Proyecto*. Cruz, whose father emigrated to the island in 1939, when the population numbered 11, offered a farmer's perspective to the idea of daughterless mice: "It's like artificial insemination in cattle," he said. "If you want females, you use the semen for females. It's the same thing."

"For me, these are issues we've created, and to sit back and do nothing, there's going to be grave consequences," Campbell said. "We know where things are heading. To actually *not* do something is … is just irresponsible. If you have the tool, and you don't use it, *you're* culpable."

We don't have the tool yet. But if the craft of molecular biology eventually captures the power of gene drive, and it is used to manage invasive species in the Galápagos or any island, it is worth remembering that almost every ecological catastrophe visited on the planet's living laboratory of evolution has come at the hands of humans. The goats, the donkeys, the rats, the cats, the pigs, the mules, the mice and, yes, even those short-lived ocelots arrived with human help, on human boats, through human agency.

In a wry observation that resonates nearly two centuries later, Darwin remarked in his journal that while birds in England had developed a well-earned distrust of humans, the birds in the Galápagos "have not learned [such] a salutary dread." He went on to offer what might serve as cautionary words about 21st-century science and gene drives in particular. "We may infer from these facts," Darwin wrote, referring to the lack of fear in birds, "what havoc the introduction of any new beast of prey must cause in a country, before the instincts of the indigenous inhabitants have become adapted to the stranger's craft or power." SA

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FROM OUR ARCHIVES

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PSYCHOLOGY

New insights into the underpinnings of empathy might help us harness the emotion—just when we need it the most

By Lydia Denworth

Illustration by María Corte

Lydia Denworth is a Brooklyn-based science writer and author of *I Can Hear You Whisper: An Intimate Journey Through the Science of Sound and Language* (Dutton, 2014). She is working on a book about the science of social behavior.

LAST YEAR A STRIKING VIDEO MADE ITS WAY AROUND THE INTERNET. IN IT, MALE SPORTS FANS SAT, ONE AT a time, opposite a female sports reporter who had been the target of abusive, misogynist tweets. Each man had to read the messages aloud to the woman who received them. One of the few printable examples was, "I hope your boyfriend beats you." The goal of the project, created by a Web site called Just Not Sports, was to force the men to experience "the shocking online harassment happening to women in sports day in, day out." By ripping away the protective anonymity of social media, the exercise drove home the message that if something is too offensive to say face-to-face, it is too offensive to type. The men were visibly pained as they read. They squirmed in their chairs. One guy looked like he had been punched in the gut. Every man involved appeared to come away with a better sense of how awful it was to be on the receiving end of such nastiness.

At its core, this exercise illustrated what empathy looks like: the capacity to share what someone else is feeling—a tingling fear as you watch a tightrope walker attempt to cross Niagara Falls or butterflies in your stomach because your nervous child is about to perform in a recital. In the 18th century, economist Adam Smith was among the first to name this emotion, calling it "fellow-feeling"—the sensation that something you see happening to another person is happening to you as well. The Germans call it *Einfühlung,* meaning "feeling into." Yet there is more to empathy than shared feelings.

Fifteen years of neuroscientific investigation has led most scientists to see empathy as an umbrella term covering three main components. Emotional empathy—sharing another's feelings and matching that person's behavioral states (feeling afraid, for instance, when someone else is on a tightrope)—is a biological response found in many different species that evolved in the context of parental care and group living. Cognitive empathy, also called perspective taking or theory of mind, is the capacity to think about and understand another's feelings. And empathetic concern, or compassion, adds the motivation to do something about another's suffering. Taken together, these components are fundamental elements of our social lives.

"People empathize because it's absolutely critical for forming close relationships or relating to people at all," says psychologist Jamil Zaki of Stanford University. Disentangling these components—even deciding if they should be disentangled—has been a thorny undertaking. In a 2008 paper, primatologist Frans B. M. de Waal of Emory University, a pioneer in the field, described empathy as a "Russian doll," with "simple mechanisms at its core and more complex mechanisms and perspective-taking abilities as its outer layers." Others take another view, focusing on the differences and preferring narrower interpretations.

Such varied definitions occupy the center of recent public debates about empathy, spurred mostly by the publication last year of Yale University psychologist Paul Bloom's book *Against Empathy*. Bloom devoted a lot of space to specifying which empathy he does not like: cognitive empathy is fine, but he views emotional empathy as a poor basis for moral behavior, arguing that "we're better off without it." We can't get rid of emotional empathy—but Bloom has a point. Empathy is not always good. Even de Waal has acknowledged, in a 2009 book, that there is "no obligatory connection between empathy and kindness." In some situations, empathy causes emotional distress, and it is naturally biased toward those closest to us and away from others.

As a society, we do not generally see it that way. In 2006 Barack Obama was not talking about the negative side of empathy when he famously decried society's "empathy deficit." And employers turning to "empathy training," which is especially popular in schools, hospitals, corporations and police departments, are looking to solve problems, not create them. Yet empathy's built-in bias lies at the heart of the bitter divisions in American society after the election of Donald Trump. "It's very difficult, and painful, and uncomfortable to try to take the perspective, really understand

IN BRIEF

Feeling afraid when watching an acrobat on a tightrope conveys the essence of emotional empathy, allowing us to share someone else's experience. It serves as a critical response in parental caregiving and group living.

Other types of empathy also help us adapt to social demands. Cognitive empathy—perspective taking—lets us contemplate another person's feelings. Empathetic concern, or compassion, provides the motivation to help alleviate another's suffering.

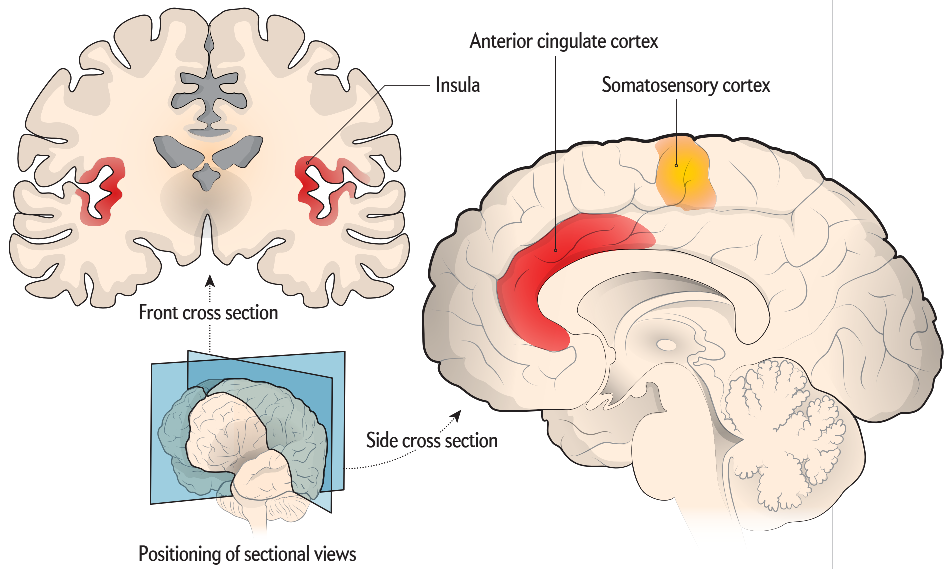
Downsides of empathy result from the recognition that these feelings and thoughts evolved to cement relationships within families and close-knit groups—not to help address perceived threats and longstanding rivalries with outsiders.

the experience, of someone who you've hurt or someone whose opinion is distasteful to you," Zaki says.

As research into empathy matures, what is emerging is a more sophisticated view of a nuanced and complex emotion that often depends on the particular context in which it is manifested. Psychologists and neuroscientists want to understand better how empathy works: when it works for us and when it works against us. The good news is that empathy, in the broadest sense, is not a pop psychological artifact. It can, in fact, be learned through training as a means to help resolve disputes. But teaching it needs to be done with care. Cognitive neuroscientist Emile Bruneau, director of the Peace and Conflict Neuroscience Lab at the University of Pennsylvania, is studying empathy's role in conflict resolution but cautions, "We need to know the pitfalls and test to make sure they're not having an ironic effect. And then we can use that information to build interventions that are more effective."

Connecting to the Pain of Others

The mysteries of how empathy is represented in the human brain have begun to unfold. Imaging studies show that certain brain regions—the insula and the anterior cingulate cortex (*red*)—become active not only when we experience physical pain but also when we witness empathetically another person suffering from the sensation. The somatosensory cortex (*orange*), in contrast, gets activated only when a person directly feels physical pain.



SOURCE: "EMPATHY FOR PAIN INVOLVES THE AFFECTIVE BUT NOT SENSORY COMPONENTS OF PAIN," BY TANIA SINGER ET AL., IN *SCIENCE,* VOL. 303; FEBRUARY 20, 2004

A MULTILAYERED PHENOMENON

PSYCHOLOGISTS have been interested in empathy for decades, but the approach of bringing in neuroscience to study the emotion is only in its adolescence. The first decade or so of work focused on establishing the independent yet interacting neural networks that underlie emotional and cognitive empathy. In 2004 neuroscientist Tania Singer, now at the Max Planck Institute for Human Cognitive and Brain Sciences in Leipzig, Germany, and her colleagues published a groundbreaking paper in *Science* that compared brain activity in a person experiencing pain with the same person's brain activity when observing a loved one experiencing pain. Sixteen women underwent functional magnetic resonance imaging while their male partner sat nearby. Varied levels of painful stimulation were administered by an electrode to one or the other partner. A signal alerted the women when their partner was feeling pain. Some areas of the women's brains were activated only on receiving pain themselves, but others—most notably parts of the anterior insula and the anterior cingulate cortex—lit up no matter who was hurting. Empathy activated the affective, or emotional, parts of the pain network but not the physical sensation of pain. That study and the many imaging studies that followed indicate that our core ability to empathize begins with the way the brain represents our own internal states and evolved to include our perception of what others are feeling.

Cognitive empathy, in contrast, represents the more taxing effort of understanding and reasoning about the state of another individual, a capacity also called mentalizing, or theory of mind. It emerges in children around their first birthday and continues to develop into adulthood. The brain's mentalizing network has consistently been shown to include the superior temporal sulcus, temporal poles and temporoparietal junction. Another area is the medial prefrontal cortex behind the forehead, which is associated with thinking about oneself. Empathetic concern activates yet another network.

The role of each facet of empathy is most obvious when one goes missing. A person with autism spectrum disorder has little ability to assume the perspective of someone else. Psychopaths, on the other hand, understand what others are feeling but have a profound lack of empathetic concern. "They know right from wrong but don't care," wrote neuroscientist Jean Decety and his colleague Keith J. Yoder, both at the University of Chicago, in a 2016 study. Multiple studies led by Decety have found that people with high levels of psychopathy show abnormal connections among neurons and neural activity in areas of the brain associated with empathy.

Most recently, in their 2016 study, Decety and Yoder assessed 265 people on scales of empathetic concern, psychopathy and sensitivity to moral questions related to a sense of justice. Participants then considered eight scenarios and were asked how permissible it would be to behave in a particular way. For example, when running for an infrequent bus, would it be acceptable not to stop to help a woman with a small child who has spilled the contents of her purse? Cognitive empathy, but not emotional empathy, was found to predict a sense of justice for others. Those high in "coldheartedness"—a measure of psychopathy—were the least motivated by a sense of justice, an individual's perception of injustice or the intensity of response to perceived

Illustration by Tami Tolpa

Empathy evolved to smooth social relationships among family and friends, not to improve dealings with outsiders.

unfairness. The researchers concluded that "it may be more effective to encourage perspective taking and reasoning [cognitive empathy] to induce concern for others than emphasizing emotional sharing with the misfortune of others."

A study published last year in *Science* was the first to suggest not just where but how the processing of empathy might work. James Burkett, a neuroscientist at Emory, found consoling behavior in prairie voles, a species known for its strong social nature. Pairs of male and female animals were caged together for a few weeks, then the female was removed briefly. She either was simply kept separate for a few minutes or was given a mild foot shock, a form of fear conditioning that generates stress. When the animals were reunited in the cage, Burkett's team observed their social interactions. If the female had not been stressed, neither animal seemed particularly anxious. But when she had been shocked, the male quickly began grooming her intensely—behavior interpreted as consoling because the pair did not engage in it otherwise and because it had a calming effect on the shocked animal.

The animal left behind showed a physiological response that mimicked that of the animal who had been taken away. Furthermore, the intensity of the consoling response varied from animal to animal. When Burkett looked at oxytocin, which promotes social bonding, in the brains of the voles, he discovered something interesting. The variation in behavior was predicted by the density of docking sites, or receptors, for oxytocin in the same part of the brain—the anterior cingulate cortex—that Singer had identified in humans who felt pain empathy for others. As the density of receptors increased, the amount of time animals spent consoling decreased. Burkett hypothesizes that oxytocin signaling in that area of the brain might encode for personal distress in response to the distress of others. "Some level of concern for the distress of others is necessary to motivate consoling, but too much personal distress causes individuals to avoid rather than engage," he says.

THE DOWNSIDE OF EMPATHY

BURKETT'S STUDY PROVIDES a possible explanation for one of the negative aspects of empathy. When the emotions experienced are stressful or painful, empathy is painful—an explanation for why we sometimes avoid such feelings. "If I empathize with everyone who is in a worse state than I am, I might be motivated to donate 95 percent of my income to charity," Zaki says. "Rather than being put in a moral double bind between guilt and poverty, I might just choose not to think about people who are less fortunate than myself." In certain professions, such as medicine and law enforcement, where exposure to human suffering can be constant, too much personal distress gets in the way of doing the job. Physicians, for example, suffer from excessive burnout and are at higher risk than others for death by suicide.

A more universal problem is that empathy is biased. "It evolved so that we have more empathy for our family and friends than anybody else," says de Waal, who has extensively studied the evolution of empathy. That makes sense: group living is designed to protect against predation, and individuals with strong social bonds live longer and have more reproductive success than others. Thus, we are drawn to kith and kin and naturally avoid outsiders. As Mina Cikara, director of the Intergroup Neuroscience Lab at Harvard University, puts it: "A fundamental component of human nature is the tendency to draw bright boundaries between us and them."

A series of studies over the past decade has explored this problem and shown that the issue of in-groups and out-groups applies not only to differences of race and ethnicity but also to long-standing sports and college rivalries. Cikara and her colleagues have found that avid Boston Red Sox fans (her husband is one) are more likely to feel pleasure not only when their team plays well but also when their archrival, the New York Yankees, plays badly. And those who feel that schadenfreude most powerfully are more likely to get into a fight with a Yankees fan and inflict harm. This holds true even when the competing groups are made up. In several studies, Cikara and her colleagues randomly assigned study participants to teams they dubbed the Rattlers and the Eagles and then measured responses to positive or negative incidents that happened to members of each team. Not only did identifying with the Rattlers dampen empathy for the Eagles, it also increased the counterempathetic response—also known as not being very nice.

In a recently published study, Bruneau, Cikara and Rebecca Saxe of the Massachusetts Institute of Technology tried to determine which aspect of empathy was the best predictor of helping behavior across group boundaries. They recruited three sets of participants: Americans asked to think about Arabs, Hungarians asked to think about Muslim refugees and Greek citizens asked to think about Germans in the aftermath of the Greek debt crisis. Participants were assessed for general empathetic concern and for "parochial empathy," the degree to which people feel empathy toward their own versus another group. Each study was slightly different, but in the American-Arab study, participants read about positive and negative events happening to characters such as "Beth" from North Dakota or "Salma" from Egypt. They were later asked questions such as whether they would provide U.S. visas to Arabs and donate to an Arab charity. In every instance, parochial empathy was the more significant predictor of the outcome. The higher it was, the less altruism was displayed. General empathetic concern predicted nothing.

This research highlights the complexity of using empathy to improve relationships between distrustful groups. "If you bring kids from either side of a conflict together, and you manage to increase their global empathy, that won't have any effect on how they treat the out-group," Bruneau says. "And if they form close ties with members of their own group, you might have actually increased empathy for the in-group more than for the out-group." To truly improve such a situation, he notes, requires precision: when such a method is proposed, say a camp bringing together Catholic and Protestant kids from Northern Ireland, for instance, "what you really mean is you want to decrease the gap in empathy between in-group and out-group."

A FORCE FOR GOOD?

IMPROVING A SITUATION IS, of course, the goal of empathy interventions. But will the sports fan made to feel the hurt of misogynist tweets change his own behavior in the future? Not necessarily. In one of the earliest and most well-known social psychology experiments, C. Daniel Batson and John Darley, both then at Princeton University, proved this outcome in spectacularly ironic fashion. In 1973 they assigned some seminary students to give a talk about the parable of the Good Samaritan and others to give one about a topic unrelated to altruism. Then they arranged things so that the seminarians had to rush from one building to another to give the talk. Along the way, each passed a miserable figure moaning on the sidewalk. The study counted which seminarians stopped to help. Being well versed in the story of the Good Samaritan made no difference in the likelihood of offering help, but being in a hurry markedly decreased the inclination to do so. Decades later, however, Batson, now a professor emeritus at the University of Kansas, established that people who feel compassion help more often than those who are upset by others' distress.

Since her pioneering work in 2004, Singer has shifted her interest to focus squarely on compassion. In several studies published since 2012, her laboratory examined the neural effects of training for compassion, which it defined as a feeling of concern that includes the motivation to help. The training consisted of a contemplative technique that extends the caring feelings people usually feel for close loved ones to other human beings. The researchers found that contemplative training increased positive emotional experiences, even when witnessing others in distress. It also raised activity in parts of the brain associated with perspective taking. In a 2014 study, Singer and her colleagues concluded that this form of compassion training might be "a new coping strategy to overcome empathic distress and strengthen resilience."

Zaki speaks of motivational empathy rather than compassion, although they are essentially the same thing. He has been exploring the extent to which intervention can enhance the desire to be empathetic. At Stanford, he joined forces with psychologist Carol Dweck, who is known for her work on how a person's mindset can affect performance. Dweck found that people with a fixed mindset about, say, intelligence believe they are powerless to change how well they perform, whereas those with growth mindsets—say, a "can-do" attitude—believe performance can be improved with effort. In a series of 2014 studies, Zaki, Dweck and Karina Schumann of Stanford discovered that similar mindsets exist for empathy. Participants who believed that effort could change one's level of empathy were more likely to try to take the perspective of someone from a social out-group than those who thought of empathy as a stable, unchanging trait. Future interventions, the researchers argued, should emphasize empathy's malleability.

In another series of studies, published in 2016, Zaki also showed that group norms can inspire people to be more helpful. In one of the studies, for example, participants had to choose how much out of $1 to donate to charity before learning whether others had been generous or stingy. Initially the average donation was nine cents, but those who then viewed generous behavior significantly increased their giving, ultimately giving nearly twice as much as those who observed stingy behavior.

Psychologist Jason Okonofua of the University of California, Berkeley, is applying these kinds of findings to schools. In a 2016 study, he examined and sought to change teachers' mindsets about discipline. He and his colleagues first randomly assigned teachers to read one of two brief articles: One reminded them of the importance of good teacher-student relationships in helping students learn self-control. The other stated that punishment was critical for teachers to take control of the classroom. When teachers were subsequently presented with examples of disciplinary incidents and asked how they would handle the situation, their responses were less punitive if they had read the empathetic mindset article. A second experiment instructed college students to imagine themselves as middle schoolers in trouble with a teacher for repeatedly disrupting class by walking to the trash can. The participants were asked how levels of respect for the teacher were affected by whether a teacher responded by assigning detention (punitive) or by asking questions and moving the trash can closer to the student's desk (empathetic). As predicted, the students reported more respect for empathetic teachers.

Finally, Okonofua set up a randomized trial to test whether a brief online module that encouraged empathetic discipline would make a difference across an academic year. Math teachers at five diverse middle schools in three districts across California participated, and students whose teachers received the empathetic intervention rather than a control one were half as likely to be suspended. Okonofua is now expanding the study to 20 schools.

It is important to note that Okonofua stipulates what his intervention does not do: It does not require the teachers to share the students' view of the situation. Rather it emphasizes understanding and valuing the students' perspective. The goal, as he and his colleagues wrote in the 2016 paper, is discipline administered "in a context of mutual understanding and trust." Is that still empathy? Okonofua thinks so. It is empathy writ large. And it is helping. SA

MORE TO EXPLORE

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CONSERVATION

Beetle Resurrection

Oil companies want the American burying beetle to be the first recovered insect taken off the U.S. endangered species list. But scientists say comeback claims are wildly exaggerated

By Hannah Nordhaus

Hannah Nordhaus is author of *The Beekeeper's Lament* (Harper Perennial, 2011), *American Ghost* (Harper, 2015), and "Cornboy vs. the Billion-Dollar Bug" in *Scientific American*'s March 2017 issue. She writes about science, history and the natural world and lives in Boulder, Colo.

THE BEETLE RANCH IS LOVELY: SLATE TILE, a Viking range, knotty oak paneling and a wood stove with a preening taxidermy turkey on the wall above it. The porch is lined with rocking chairs that face out to a massive walnut tree and, beyond it, the pastures and thickets of southern Oklahoma's Lower Canadian Hills. Clover fields glow in the afternoon sun. A phoebe hollers from her nest; a scissortail flits between fence and field.

People working at the ranch carry all sorts of weapons. Amy Smith, a biologist who conducts research here, keeps a .38 handgun strapped to her waist. Preston Smith, an owner of the property (and no relation to Amy Smith), is a six-and-a-half-foot-tall Texan who wears a beautiful silver-and-black combination .45 and .410 revolver engraved with his name. Grace McNichols, an undergraduate research assistant at John Brown University in Arkansas, where Amy Smith teaches, carries a bowie knife. The ranch beyond the house covers 4,000 acres of beautiful but wild country, and the group totes weapons to protect themselves from rattlesnakes and feral hogs. "You packing?" Amy Smith asks her team. They pat their weapons and head out.

The nearby forest is fading to black as the researchers jump into a mud-spattered Kawasaki Mule all-terrain vehicle loaded with coolers, plastic tubs and shovels. Smith takes the wheel and blasts through two fearsome puddles, then jostles up a ridge through scrub and woodland to a meadow speckled with coreopsis and Indian paintbrush. The women haul two buckets and a cooler to a spot underneath an elm tree. It's breezy this evening, with a faint whiff of death.

The smell comes from the cooler, from which McNichols now pulls three dead animals—a small bunny, a large rat and a standard-sized quail—all decomposing. The women set down a wide plastic tub with the bottom cut out, weigh the animals and lay them against the edges of the plastic. In between the dead animals, Smith places a petri dish containing two stunning inch-and-a-half-long insects. They are American burying beetles (*Nicrophorus americanus* or ABB for short): black-and-orange-Rorschach-blotted creatures, with two orange puffballs at the tips of their antennae that recall, from a certain angle, handlebar mustaches. The beetles feed and breed on rotting carcasses, and this particular experiment is aimed at understanding what type of dead creatures the beetles prefer.

The beetles are on the federal Endangered Species Act list. A century ago they could be found across much of the U.S., but by 1989 their known population had dwindled to two spots: eastern Oklahoma and a small island off the coast of Rhode Island. The ranch—officially, the American Burying Beetle Conservation Bank—represents an effort to stem that decline. Oil and gas producers, transportation agencies and others can drill or build in beetle habitat in Oklahoma, but in a trade-off, they are required to give money to conservation banks to create a beetle haven elsewhere. Amy Smith's job is to help make the ranch the best place a beetle could possibly live.

If all goes according to plan with Smith's experiment, the beetles will, by morning, have selected a carcass, buried it and mated. But arthropod activities don't always go according to human plans. Sometimes the beetles reject the carcasses and refuse to mate. "So," Smith says, "I sing a little Barry White for them." She hopes they will feel love coming on.

Not everyone, however, is so enamored of the insect. In Oklahoma, where beetle habitat overlaps the oil and gas fields that power the state's economy, congressional representatives, along with fossil-fuel industry groups, have targeted the beetle

IN BRIEF

On the federal endangered species list since 1989, the American burying beetle needs small animal carcasses to live.

Beetle habitat overlaps with oil and gas industry operations, and the industry wants the insect off the protected list.

Arguments turn on whether the beetle's current population is robust enough to survive in a habitat that includes more pipelines, drilling rigs and roads.

PRECEDING PAGES: JOEL SARTORE *Getty Images*

ON THE HUNT: Outside Stuart, Okla., biology consultant Andy Middick (*brown shirt*) checks an American burying beetle trap (*1*). A burying beetle crawls across animal fur (*2*). Middick photographs and measures a beetle during a population survey (*3*).

MATT BARNARD *Tulsa World* (1 and 3); MARK MOFFETT *Getty Images* (2)

for removal from the list of federally protected species. "The listing of the American burying beetle unnecessarily places burdensome land-use restrictions to build roads, water resources, and energy infrastructure in many of our communities," Senator James Lankford of Oklahoma said in a statement earlier this year. He and others argue that current beetle populations are stable and not under threat. In March of last year, responding to a petition by a group of fossil-fuel and property-rights advocates, the U.S. Fish and Wildlife Service (FWS) agreed to review the beetle's status on the federal list. The agency is expected to issue a preliminary ruling this month, and many people believe it is poised to say that the beetles are back.

Conservation scientists do not agree, however. "We have found more beetles because we've been looking harder," Smith says. "But they're still in less than 10 percent of their historical range." She and other beetle experts fear that more disruptions to habitat will trigger new population declines. The dispute highlights the murky science around species recovery and its intersection with politics and policy. The pressure to delist the beetle reflects a disquieting trend in which political considerations may be every bit as important as actual data in determining a threatened species' fate. "There is much more behind all this," says Andy Middick, a consultant who tracks beetles for energy companies, "than the survival of a species."

MEET THE BEETLES

THE AMERICAN BURYING BEETLE is one of the biggest and brightest insects in North America, but most Americans will never see one—and not just because it is endangered. The beetle spends much of its life underground, and the aboveground part takes place at night, in proximity to dead things. Even scientists who have devoted their careers to the species—there are a handful who stumbled into the field while studying something else—don't know a whole lot about the beetle. They know, thanks to extensive museum collections, that the insects were once found in 35 states and three Canadian provinces and that sometime around the 1920s their populations began a steep decline.

They also know that the beetles are habitat generalists—they can be found in forests, wetlands and grasslands but require a moist environment to survive. The animals are mobile, traveling a mile each night, on average. The beetles aren't especially picky about what type or size of remains they eat—mammals, birds and snakes are all fair game—but for breeding purposes, the dead animal's weight must fall between about four and 10 ounces. If the carcass is too big, the insects can't move or process it; if it's too small, it won't feed enough of the beetles' offspring. When beetles find a suitable carcass, they flip over, using their legs as a conveyor belt to shuffle the creature to a spot where the soil is right. They like loose, loamy, silty soil "that's easy to dig in," Smith says. Like backhoes, the beetles excavate the soil from under the critter and then, when it is fully buried, strip it of fur or feather and use an oral-anal secretion to transform the carcass into an orb of slime—a carrion meatball, if you will. Then the beetles mate. The female lays an average of 15 eggs. When the larvae hatch, male and female alike feed the young from the buried cache, much as birds nourish their chicks, mouthful by rotted, regurgitated mouthful. After an additional 45 to 60 days, the grown insects emerge from the ground and begin searching for their own moldering meals.

There are still glaring gaps in our knowledge, though. Scientists and regulators do not, for instance, have any idea how many beetles there actually are in North America. Surveys of small locations do not shed much light on wider beetle populations. With other species, ecologists use a variety of assumptions to extrapolate total populations from trapped specimens, "but this beetle violates a lot of those assumptions because it's so mobile," Smith says. "If I extrapolated, it would just be a crapshoot."

Populations also vary dramatically from year to year—Smith has found dozens of beetles in a spot one year and none the next. No one knows why. In 2007 husband-and-wife biologists Dan Howard and Carrie Hall discovered a population at the Tallgrass Prairie Preserve in northern Oklahoma, a 40,000-acre Nature Conservancy property. Earlier surveys had not turned up any beetles on the preserve; Howard and Hall believe that populations there are highly cyclical—teams will find thousands one summer and just a handful the next. "Life is hanging on the edge here," says Howard, now at the University of New Hampshire. In the years since the listing, scientists have also found beetles in Kansas, Nebraska, South Dakota, Arkansas and Texas.

"We are still trying to figure out basic life history information," says J. Curtis Creighton, a biologist at Purdue University Northwest. They suspect the beetles live for about a year in the wild, but they aren't certain. "How often can they reproduce?" Creighton asks. No one knows. "What kind of carcasses can they subsist on?" That is the question behind Smith's rat-bunny-quail research and a higher-tech study Creighton has designed with Smith's help to analyze stable isotopes in beetle exoskeletons to see what they have consumed as larvae.

The biggest unknown is why the beetles began disappearing in the first place. There are theories. After the beetle was first listed as endangered, Rhode Island Division of Fish and Wildlife biologist Christopher Raithel began wondering how the animals stuck it out on Block Island, the spot off the Rhode Island shore that is the only place east of the Mississippi where the beetles are still found. "I started asking, 'What does Block Island have more of than anywhere on the mainland?'" What it had, Raithel concluded, was carcasses—ring-necked pheasants, introduced from Asia to North America in the 19th century and still plentiful on the island. On the mainland, right-sized carrion species had declined because of hunting, habitat fragmentation, and competition from raccoons and other carrion feeders that prosper on the edges of human habitation. One theory ties the beetle's decline to the extinction of the passenger pigeon, which once blanketed the eastern half of the U.S. in massive, sky-darkening flocks of billions of birds. On Block Island, pheasants appeared to fill that hole in the food chain.

There were no comparable populations of pheasants in Oklahoma, but Raithel and other beetle specialists believe that the two environments do have some things in common. Like Block Island, Oklahoma is relatively dark: outdoor lights appear to disorient American burying beetles more than other species of nocturnal burying beetles, and electrification may have been a factor in their decline. And neither place has extensive agriculture—the beetles are not found among row crops. But as with many ecological puzzles, there is likely not one smoking gun to explain the beetles' decline. "Ultimately," Creighton says, "it comes down to the fact that we've altered their habitat."

RANGE ROVERS

ACADEMIC SCIENTISTS are not the only people interested in the American burying beetle's habitat. Federal regulators in Oklahoma will not issue permits for oil and gas wells, wind farms, roads, pipelines and transmission lines in potential beetle habitat unless those locations have been surveyed for the beetles. To do so, permittees hire consultants such as Middick, a large man with a large beard and a large, mud-specked white truck that stinks of decay. His firm is called Beacon Environmental Assistance. All throughout beetle season, roughly May through October, Middick keeps the bed of his truck loaded with coolers of decomposing chicken gizzards and hearts and a "secret proprietary concoction" of "rotten juice"—putrid gizzards soaked in water. "My neighbors love me," he jokes.

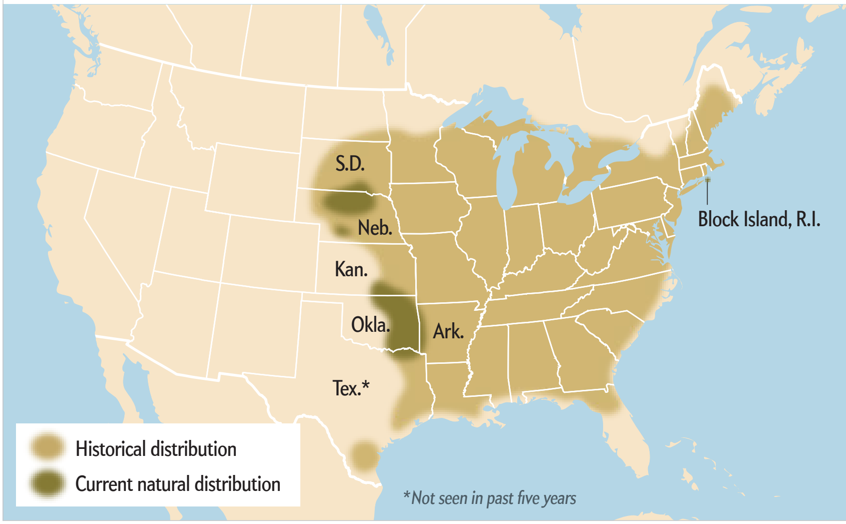
Middick places his "gizzard gravy" in a pitfall trap, which consists of a five-gallon bucket staked down and then covered with a piece of wood with a hole in the top. The beetles, attracted by the carrion smell, fall through the hole and can't fly out. He sets 250 to 300 beetle traps a year on behalf of oil and gas and other clients seeking permits to disturb potential beetle habitat, putting about 30,000 miles on his truck during the summer. He goes anywhere a beetle might live and a driller might drill. As Middick steers his truck north out of Tulsa, the subdivisions and scrubby hill country give way to rolling tallgrass prairie—country utterly different from the buggy, muggy, densely vegetated forest farther south near the beetle bank. Beetles live here, too. What the two landscapes have in common, he says, are large, undeveloped tracts of land.

Those tracts aren't, however, as undeveloped as they used to be. Middick turns off a paved country road onto a smaller dirt one. It's an area he's surveyed often, a rural spot gone industrial—a tangle of derricks, frack tanks, drilling pads, flow lines, pipelines and rigs. A string of saltwater trucks hauling produced water from wells clatters past on the narrow road, coating Middick's truck in a layer of road dust, fine as baby powder. Oil country, Middick says, is also methamphetamine country,

Are the beetles still endangered? It is true that they are found in more states now. But they are gone from most of the places they once frequented, about 90 percent of their historical range.

Where Beetles Roam

The American burying beetle once ranged over the entire eastern U.S. Today natural populations are confined to three regions. One encompasses eastern Oklahoma and touches bordering states, although in Texas, the insects have not been seen for years. Another is centered on Nebraska and South Dakota. The third is on Block Island, off the Rhode Island coast. Reintroduction attempts in Ohio and Massachusetts have failed to produce self-sustaining populations; Missouri is home to a small reintroduced group.



where a big man with a big beard hauling five-gallon buckets through the underbrush—the same type of bucket some people use to mix meth—has to be careful. He likes to place his traps in ditches on the sides of county roads hidden from nearby properties. "There are lots of guys kind of eyeballing me," Middick says. "People are always out there stealing stuff, and they get pretty protective." For insurance reasons, his clients prohibit him from carrying a gun. "But," Middick says, "don't look in my backpack."

In his searches, Middick follows very specific instructions set out by the Fish and Wildlife Service. To ascertain whether beetles are present on any given property, he must lay traps on a minimum of five consecutive nights of good weather, at a maximum of one mile apart. There is nothing systematic about where he looks for them, however: "I go where the oil goes," Middick says. If a pipeline or a drilling area expands to the west, his surveys expand to the west. If beetles are found, the known beetle range expands as well. Much of what we know about the beetle's range has come from surveys like Middick's, but the data, he says, "are very random."

If Middick does find beetles, his clients have three choices: they can relocate their projects to beetle-free territory; they can buy their own beetle habitat to replace what they disturb; or they can pay one of Oklahoma's two conservation banks to do it for them. Both banks opened for business in 2014, and each protects around 4,000 acres. The money that permittees pay into the banks goes both to the acquisition of new beetle habitat and to long-term stewardship and maintenance of the property. Preston Smith says this kind of real estate speculation makes nobody rich. "I wouldn't put it up as a real highly competitive investment," he says. "But the intangible side of this is rewarding as well." Smith likes hunting on the property; he likes protecting beetles.

The beetles do seem be prospering at the ranch. The land's previous owner had used it for hunting. "He had some food plots in place, ponds, forested areas—he basically had accidentally managed for American burying beetles," Amy Smith says. The conservation bank has improved on that happy accident, using prescribed fire to knock back invasive plants and open the tree canopy and reseeding native grasses. "It's a little too soon to tell," she says, "but the numbers are good." Each year Smith has captured more beetles than she did the year before.

GROWING CONFLICT

THE NUMBERS AREN'T AS GOOD, however, for people paying into the banks. The credits are expensive—between $8,000 and $15,000 for every acre of beetle habitat disturbed, depending on location, timing, number of credits and duration of the disturbance. Small operators can sink a modest vertical well for less than $100,000 in areas with the right geology. "When mitigation credits hit, and they're $60,000, that's a big cost," Middick says. Transportation projects, too, have encountered insurmountable beetle obstacles. One Oklahoma county had to scrap a planned road because the cost of mitigation exceeded its budget. The result has been a steady drumbeat of news articles about beetle frustrations. "It gets very nasty at times," Middick says. "Most people don't understand why a beetle matters."

It is those costs and conflicts that led to the push to remove the beetle from the endangered species list. "There are a lot of problems with regulating a species that's essentially invisible," Raithel says. In the years since mitigation credits were introduced, local FWS officials have found themselves under enormous political pressure. In 2014 a U.S. Department of the Interior review found that senior officials in the FWS's Tulsa office used flawed models and misleading maps and downplayed the impacts of the pending Keystone XL pipeline on the ABB, then retaliated against scientists who objected. In 2015 Oklahoma's two Republican senators, Lankford and James Inhofe, attempted to attach a provision delisting the beetle to the National Defense Authorization Act. The measure did not pass, but Lankford did not give up. He directed the Government Accountability Office to investigate whether beetle mitigation funds were being misused. The final report, issued in January 2017, found no major malfeasance but recommended better monitoring.

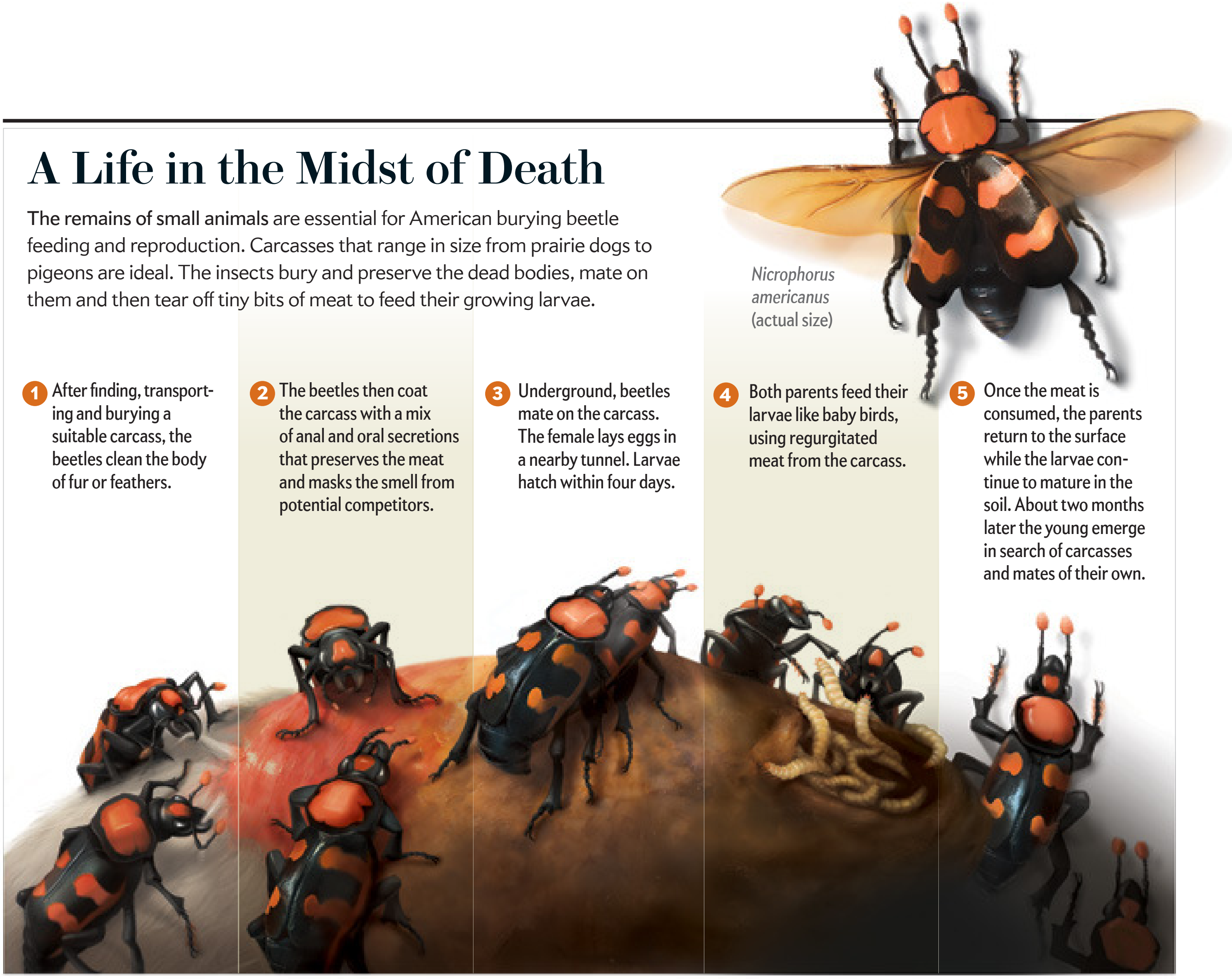
In August 2015 American Stewards of Liberty, a property-rights organization, filed its petition to delist the beetle, arguing that the historical range of the ABB was based on unreliable

SOURCES: COSEWIC ASSESSMENT AND STATUS REPORT ON THE AMERICAN BURYING BEETLE *NICROPHORUS AMERICANUS* IN CANADA. COMMITTEE ON THE STATUS OF ENDANGERED WILDLIFE IN CANADA, 2011; WYATT HOBACK *Oklahoma State University (consultant)*

Map by Dolly Holmes

A Life in the Midst of Death

The remains of small animals are essential for American burying beetle feeding and reproduction. Carcasses that range in size from prairie dogs to pigeons are ideal. The insects bury and preserve the dead bodies, mate on them and then tear off tiny bits of meat to feed their growing larvae.



SOURCE: WYATT HOBACK *Oklahoma State University (consultant)*

anecdotes and that existing populations were healthy. The petition was followed, a year later, by the FWS agreement to review beetle status. "Today we know that the species is residing in a lot of states, a lot of counties, more than 100-fold beyond when the species was listed," says Margaret Byfield, executive director of American Stewards of Liberty. "It's in more places than we knew."

But the review appears to have only raised more questions about what and how we count when attempting to save a species that gets in our way. The delisting petition, for instance, included in the beetle's current range not only those locations where the insect has been found since the initial listing but also three states where zoos and wildlife agencies have attempted to reintroduce it—Massachusetts, Ohio and Missouri. But the Massachusetts and Ohio populations have not done well. Scientists have seen more encouraging results in southern Missouri, where the Saint Louis Zoo began reintroduction efforts in 2012. But it is still far too early to call the effort a success. "The goal is to be able to walk away from it and say, 'Here is a self-sustaining population,'" says the zoo's Bob Merz, who heads the Missouri reintroduction effort. "We may find parameters that make reintroduction work, but at this point, it's many years away."

Are the beetles still endangered? It is true that they are found in more states now. But they are still gone from most of the places they once frequented. "I thought if we looked, we'd find them in other places," Creighton says. "But we haven't." Even with the new discoveries, the beetle is still missing from 90 percent of its historical range. "And in the few populations that we know of," Creighton says, "at least two have disappeared." One was in Texas, where the beetle has not been seen in about five years, and the other was in the Ouachita National Forest in Oklahoma, where a logging land swap knocked out what had been a robust population. "The data," Creighton says, "are certainly consistent with a species that is in danger of disappearing."

The data grew even more convoluted this past summer, when the Fish and Wildlife Service circulated a draft Species Status Assessment for scientific review. The results surprised everyone. The assessment used geographical models to determine that current habitat, in terms of total beetle-friendly acres, is sufficient to support the beetle and that roads, pipelines and fossil-fuel projects that crisscross and disturb that habitat are minor impediments to the insect's survival. Beetle scientists question that logic, however. "I'm not convinced that such projects are really 'minor' when beetles need a large, unimpeded area," says Oklahoma State University entomologist Wyatt Hoback. Beetles, he notes, rely on other creatures to breed, and those animals "also rely on unbroken areas."

The report then went a step further. It used climate models to determine that the beetle was likely, over the next 80 years, to

Illustration by Kelly Murphy

go extinct throughout the entire southern part of its range: Oklahoma, Arkansas and Texas. "It seems that when temperatures are high"—around 75 degrees Fahrenheit at midnight—"the beetles are not active or can't reproduce," Hoback says. These observations are anecdotal, however; there has not yet been any research, peer-reviewed or otherwise, to prove them. "Historically," he notes, "ABBs occurred down through southern Texas and Florida, so there is some debate."

Tossing climate change into the equation bothers both fossil-fuel and beetle advocates. Oil and gas groups worry that regulators plan to use the climate change hypothesis to maintain federal protections for the beetle when other factors suggest it should be delisted. Beetle devotees, meanwhile, fear that the FWS will use the climate models to delist the species in the parts of its range where, conveniently, nobody wants it, rendering both the beetles and the Oklahoma conservation banks obsolete. "What's scary about that conclusion," Hoback says, "is that they can say that the southern population of beetles is not worth trying to save."

This month the FWS plans to issue a "12-month finding" on the beetle; it will not be clear until then whether the conclusions match those of the draft assessment. Following a 30- to 60-day public comment period, the agency will then have a year to finalize its conclusions. Whatever decision the FWS makes, it is almost inevitable that the agency will be sued—by industry and property-rights groups if the beetle's status stays the same or by environmental organizations if protections are lifted. In September, in fact, American Stewards of Liberty filed suit because the FWS failed to issue a ruling within the required 12-month period after receiving the petition to delist. "Fish and Wildlife is going to end up in court regardless," Hoback says.

FOUND: A beetle from Oklahoma walks on Middick's hand.

MATT BARNARD *Tulsa World*

AT THE BRINK

IF THE AMERICAN BURYING BEETLE is removed from the federal list of endangered species, what will become of it? That will likely depend on its location—thanks to variations in climate both atmospheric and human. In 2015—the same year the delisting petition was filed—a group of Rhode Island third graders campaigned successfully to make the ABB the state's official insect. If the beetle loses federal protections, Rhode Island will almost certainly continue to shelter a bug that has become beloved in the state. Wildlife workers on Block Island provide carrion and discourage outdoor lighting; 40 percent of the island is protected open space; they teach about the beetle in schools all over the state. "We just spent 25 years monitoring and trying to protect this thing," Raithel says. "We're not going to walk away from it."

The beetle's future is less certain, however, in Oklahoma and neighboring states. Small populations may persist for some time on protected lands such as the beetle banks and the Tallgrass Prairie Preserve. But, Hoback says, "the more habitat fragmentation that happens, the smaller the populations of ABBs remain, and small populations can't respond as well" to environmental threats. Then, Creighton adds, "it's just a matter of time before the beetle's gone." There are many people in Oklahoma who are willing to live with that prospect.

The American burying beetle is not an easy creature to root for. It traffics in death. It gets in the way of human endeavor. It is expensive; it is inconvenient—less exoskeleton-and-hemolymph insect than symbol of all that opponents believe is wrong with American environmental laws: land-use restriction, excessive regulation, infuriating delays, meddling bureaucrats and an industry of consultants such as Middick, with their coolers full of dead things to attract imperiled things that no one knows are there and no one is likely to miss.

Does an insect matter? Should we care for the smallest among us? These invertebrates do provide essential services to the rest of the world: nutrient cycling, pollination, pest control and decomposition. Sometimes the benefits are more direct: researchers are currently investigating the antimicrobial compounds that the burying beetles secrete for use as antibiotics or preservatives. The beetles also reduce breeding grounds for maggots. One dead mouse can spawn 15 beetles—or, alternatively, play host to 300 disease-transmitting flies. "The beetles are important," Hoback says.

But of course, the vast majority of North Americans have survived for almost a century without the help of burying beetles. And if protections are removed and groups such as the American Stewards of Liberty are wrong about beetle population strength, we may have to live without them in the next. Saving an endangered species is an altogether human project—deciding as a nation that we should protect something at risk. Scientists and citizens labor in muggy dawns and dusks, in thickets teeming with chiggers and deer ticks, surrounded by the smell of death. It is an effort as peculiar as the beetle itself: underground, beneath notice, bearing a whiff of loss and futility. SA

MORE TO EXPLORE

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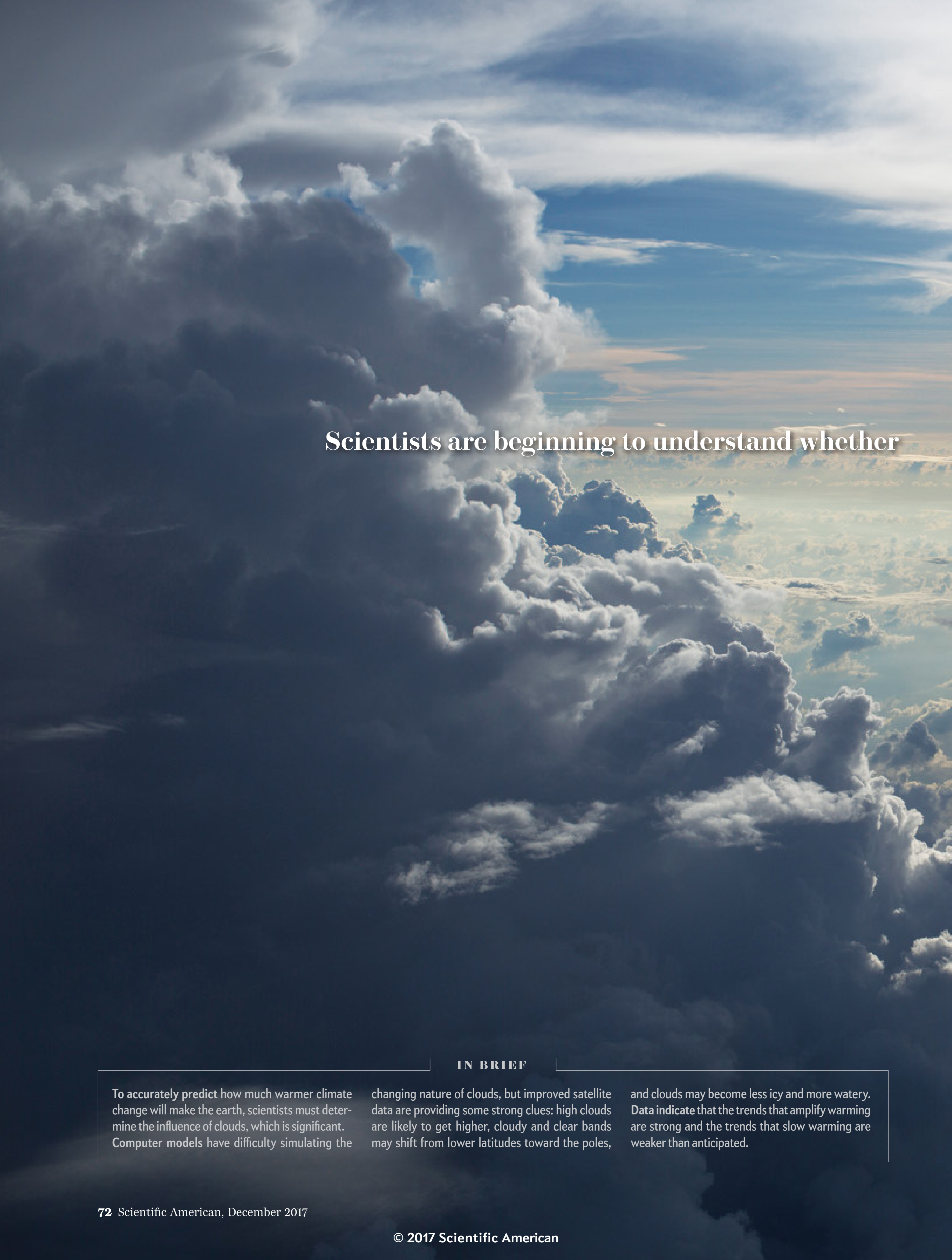


Scientists are beginning to understand whether

IN BRIEF

To accurately predict how much warmer climate change will make the earth, scientists must determine the influence of clouds, which is significant.

Computer models have difficulty simulating the changing nature of clouds, but improved satellite data are providing some strong clues: high clouds are likely to get higher, cloudy and clear bands may shift from lower latitudes toward the poles, and clouds may become less icy and more watery.

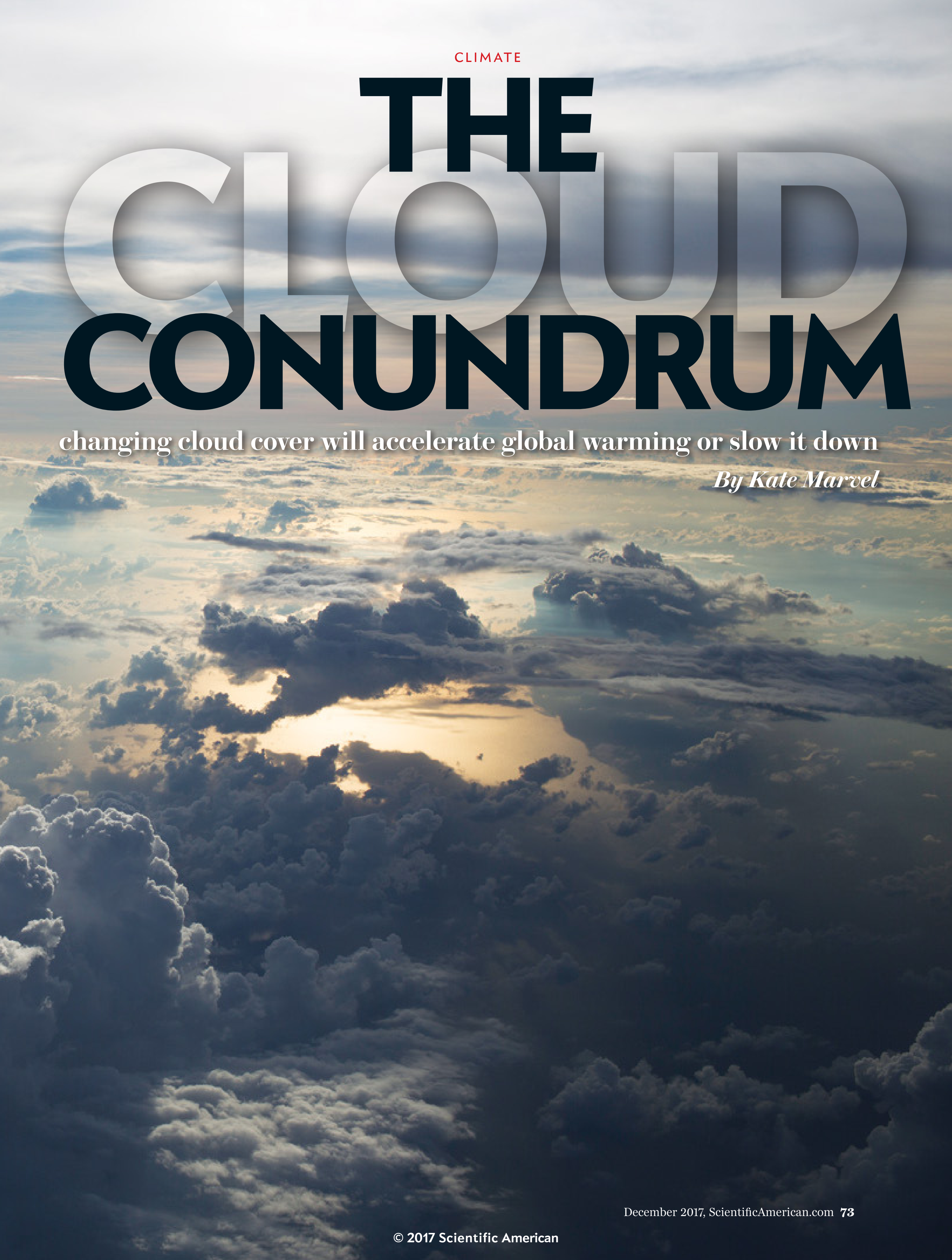
Data indicate that the trends that amplify warming are strong and the trends that slow warming are weaker than anticipated.

CLIMATE

THE CLOUD CONUNDRUM

changing cloud cover will accelerate global warming or slow it down

By Kate Marvel



Kate Marvel is an associate research scientist at Columbia University's department of applied physics and applied mathematics and at NASA'S Goddard Institute for Space Studies.

I HATE CLOUDS. NOT BECAUSE THEY SOMETIMES BRING RAIN BUT BECAUSE THEY ARE HARD. CLOUDS come in all shapes and sizes: wispy, high cirrus, puffy cumulus, the low, gray stratocumulus layers that blanket gloomy days. This great diversity makes it difficult to predict how clouds will react worldwide as the earth's atmosphere changes.

Climate scientists like me know from reams of data that the earth will warm up this century and beyond. But we are struggling to pin down how much hotter it will get: Perhaps another one degree Celsius? Or two degrees, or three or four? The answer depends largely on clouds. Climate change is affecting the distribution of clouds in the atmosphere, which could actually help slow down global warming—or speed it up. Knowing this outcome would be tremendously helpful in guiding actions the world takes today and tomorrow.

Large teams of experts have developed more than 20 sophisticated climate models, tested against extensive climate data. All the models show the earth warming in response to ongoing greenhouse gas emissions, but for years they stubbornly disagreed on clouds. That is starting to change. Simulations of cloud effects are beginning to converge. Satellite data and other observations are revealing how changing cloud cover is altering the planet. Do the new insights give us hope or extend our fears?

BIG FEEDBACKS OR SMALL

IMAGINE THE EARTH just before the Industrial Revolution. Humans on six continents have cut down forests for pastures and towns. Yet the concentration of carbon dioxide in the atmosphere has been stable at about 280 parts per million (ppm) for thousands of years. Then the internal-combustion engine arrives. Fast-forward to the late 1900s, and CO_2 concentrations have soared. The shock reverberates throughout the entire planetary system. The troposphere that holds the air we breathe is warming. By 2017 the CO_2 concentration is above 400 ppm. The continents are heating up. The shallow oceans are, too. The circulation of air and water vapor in the atmosphere is beginning to change. As current trends continue, atmospheric CO_2 levels double the preindustrial values by midcentury. More heating occurs. Finally, after several hundred years, the planet reaches a new equilibrium at a higher temperature.

The planetary response to carbon dioxide doubling is called equilibrium climate sensitivity, or ECS. Every climate model tells us that ECS is larger than zero: we should expect some warming. But the degree of warming they predict ranges from approximately two to 4.5 degrees C—from significant to catastrophic.

The models do not align, largely because they disagree on what clouds will do in the future. A better handle on clouds will allow us to narrow that range and make a much tighter prediction. But zeroing in on the influence of clouds is hard for two reasons. First, warming affects different types of clouds differently. Second, cloud changes affect warming in different ways.

This two-way interaction is called a feedback. Certain climate feedbacks are well understood. Sea ice, for example, is bright white and therefore reflects most of the sun's rays back into space, but as it melts it reveals darker water that does not reflect as much sun. That warms the air more, which melts more reflective ice and exposes more dark ocean, which reflects even less sun—and the feedback cycle builds, accelerating global warming. We understand this building, or "positive," feedback well, and most models are in reasonable agreement about how it can affect climate change.

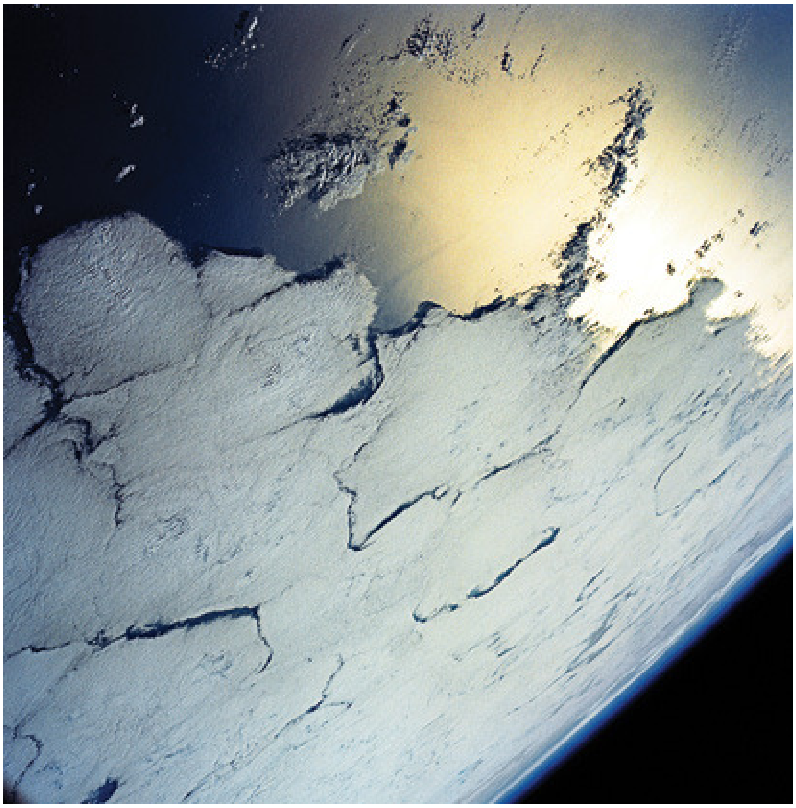
Understanding cloud feedback is more complicated. Like archivists in a natural history museum, climate scientists have created a rough taxonomy of clouds, grouping them by distinguishing features. Two basic properties are their height above the earth's surface and their opacity. Low clouds can be relatively transparent, like scattered puffs on a sunny day, or opaque, like uniform blankets of coastal fog. High clouds, too, can range from wisps through which almost all sunlight passes to the towering anvils that blacken skies during a thunderstorm.

This taxonomy is useful because it highlights the main ways in which clouds warm or cool the planet. Some clouds enhance the greenhouse effect. They trap heat rising from the earth and reradiate some of it toward outer space; the planet would be colder without them. Clouds in the cold upper reaches of the atmosphere are particularly effective in this regard.

Other clouds have the opposite effect: they prevent sunlight from reaching the earth's surface in the first place, keeping the planet cool. This effect is pronounced in low, thick clouds. In our current climate, that influence is larger than the cloud greenhouse effect. In fact, the net cooling of clouds today is immense, roughly five times greater than the warming of CO_2 doubling.

This means that even small changes to cloud cover can have big impacts. Add more high, transparent clouds that let sunlight

PRECEDING PAGES: MICHAEL TUREK *Gallery Stock*



CLOUDS COVER more than 70 percent of the earth on a typical day, strongly influencing climate. Here they blanket the Pacific Ocean.

GETTY IMAGES

through but keep heat in, and the earth warms up. Add more low, opaque clouds that keep sunlight out, and it cools down. Cloud migration matters, too; redistributing reflective clouds from sunny tropical and subtropical latitudes to the cold, dark poles diminishes their cooling effect. Altitude is important as well; lifting high clouds even higher to colder upper reaches of the atmosphere increases their greenhouse effect. A warmer world may also change the ratio of ice crystals to water droplets in cold clouds, making them moister and thicker and therefore more efficient at blocking incoming sunlight.

None of these effects occurs in isolation, which is why models struggle. Some show feedbacks that are strongly positive—they amplify warming significantly. Some show feedbacks that are weakly negative—they slow warming slightly. The models that predict the strongest positive feedback end up predicting ECS at the high end of the range between two and 4.5 degrees C.

It is also no surprise that models do not simulate clouds well because clouds are simultaneously large and small. They are formed by tiny water droplets and ice crystals, yet they typically cover more than 70 percent of the earth at any given time. In programming a computer model, we must make a choice: zoom in and explicitly simulate the turbulent motions of droplets that make each cloud form and dissipate in a small area, or simulate the large-scale motions of rising and sinking air that distribute water vapor around the planet. We cannot do both, because it takes too much computing power to carefully track the behavior of every water droplet in the entire atmosphere at every moment.

We therefore try to combine small and large scales, knowing there will be compromises involved. A global climate model tries to find simplified parameters that describe the aggregate behavior. We develop these parameters based on the physics of the atmosphere and test and improve them through comparisons with finer-scale models run over small areas of the globe.

Still, there is no perfect way to mix large and small. But can we improve?

CHANGING FORCES

LET'S TACKLE THE FIRST CHALLENGE: high clouds. Measurements give us good reasons to believe that climate change will literally reshape the atmosphere, pushing ever higher the boundary between the troposphere—the lower atmosphere where weather occurs—and the stratosphere right above it. High clouds, we suspect, will rise along with the rising boundary.

Mark Zelinka, a scientist at Lawrence Livermore National Laboratory, has thought a lot about the implications of this rise. As the planet warms from CO_2, Zelinka says, it tries to cool itself by losing energy in the form of infrared radiation toward space. If high clouds remain at their typical altitude, they would warm in lockstep with the atmosphere and, in so doing, increase the amount of heat they lose to space. Zelinka and others think, however, that high clouds will rise so they can remain at nearly the same temperature they seem to prefer now. As a result, they would not radiate as much of the increasing heat energy to space, and that energy would instead further warm the atmosphere. This is a positive feedback: by rising more and more, high clouds further reduce a warming planet's ability to cool itself off.

Next, what about low clouds? Climate models seem to agree that a warmer world means fewer low clouds. Yet Mark Webb, a climate scientist at the Met Office—the U.K.'s national weather service—and the Cloud Feedback Model Intercomparison Project, knows it is more complicated than that. (It is either an interesting quirk or a reflection of our field's lack of diversity that so many cloud experts are named Mark.) Webb says he and colleagues are debating why a warmer planet might have fewer low clouds. The mechanism seems to depend on the way moist air in low clouds is diluted by the convection or turbulence of drier air above. Conventional models, Webb says, do not have the computing power to represent these local processes directly and end up approximating them differently. Various models show larger or smaller changes in low cloud cover, but crucially, most of them project reductions. Fewer low clouds means less sunlight is reflected to space—another positive feedback that amplifies warming.

There is yet another effect to consider. The atmosphere's overall circulation is largely driven by the differences in sunlight and temperature between the equator and the poles.

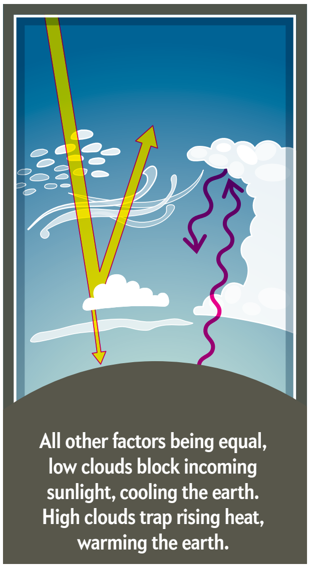
Warm tropical air rises, cooling as it does. Once it is high in the sky, it starts moving laterally toward the colder poles. Along the way, it cools sufficiently to sink back down to the surface, at around 30 degrees latitude, warming and drying as it descends. On the ground, we get rainy climates under the tropical band of air that rises and sheds water as it cools, and we get desert-like climates under the bands where air descends.

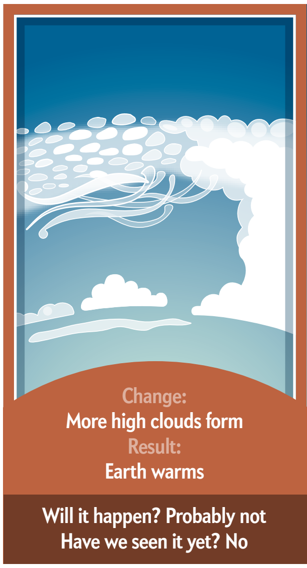
Climate change will shift this pattern. The northern high latitudes will warm faster than the tropics, a phenomenon known as Arctic amplification, which reduces the temperature difference between the poles and the equator. The reduction, already under way, changes everything. Most important, perhaps, is that the tropics expand, pushing the rainy and dry bands toward the poles. One effect on land is that marginal zones—the Mediterranean, the Sahel, the American Southwest—will likely become drier. Indeed, satellite observations that I recently analyzed with Céline Bonfils of Lawrence Livermore show that precipitation patterns are shifting just as predicted. If clouds follow the migration, then decks of reflecting clouds may be pushed from lower to higher latitudes, where the incoming sunlight is weaker, reducing their cooling effect compared with their long-standing position over the tropics.

One more complicating factor must be figured into improved climate models: a warmer world can change the makeup of clouds. Clouds contain tiny water droplets and ice crystals. Thick, low clouds tend to be more watery and are more opaque than thin, high clouds, which tend to be more icy. In a warmer world, more ice in high clouds turns liquid, making them more opaque, blocking more incoming sunlight. Thawing ice clouds will become "juicier," Zelinka says, providing a negative feedback—an important cooling check on warming.

Hot or Cold? How Changing Clouds Affect the Earth

Globally, shifts in the latitude or height of clouds (or in the mix of vapor and ice that compose them) can make the earth warmer or cooler. Some of the changes shown here are already under way, according to satellite data. So far they lean toward warming, and the trends could become more extensive.





A TIGHTER PREDICTION

THE CHANGING NATURE of clouds makes it seem even more difficult for models to narrow the anticipated rise of global temperatures—to reduce that two- to 4.5-degree C range. But one powerful data set matters more than any other: the history of what has already happened.

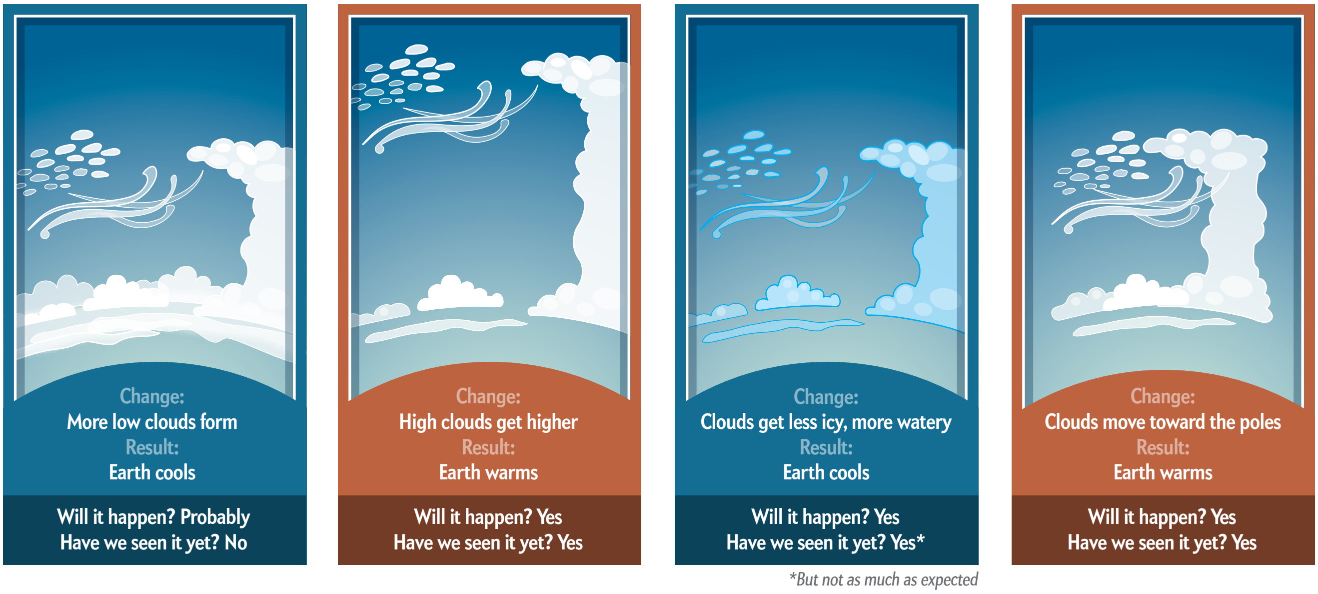
We have been measuring clouds almost since we began putting weather satellites into orbit in the 1980s. We can compare our models with actual observations to make our models better. Some of the older satellite measurements can be problematic, though. Cameralike instruments in Earth-observing satellites can find clouds by looking down for white objects against dark backgrounds, but they strain to differentiate between different white things, particularly icy clouds above snowy ground. Moreover, high clouds can obscure changes in lower cloud cover.

Our observations have improved greatly in the past decade, however, thanks in large part to the A-train. NASA's Afternoon Constellation, or A-Train, is a collection of six Earth-observing satellites that fly in formation, burning fuel to keep a stable orbit. Two of them, CloudSat and CALIPSO, provide invaluable information. CloudSat uses radio waves that can easily penetrate high, thin clouds to measure low, thicker clouds. It can also tell if a cloud is raining or snowing. CALIPSO uses laser-based radar, known as lidar, to image clouds. It can tell whether clouds are made of ice crystals or liquid droplets.

Together these satellites have enhanced our understanding of cloud cover and given us hints about how clouds may change in the future. For example, the observations seem to support the notion that high clouds will rise higher as the planet warms, reducing the planet's ability to cool itself. And a recent study has shown that only some high clouds contain more water and less ice than anticipated. That means that the negative feedback associated with clouds becoming juicier may not be as strong as we had earlier thought.

CloudSat and CALIPSO were launched in 2006, so their data records are too short for us to detect climate change effects against the background of natural climate variability. To add perspective, scientists are patching together older observations from systems designed to monitor short-term weather trends. Two efforts of note are the International Satellite Cloud Climatology Project and the Pathfinder Atmospheres–Extended project. Unfortunately, says Mark Richardson of NASA's Jet Propulsion Laboratory, various weather satellites investigated by the projects were designed differently and took data at different times of day. Still, there are clues in these records if you know where to look. In a 2015 study, Zelinka and I gave it a try.

We began by asking a simple question: Where, in the observations, are the cloudiest and clearest latitudes on the earth? As expected, we found peak cloudiness in the tropics. Cloud cover was also relatively high in narrow bands in the midlatitudes, where storms are driven by the prevailing winds. In the subtrop-



ical "desert" latitudes, high atmospheric pressure led to dry, sunny conditions that impeded cloud formation—the clearest bands.

We then looked to see if the locations of the cloudiest and clearest latitudes changed over the course of the long-term weather satellite record, from 1984 to 2009. What we found was remarkable: the cloudiest midlatitudes and clearest subtropical latitudes were being pushed toward the poles, exactly as the models told us they would. Moreover, each of the independent data sets agreed that changing atmospheric circulation patterns were dragging cloud patterns toward the poles. By comparing this with climate models run in modes that do not include human emissions, we established that the changes were too large to be attributable to natural variability alone. And the changes were larger than scientists had predicted.

The implications are troubling. If decks of low, reflecting clouds are shoved too far toward the poles, then their cooling power will be substantially reduced: they will block weak, temperate sunlight instead of intense, tropical sunlight. This migration would constitute a strong positive feedback and indicate a higher climate sensitivity.

A subsequent study led by Joel Norris of the University of California, San Diego, that took into account known discrepancies in the satellite record found a poleward shift in the cloud patterns, too. These data also suggested that high clouds may be rising. Scientists are debating the significance of these changes and whether they can be attributed to greenhouse gas emissions, waning of particulates spewed into the atmosphere by the 1991 Mount Pinatubo eruption or natural climate variability, or some combination of these factors. But one thing is clear: the long-term observations do not show any indication that clouds will slow down warming.

THE CLOUDS WON'T SAVE US

The picture that is emerging from the observations is becoming clearer. High clouds are rising, and cloud patterns are generally shifting toward the poles. Both trends would accelerate planetary warming. Short-term observations suggest that reductions in tropical clouds will block less sun, thereby enhancing warming, and that thawing clouds may be a weaker check on warming than we had previously thought. There is little here to comfort us.

So do we now think that clouds will steer warming closer to the upper end of the ECS range? Equilibrium climate sensitivity is a theoretical quantity. It describes the eventual climate response to the swift doubling of carbon dioxide in the atmosphere—an artificial scenario that gives us a very real way to explore. Increased CO_2 is not theoretical, however; the doubling will happen by midcentury if nations worldwide continue on their present course. More satellite observations, higher-resolution models and creative, up-and-coming scientists will help us pin down the answer to how much hotter the planet will become.

In the meantime, work is needed on another, more relevant quantity that has also stubbornly refused to budge: the 50 percent of the U.S. population that does not accept the fact that humans are changing the climate. Ultimately, if CO_2 emissions continue unabated, the earth will warm a lot. Clouds, it seems, will make matters worse and, at minimum, will do nothing to alleviate the problem. That task falls to us. SA

MORE TO EXPLORE

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Illustration by Jen Christiansen

ARCHAEOLOGY

HOW CAPTIVES CHANGED THE WORLD

Stolen people—mostly women and children—were a driving force in the evolution of modern society

By Catherine M. Cameron

Illustration by Katie Edwards

IN BRIEF

Although small-scale societies are often depicted as communities of people who saw one another as equals, most of them actually contained a number of marginalized individuals, many of whom were captives from other groups.

World history has long ignored the lives of these stolen people. But analyses of early travelers' accounts and other reports indicate that they profoundly influenced their captors' societies.

Captives created power and wealth—factors that helped lay the groundwork for a major social transition: the evolution of complex, state-level societies.

AS THE ARMIES OF ISIS SWEPT across Syria and northern Iraq in the summer of 2014, they overran villages of Yazidi people, whom they considered infidels. The soldiers killed Yazidi men and seized the girls and women. Girls as young as 12 became “wives”—sex slaves passed around among the ISIS fighters. The horror was all too familiar: the nightmare the Yazidi women have endured is that of captive women through the ages.

Catherine M. Cameron is an archaeologist at the University of Colorado Boulder. Her work focuses on sites in the American Southwest, including Chaco Canyon. She has been studying captives in early small-scale societies around the world for the past 12 years.

For the past decade I have studied captive taking in historical and ancient cultures. I am an archaeologist interested in social and demographic processes in small-scale societies of the type that scholars call “tribes” or “chiefdoms”—groups of fewer than 20,000 people who are related through blood or marriage and whose leaders have relatively limited power. Captives were ubiquitous in these societies: early travelers’ accounts, ethnohistorical documents, ethnographies, captive narratives and archaeological reports describe captives in every corner of the world, from northern Europe to southern South America. My analyses of these early writings represent the first attempt at a cross-cultural examination of abduction and its consequences.

The worlds described in these documents contrast sharply with the idealized image of small communities of people who treated one another as equals. Instead most small-scale societies contained a number of individuals who did not have access to the same resources and benefits as other members of the group. Some of these disadvantaged people were orphans, incompetents or criminals, but most were captives from other groups. Indeed, in some small-scale societies stolen people might constitute up to 25 percent of the population. Because they had no kin in the groups they unwillingly joined, captives were automatically marginal; in many cases, native group members did not even see them as human.

Although captives formed the lowest social stratum of the groups they entered, they nonetheless influenced these societies in profound ways. They introduced their captors to new ideas and beliefs from their natal group, fostering the spread of technologies and ideologies. And they played key roles in the creation of status, inequality and wealth in the groups that abducted them. These factors may well have laid the groundwork for the emergence of a much more sophisticated social structure: the state-level society, in which one person or small group of people hold significant power and authority over a population numbering more than 20,000 and in which group membership is built not on kinship ties but on social class or residence within the boundaries of a nation-state. For all the misery they endured, captives changed the world.

TAKEN BY FORCE

PEOPLE TYPICALLY BECAME CAPTIVES through warfare or raids. During his first voyage to the Americas in 1492, Christopher Columbus heard about the fierce Kalinago people of the Caribbean’s Lesser Antilles islands. Documents from the 15th and 16th centuries reveal that the Kalinago traveled hundreds of miles in their war canoes to attack other islands and steal their goods and people. The raiders ritually killed the adult males they took soon after returning home. Young boys were emasculated and used as slaves until they reached adulthood, at which point they were sacrificed. The young women entered Kalinago society as their captor’s concubine or his wife’s servant. The hunter-gatherers of the Northwest Coast of North America raided for captives to put to work as slaves or to trade for other goods. Nineteenth-century accounts describe fleets of war canoes carrying warriors who attacked neighboring groups or made longer-distance raids. They took mostly women and children but also men not killed in battle. From the eighth to the 11th centuries Vikings raided throughout the North Atlantic and the Mediterranean, taking large numbers of captives to enslave or sell. During the 12th to 16th centuries coastal chiefdoms in the Philippines sent slave-raider fleets across the region, attacking smaller groups. According to archaeologist Laura Junker of the University of Illinois at Chicago, the raiders returned with captive women whom they enslaved or married. The women worked in agricultural fields or made pottery or textiles for their master to trade.

A society’s captives rarely attained equal status with the native-born. When warriors returned, those captives destined to be slaves almost always underwent a process that sociologist Orlando Patterson of Harvard University calls “social death,” in which they were stripped of their natal identity and “reborn” as slaves. During this process slaves were often forced to adopt some visible mark of their servitude and received a new “slave name.” The Conibo people of eastern Peru, for instance, cut the hair of female captives to give them short bangs that denoted slave status. They also replaced the captives’ traditional clothing, which the Conibo considered immodest and savage. The Kalinago beat and insulted their new captives, cut their hair as a sign of servitude, and renamed them “female slave” or “male slave.” Because they were ultimately sacrificed and consumed, the young male slaves were also called “my barbecue.”

Early 19th-century accounts describe the traumatic destruction of the social and cultural identity of captives in Southeast

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CAPTIVES in small-scale societies were typically put to work as slaves, as seen in a Northwest Coast Indian carving (*1*). Some, such as Helena Valero, who was abducted by the Yanomamö of the Amazon in the 1930s (*2*), became wives. The influence of captives on the groups they entered is visible in artifacts such as an Iroquois mask for a medicinal tradition that Huron captives may have introduced (*3*).

1

Asia, including a Dutch sea captain taken by Iranun slavers from the Philippines. The slavers stripped him of his clothes and bound him hand and foot to the bottom of a boat. According to ethnohistorian James Warren of Murdoch University in Australia, such pirates beat their captives on the elbows and knees so they could not run or swim away. Tied up for months at a time, poorly fed and constantly abused, the captives eventually gave up hope of escape.

In Northwest Coast societies, captives not only became slaves with no possibility of ever becoming members of their captor's society, but their children shared their fate. Like African slaves in the American South or industrial slaves in ancient Rome, slaves in Northwest Coast groups passed their status down to their offspring.

AGENTS OF CHANGE

ONE MIGHT EXPECT abused captives dragged into a new society to have little opportunity to transmit knowledge or skills to their captor's group. My cross-cultural study paints an emphatically different picture, however. People today tend to view small-scale societies as timeless and unchanging, but in truth, they were often eager to learn new things. Captives brought opportunities for social, economic and ideological progress, and their captors took full advantage of them.

A number of accounts hint that at least some captives were targeted for their technological know-how. English ship's armorer John Jewitt, taken in the early 19th century by the Mowachaht people, a Northwest Coast group, was spared in a lethal attack because the chief wanted the metal weapons Jewitt knew how to make. Jewitt, who detailed his ordeal in a memoir published in 1815, also showed his captors how to wash soiled clothes rather than discard them, although Jewitt himself had to do the washing. Helena Valero, who was kidnapped by the Yanomamö of the Amazon in the 1930s, when she was a child, reported that her abductors were furious when she told them she did not know how to make metal tools. She recounted her years with the tribe in a 1965 book, noting, "The women said 'She is a white woman, she must know; yet she doesn't want to make clothes, machetes, or cooking pots for us; hit her!' " But the headman and one of Helena's co-wives defended her, and she survived. Metalworking skills were similarly prized among the Germanic tribes of northern Europe, who captured Roman metalsmiths and apparently put them to work. Archaeologists have found locally made Roman-style metal objects, such as statuettes, drinking horns and weapons, as far north as Denmark.

Captives could also change the religious practices of their captors' society. On the Northwest Coast of North America, Haida people learned from their Bella Bella captives about ceremonial gatherings called potlatches that were organized to build or repair a house. The people of Ouidah, a West African coastal slaving port, practiced a variety of vodun cults in the 19th century, some of which were introduced by slave women taken from interior African groups. And Germanic tribes who attacked the Roman Empire during its decline learned Christianity from Roman captives.

Although captors typically disdained their captives, they often believed they had curing powers. Spaniard Álvar Núñez Cabeza de Vaca was exploring the Gulf Coast a few decades after Columbus's voyage when he and several companions were shipwrecked and taken by native groups in what is now Texas. Their captors were sure these foreigners knew how to cure illness, and Cabeza de Vaca and his group became widely known for the healing ceremonies they invented. When the Spaniards escaped and made their way to what is now Mexico, the many native peoples they encountered along the way requested their skills as healers. Similarly, in the mid-19th-century American West, a wounded Oglala Sioux chief demanded his captive, a young pioneer woman named Fanny Kelly, attend him because he believed a white woman's

MUSEUM OF ANTHROPOLOGY, UNIVERSITY OF BRITISH COLUMBIA (1); JOSE ANTONIO CARRERA MUNOZ (2); WERNER FORMAN *Getty Images* (3) touch would cure him. And in the Northeast region of North America, Huron captives are thought to have introduced the medicinal False Face Society, in which curers wore wood masks, to their Iroquois captors.

YAZIDI WOMAN was among the thousands taken as sex slaves by ISIS fighters in 2014.

SAFIN HAMED *Getty Images*

STATUS SYMBOLS

PERHAPS THE MOST SURPRISING finding from my study is that captives were a potent source of social and political power for their captors. In small-scale societies, social power stemmed from the number of followers a leader controlled, most of whom were relatives. However unwillingly, captives added significant numbers of nonkin followers and thus increased the status of their captors. Captives, especially women of reproductive age, allowed leaders or status-seeking men to increase the size of their family or number of followers without incurring the traditional marriage obligation of paying a bride price to the bride's family. And by definition, captives created instant inequality in the societies they joined. As the most marginal and despised members of the group, they raised everyone else's standing.

In most of the small-scale societies I examined, men gained prestige through success in war. Captives were the best evidence of victory. Among the Kalinago, for instance, a man could only achieve an advantageous marriage into a high-ranking family if he triumphed in war, which meant taking captives. Young Iroquois men in the Northeast region of North America could not expect to become leaders or marry well unless they were successful warriors—again, signified by captive taking. Men in societies throughout the Northeast used the "calumet ceremony," an alliance-building ritual that revolved around smoking sacred pipes, to boast of their success as warriors and captors. During the ceremony each warrior recounted the battles he had participated in and described every slave he had obtained. In the Philippine chiefdoms of Southeast Asia during the 12th through the 16th centuries, those warriors who took the most captives and the most booty during raids earned the highest status. They aspired to the successes of mythical warriors whose supernatural powers allowed them to overcome enemies and make off with their people.

Masters also attained social status through the public display of their power over their slaves. The stark disparity in daily routines between masters and captives constantly reinforced their relative standing. In this sense, high social status required not only master and servant but an audience to bear witness to the domination. Patterson has noted that the cult of chivalry of the American South, which emphasized the "honor" of Southern men, was only possible because white men could contrast themselves with powerless and, in their eyes, "honorless" slaves (regardless of whether they actually owned slaves). Similar dynamics played out in small-scale societies. For example, prominent Northwest Coast men called titleholders displayed their prestige in day-to-day interactions with their slaves. Titleholders performed only administrative tasks such as organizing ceremonial events and almost never did real work—the duty of slaves. Titleholder wives and daughters eschewed work, too. Slaves followed them everywhere to fetch wood and water, cook, carry burdens and mind children.

Among the Conibo, captives could also become retainers—household servants to high-ranking individuals or families—further elevating the social status of their masters. Likewise the Makú captives of the eastern Tukano people who inhabited the Vaupés River Basin of Brazil and Colombia cared for their master's personal needs and those of his wife. They held their master's large ceremonial cigar when he smoked and even breastfed their mistress's babies, according to anthropologist Fernando Santos-Granero of the Smithsonian Tropical Research Institute in Panama. Yet the Tukano scorned the Makú. Men might take Makú women as concubines but would never consider marrying one.

WEALTH BUILDERS

SCHOLARS HAVE ARGUED that slaves in small-scale societies were only status symbols with no real economic role. They have drawn a sharp contrast between this kind of slavery and large-scale slavery, the economic impact of which is evident from recent history: African slaves produced the wealth of the American South, a driving force in 19th-century American economic development. But the groups I studied suggest that captives in ancient smaller-scale societies actually began the process of creating the wealth, status and inequality that presaged the economic consequences of large-scale slavery in the U.S., Rome and elsewhere.

Leaders had to reward voluntary followers to maintain their loyalty, so their power was tied to their ability to control and provide food or items for trade. In small-scale societies, an aspiring leader generally turned to his kin to create the surplus he needed to gain and retain followers, but kin could reject the demand of the would-be leader. Powerless captives, of course, could not.

Precolonial examples of the economic impact of captives abound in the literature. Consider the 16th-century chiefdoms in the Cauca Valley of Colombia, which were constantly at war. The earliest Spanish visitors—soldiers and priests—reported that victors took hundreds of captives. They sacrificed some but kept many more as slaves, which allowed each master to significantly expand his crop production. On North America's Northwest Coast, salmon was a dietary staple for many groups, but it was available only at certain times of the year, so people had to preserve it for storage. The tribes considered salmon processing women's work. But they readily set slaves of both sexes to this task, which created surpluses of dried salmon. Elsewhere in North America, on the Great Plains in the century before Europeans arrived, men became wealthy through the production and trade of high-status bison robes and hides. Producing hides and robes was labor-intensive women's work. Archaeologist Judith Habicht-Mauche of the University of California, Santa Cruz, has found evidence that Plains men captured women from Pueblo Indian villages to increase their numbers of wives. Remains of pottery made in the Plains using techniques associated with Pueblo culture track the movement of these Pueblo women into Plains groups. Cooperative work among many wives could double hide production and significantly increase a man's wealth and status, Habicht-Mauche contends.

The resources generated by captives allowed chiefs and aspiring leaders to sidestep reciprocal obligations to kin and to consolidate their social and economic power. In the Philippines, captive women produced food, textiles or pottery. Chiefs used the surplus goods to sponsor feasts that attracted warriors to follow and fight for them, thus growing their armies; would-be chiefs, meanwhile, traded the goods throughout Southeast Asia to build their wealth. The Conibo of Peru had a similar means of converting the surplus wealth generated by captives into power and status—namely, the "competitive feast." According to archaeologist Warren DeBoer of Queens College, C.U.N.Y., an authority on the Conibo, it was important for ambitious Conibo men to have multiple wives helping with the feast. Both traditional and captive wives farmed the staple manioc and brewed it into beer, the centerpiece of competitive feasts. The more wives a man had—and successful raids of the small villages upriver yielded a steady supply—the more beer his household produced. The more beer he could offer, the bigger the feast he could hold and the greater his standing. This dynamic appears to have deep roots: discoveries of first millennium pots for brewing, storing and drinking beer suggest that competitive feasting, and most likely the captive women who supported it, were common among the prehistoric ancestors of the Conibo and many other ancient societies.

Captives not only produced wealth, they literally embodied it. Virtually all the small-scale societies I studied gifted, traded or sold stolen people. As was true in the slavery system of the American South, low-status captives were high-status prestige goods and often the most valuable commodities men in small-scale societies owned. In the Northeast region of North America in the 17th and 18th centuries, indigenous groups used captives as gifts to create alliances or smooth over disputes. On the Northwest Coast, slaves were exchanged or sold from group to group, moving along well-established trade routes. In Colombia's Cauca Valley, the oldest known explorers' accounts, from the mid-1500s, describe slave markets—an institution that very likely predated European contact. In some parts of the world, slaves even functioned like money. In early medieval Ireland, for instance, the female slave was the highest unit of value and was used as a method of payment.

FROM TRIBE TO STATE

GIVEN THE IMPACTS of captives on the cultures they entered, I suspect they played an important role in one of the fundamental social transitions in human history: the formation of complex, state-level societies. University of Michigan archaeologist Norman Yoffee has argued that state-level societies did not emerge until socioeconomic and governmental positions were no longer linked to kinship. And most archaeologists and other social scientists agree that states were at least in part the result of a few people creating and controlling surplus goods. Captive taking helped early human groups meet both these conditions for the evolution of statehood. Captives were not the only factor in the formation of states, of course. They existed in many small-scale societies around the world without affecting this dramatic social change. But captives were (and still are) taken to bolster the social status of ambitious men and, in my view, gave some of these men the opportunity to accrue the quantities of wealth and power that must have been the foundation of early states.

If captive taking was involved in the formation of state-level societies, then we should expect to find signs of captives among the remains of early states. Exactly such evidence has come from one of the places that I have worked at in the American Southwest, New Mexico's Chaco Canyon. The Chaco polity existed from around A.D. 800 to 1250 and has been argued to be the only state-level society in the Southwest. Studies of human remains have revealed significantly more females in the surrounding area in the period during which Chaco was in power compared with when it was not. Burials from Chaco Canyon itself contained many women ages 15 to 25, the most common sex and age range for captives. In addition, a study of human remains from a Chaco-style great house near Chaco Canyon found women with evidence of healed head wounds and other trauma of the kind often associated with captives and other marginalized and abused people. Other evidence of violence in the Chaco region, as well as oral traditions among the modern-day descendants of the Chacoans, also attest to the presence of captives in Chaco.

Chaco is not the only example. Archaeologist Peter Robertshaw of California State University, San Bernardino, examined the development of two East African states, Bunyoro and Buganda, after the mid-15th century, in what is now western Uganda. He found that many of the women who worked in the banana or millet fields there had been captured and were treated as commodities. Demand for women's agricultural labor may have been the motor of sociopolitical evolution of these societies, Robertshaw suggested.

The notion that captives contributed to sociopolitical change that ultimately gave rise to the modern world does not in any way justify the egregious mistreatment of captives in ancient, historical or modern times. Three years after ISIS forces ravaged their homeland, some of the Yazidi women and children they enslaved have returned home. Thousands remain in captivity. I fervently hope that more Yazidi captives will be reunited with their families. Women in such situations through the millennia almost never had such hope. Archaeologists can, at least to some small degree, acknowledge and honor their plight by telling their stories.

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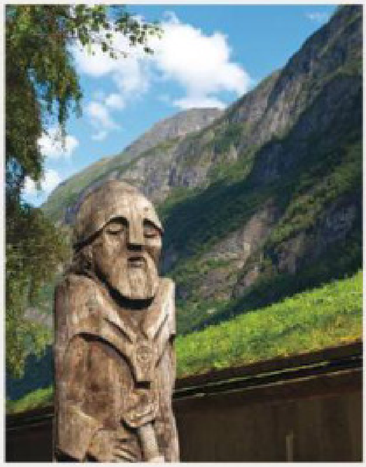
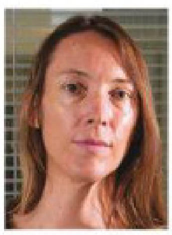
The Social Psychology of Modern Slavery. Kevin Bales; April 2002.

scientificamerican.com/magazine/sa



Ben Schumacher, Ph.D.

Dr. Benjamin Schumacher is Professor of Physics at Kenyon College, where he has taught for 20 years. He received his Ph.D. in Theoretical Physics from The University of Texas at Austin in 1990. Professor Schumacher is the author of numerous scientific papers and two books, including *Physics in Spacetime: An Introduction to Special Relativity*. As one of the founders of quantum information theory, he introduced the term qubit, invented quantum data compression (also known as Schumacher compression), and established several fundamental results about the information capacity of quantum systems. For his contributions, he won the 2002 Quantum Communication Award, the premier international prize in the field, and was named a Fellow of the American Physical Society. Besides working on quantum information theory, he has done physics research on black holes, thermodynamics, and statistical mechanics.



Tara Shears, Ph.D.

Dr. Tara Shears is an experimental particle physicist and Professor of Physics at the University of Liverpool. She received her Ph.D. in 1995 from the University of Cambridge, and spent the rest of that decade continuing to investigate the behavior of fundamental particles and forces with the OPAL experiment at CERN. Tara was awarded a Royal Society University Research fellowship with the University of Liverpool in 2000 to continue her research at the Collider Detector at Fermilab facility near Chicago. She joined the LHCb experiment at CERN's Large Hadron Collider in 2004, where she initiated a program of electroweak physics. She became an academic in 2007, and the first female professor of physics at Liverpool in 2012. Her current research focus is exploiting LHCb. She has appeared in press, radio, and film and given talks to a wide variety of audiences.

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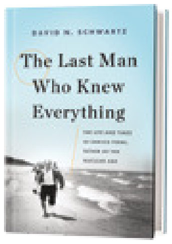
RECOMMENDED

By Andrea Gawrylewski

The Last Man Who Knew Everything:
The Life and Times of Enrico Fermi, Father of the Nuclear Age

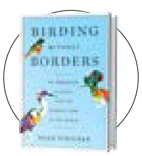
by David N. Schwartz. Basic Books, 2017 ($35)



No one can know everything, but Enrico Fermi might have known everything it was possible to know about physics, writer Schwartz suggests. The Italian-born physicist was a prodigy, unusually gifted at both experimental and theoretical work, and made breakthroughs in particle physics, astrophysics, nuclear physics, condensed matter physics, and more before his premature death at age 53 in 1954. Best known for his pivotal role on the Manhattan Project, he was prolific in his field. Among other achievements, he helped to develop statistical mechanics and discovered that some elements become radioactive when bombarded with neutrons, a breakthrough that won him the Nobel Prize in 1938. In this engrossing biography Schwartz delves into Fermi's childhood in Italy, his move to the U.S. to flee fascism and his ambivalent feelings about his role in inventing nuclear weapons. *—Clara Moskowitz*

Birding Without Borders:
An Obsession, a Quest, and the Biggest Year in the World

by Noah Strycker. Houghton Mifflin Harcourt, 2017 ($27)



Birds inhabit nearly every corner of the earth, occupying landscapes as diverse as barren tundra and lush rain forest. They can be as small as a bumblebee or as big as a pony. One recent estimate put the total number of bird species at 10,365. For serious birders, a major goal is to see as many of these species in a year as physically possible. They call it the "Big Year." Bird fanatic and journalist Strycker undertook this quest in 2015, setting out on a 40-country tour with hopes of spotting roughly half of the planet's known bird species (5,000) and crushing the previous Big Year record. Along the way he encountered the elusive and towering Harpy—a bird of prey with a seven-foot wingspan—and a glistening green Resplendent Quetzal, an endangered tropical bird with a three-foot streamer tail.

Exact Thinking in Demented Times:
The Vienna Circle and the Epic Quest for the Foundations of Science

by Karl Sigmund. Basic Books, 2017 ($32)

On Thursday evenings, from 1924 to 1936, in a University of Vienna lecture hall, mathematician Moritz Schlick would call to order an impressive meeting of minds. The "Vienna Circle" was formed after the First World War with the goal of rebuilding the foundations of math, science and philosophy. Sigmund, a mathematician who teaches inside the same university walls, gives a passionate and subtly humorous account of the group, which included such figures as mathematician Hans Hahn, philosopher Otto Neurath and logician Kurt Gödel. The circle became the center of a movement called logical empiricism and shaped modern scientific thinking, enduring in an anxiety-ridden Austria on the cusp of the Second World War. *—Yasemin Saplakoglu*

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

Outlawing War

Why "outcasting" works better than violence

By Michael Shermer

After binge-watching the 18-hour PBS documentary series *The Vietnam War,* by Ken Burns and Lynn Novick, I was left emotionally emptied and ethically exhausted from seeing politicians in the throes of deception, self-deception and the sunk-cost bias that resulted in a body count totaling more than three million dead North and South Vietnamese civilians and soldiers, along with more than 58,000 American troops. With historical perspective, it is now evident to all but delusional ideologues that the war was an utter waste of human lives, economic resources, political capital and moral reserves. By the end, I concluded that war should be outlawed.

In point of fact, war *was* outlawed … in 1928. Say what?

In their history of how this happened, *The Internationalists: How a Radical Plan to Outlaw War Remade the World* (Simon & Schuster, 2017), Yale University legal scholars Oona A. Hathaway and Scott J. Shapiro begin with the contorted legal machinations of lawyers, legislators and politicians in the 17th century that made war, in the words of Prussian military theorist Carl von Clausewitz, "the continuation of politics by other means." Those means included a license to kill other people, take their stuff and occupy their land. Legally. How?

In 1625 the renowned Dutch jurist Hugo Grotius penned a hundreds-page-long treatise originating with an earlier, similarly long legal justification for his country's capture of the Portuguese merchant ship *Santa Catarina* when those two countries were in conflict over trading routes. In short, *The Law of War and Peace* argued that if individuals have rights that can be defended through courts, then nations have rights that can be defended through war because there was no world court.

As a consequence, nations have felt at liberty for four centuries to justify their bellicosity through "war manifestos," legal statements outlining their "just causes" for "just wars." Hathaway and Shapiro compiled more than 400 such documents into a database on which they conducted a content analysis. The most common rationalizations for war were self-defense (69 percent); enforcing treaty obligations (47 percent); compensation for tortious injuries (42 percent); violations of the laws of war or law of nations (35 percent); stopping those who would disrupt the balance of power (33 percent); and protection of trade interests (19 percent). These war manifestos are, in short, an exercise in motivated reasoning employing the confirmation bias, the hindsight bias and other cognitive heuristics to justify a predetermined end. Instead of "I came, I saw, I conquered," these declarations read more like "I was just standing there minding my own business when he threatened me. I had to defend myself by attacking him." The problem with this arrangement is obvious. Call it the moralization bias: the belief that our cause is moral and just and that anyone who disagrees is not just wrong but immoral.

In 1917, with the carnage of the First World War evident to all, a Chicago corporate lawyer named Salmon Levinson reasoned, "We should have, not as now, laws of war, but laws against war; just as there are no laws of murder or of poisoning, but laws against them." With the championing of philosopher John Dewey and support of Foreign Minister Aristide Briand of France, Foreign Minister Gustav Stresemann of Germany and U.S. Secretary of State Frank B. Kellogg, Levinson's dream of war outlawry came to fruition with the General Pact for the Renunciation of War (otherwise known as the Peace Pact or the Kellogg-Briand Pact), signed in Paris in 1928. War was outlawed.

Given the number of wars since, what happened? The moralization bias was dialed up to 11, of course, but there was also a lack of enforcement. That began to change after the ruinous Second World War, when the concept of "outcasting" took hold, the most common example being economic sanctions. "Instead of doing something *to* the rule breakers, Hathaway and Shapiro explain, "outcasters refuse to do something *with* the rule breakers." This principle of exclusion doesn't always work (Cuba, Russia), but sometimes it does (Turkey, Iran), and it is almost always better than war. The result, the researchers show, is that "interstate war has declined precipitously, and conquests have almost completely disappeared."

Outcasting has yet to work with North Korea. But as tempting as a military response may be to some, given that country's geography we might heed the words from Pete Seeger's Vietnam War protest song: "We were waist deep in the Big Muddy/The big fool says to push on." We know how that worked out. SA

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Illustration by Izhar Cohen

Steve Mirsky has been writing the Anti Gravity column since a typical tectonic plate was about 36 inches from its current location. He also hosts the *Scientific American* podcast Science Talk.

Squirrels That Chunk

Smart cookies remember their buried treasure

By Steve Mirsky

Faculty members of the University of California, Berkeley, have received 22 Nobel Prizes. But some of the most impressive displays of intelligence in recent years on the Berkeley campus have been made by squirrels.

"I dedicated seven years of my life to squirrels," said the also cerebral Mikel Delgado when I spoke to her in September, the month after she'd completed her doctorate at Berkeley. (She's now a postdoc at the University of California, Davis.) She and her mentor Lucia Jacobs had just published their most recent study on cognition in the furry acrobats in the journal *Royal Society Open Science*. They wanted to know how fox squirrels keep track of their nuts.

"Fox squirrels are obligate scatter hoarders," Delgado explained by phone. "And that means they store every nut in a different location. So my research has been focused on the cognitive strategies that they might be using to help them find their nuts later." After all, squirrels can't use direct-mailing lists to keep track of the nuts that sustain them the way that, say, vein-popping conspiracy-purveying radio hosts can.

But back to intelligent beings. Delgado and Jacobs thought that the squirrels—just one of which can bury up to 10,000 nuts annually, many of which they do go back and find—might be using a cognitive strategy known as chunking.

"I think about chunking as any shortcutting strategy or mnemonic device that would allow an animal, be it human or otherwise, to increase its memory capacity and improve recall," Delgado said. Perhaps the best-known example of human chunking is how we remember telephone numbers: the three-digit area code, three-digit exchange (the ubiquitous movie *555*) and four-digit line number. With just three items, instead of 10, to remember, you can use your brain's express lane. "In this study, I wanted to know if squirrels would basically arrange their nuts in a way making it more convenient for them to remember where nuts were stored."

The researchers recruited 45 campus squirrels for this investigation. Although informed consent was not formally acquired, the subjects were compensated with almonds, hazelnuts, pecans and walnuts, all in shells. Which, conveniently, was also the necessary first step in tracking what they then did with the booty.

In one version of the trial, a human gave a squirrel an almond, for example, after which other humans tracked the squirrel to record where it buried said comestible. The squirrel was then coaxed back to the nut dispenser (playing the role of a high-quality tree), who handed out another almond. After acquiring four almonds, the squirrel would get four of another nut type. This setup was called the clustered condition. That's right: nut clusters.

Delgado referred to the second variation as the random, or "confuse a squirrel," condition. The squirrels, unlike congressional districts, never got two in a row of the same kind of nut.

Two other trials had the squirrel nut schleppers get four consecutive or random-order nuts, but wherever a squirrel performed its burial rights was where it received its next payout.

And regardless of the order of the nuts (also the rumored name of a new alt-right honor society), when squirrels got their supplies from the central location, they did indeed spatially chunk. Squirrels can evaluate nuts for weight and quality, and they thus buried all the nutritionally rich walnuts near one another, all the lesser-value almonds near one another, and so on. But when they got a nut where they'd just buried one, they didn't chunk. "In a very wooded area," Delgado said, "you have many choices about where to forage, and so there would be times where it would be more efficient for squirrels to search closer to where they currently were." Or they may have hit their cognitive limit, although this study didn't tackle that issue, and squirrels I consulted had no comment.

Delgado's finding adds to the literature of animal intelligence—and to her appreciation of squirrels. "For a lot of people, they're really one of the few interactions we have with animals. And so I think they're a really good gateway animal to get people interested in animal behavior," she said. "Squirrels are busy at work right under your nose, and they're doing really cool things."

Of course, any perspicacious viewer of *Rocky and Bullwinkle* knew that the squirrel was the brains of the outfit. SA

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Illustration by Matt Collins

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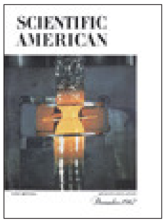

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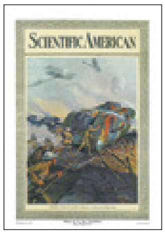


1917

1867

1967 X-ray Stars

"In the five years since Scorpius X-I was discovered a total of about 30 X-ray stars, or at least sources of X radiation, have been detected in rocket surveys. A general, diffuse background of X rays in space has also been observed. About a dozen rockets have been flown on these missions, and the total observing time so far adds up to only one hour (five minutes being available in each flight). Technical means and devices that are just over the horizon will soon enable us to study the X-ray stars in much greater detail. For one thing, before long the instruments will be installed in satellites rather than in short-lived rockets. —Riccardo Giacconi"

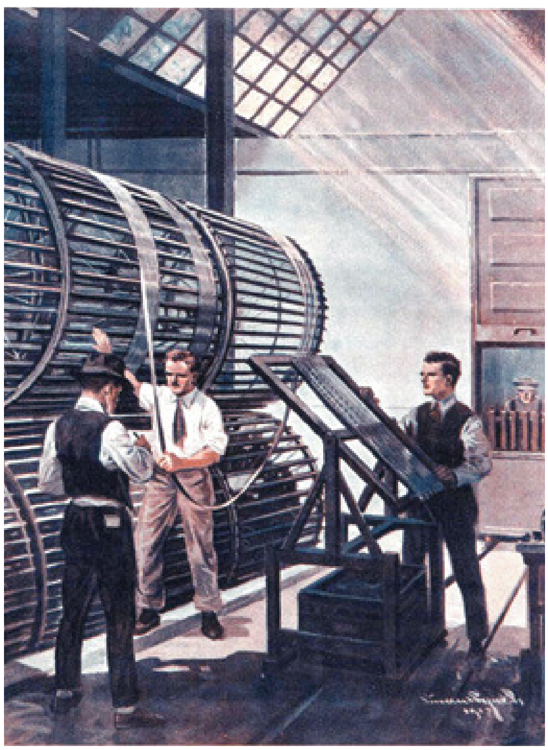
Giacconi was a co-winner of the 2002 Nobel Prize in Physics.

Bacterial Resistance

"Until recently it was assumed that the appearance of drug-resistant bacteria was the result of a predictable process: the spontaneous mutation of a bacterium to drug resistance and the selective multiplication of the resistant strain in the presence of the drug. In actuality a more ominous phenomenon is at work. It is called infectious drug resistance, and it is a process whereby the genetic determinants of resistance to a number of drugs are transferred together and at one stroke from a resistant bacterial strain to another bacterial strain, of the same species or a different species, that was previously drug-sensitive, or susceptible to the drug's effect. Since its discovery in Japan in 1959 it has been detected in many countries."

1917 Film for Movies

"A grain of dust, a slight variation in a chemical solution, an impure water supply, an otherwise insignificant fluctuation in the voltage of the current supply of the printing lamps, a trifling rise or fall in the temperature, an inconsiderable shrinkage of the film—all these factors can mark the difference between a clean, clear and steady picture on the motion-picture screen and a spotty, indistinct, and jumpy film unfit for use. Which means that once the film leaves the camera, the work of the actors, director and cameraman is entirely in the hands of the laboratory staff. Our color image shows the celluloid strips after they are sent to the drying room. Here they are wound on huge wood or metal drums which are revolved at a fair speed."



1917: Motion-picture film—most likely for black-and-white movies—during the developing process being dried on large drums.

SCIENTIFIC AMERICAN, VOL. CXVII, NO. 23; DECEMBER 8, 1917

1867 Caribbean Tsunami

"'Sir: I have to state, with deep regret, that the United States steamship *Monongahela,* under my command, is now lying on the beach in front of the town of Frederickstadt, St. Croix, where she was thrown by the most fearful earthquake ever known here. The first indication we had of the earthquake was a violent trembling of the ship, resembling the blowing off of steam. This lasted some 30 seconds, and immediately afterward the water was observed to be receding rapidly from the beach. When the sea returned, in the form of a wall of water 25 or 30 feet high, it carried us over the warehouses into the first street of the town. This wave in receding took her back toward the beach, and left her nearly perpendicular on the edge of a coral reef. Providentially only four men were lost.' —S. B. Bissell, Commodore Commanding"

The U.S.S. Monongahela, *a 2,078-ton steam-powered, propeller-driven sloop, was refloated six months later.*

Wouldn't It Be Luvverly?

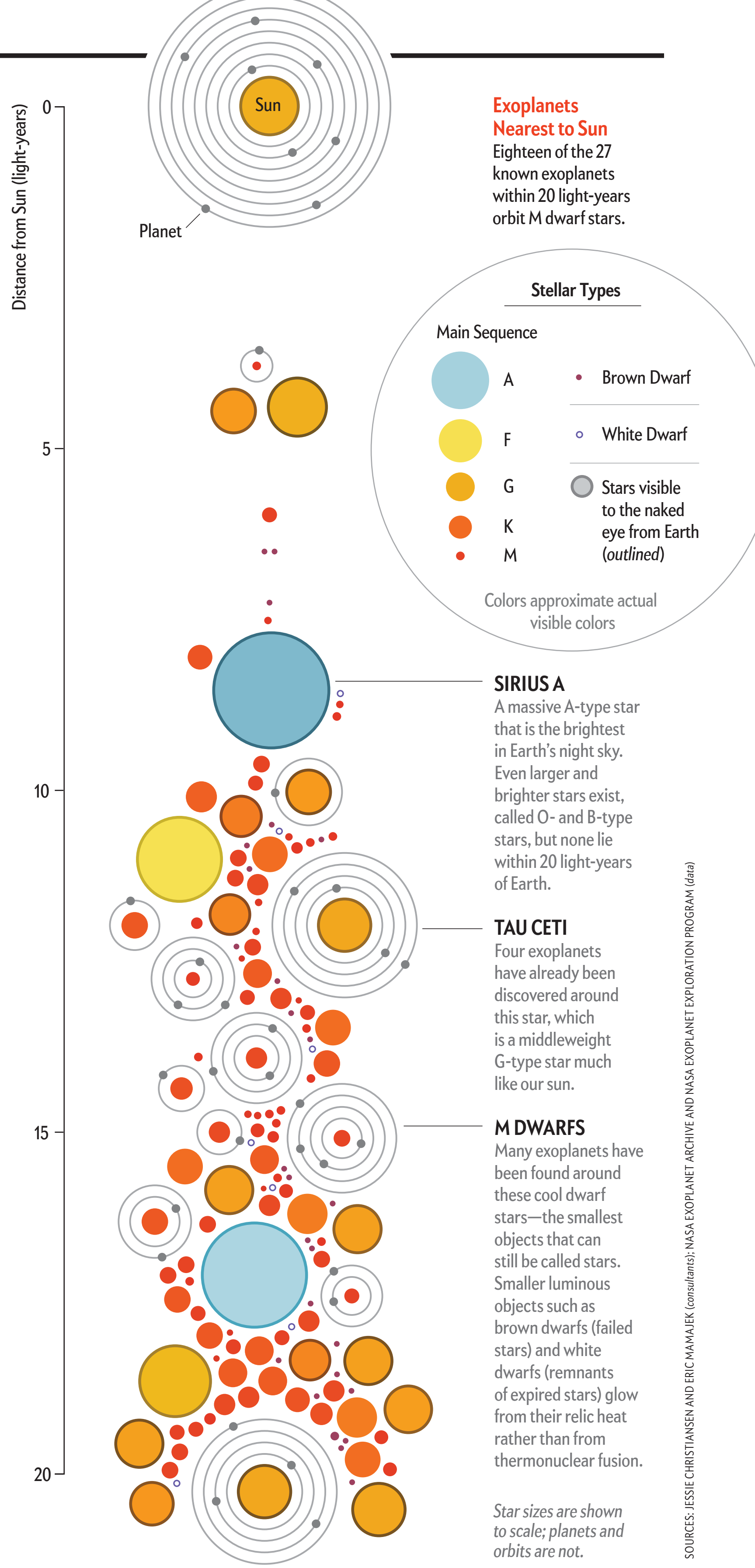
"Riding downtown these cold mornings in the horse cars, the unpleasant sensation of chilled feet reminds us of the plan adopted in France to keep the feet of car passengers warm. This is accomplished by inserting a flattened iron tube along the bottom of the car. When the car leaves the depot, this tube is filled with hot water from a boiler kept heated for the purpose. This water retains heat, generally, for about two hours. We would be glad to see this plan introduced here. But it is not to be expected that our city railroad companies will do anything for the comfort of their passengers, while without such trouble they continue to reap rich harvests. Very likely the idea of loading a lot of hot water upon their cars for passengers to stand upon, would strike them as a good joke. Their poor, broken down, spavined horses, could not stand any additional load."

Text by Lee Billings | Graphic by Nadieh Bremer

Meet the Neighbors

Most of the alien worlds closest to our own are found around the smallest, dimmest nearby stars

Astronomers know of more than 3,500 exoplanets—worlds orbiting stars other than our sun—and will probably find thousands more in the next few years. Some of these newfound worlds will resemble our own planet in size, composition and temperature. Yet many of these potential "mirror Earths" will be alien in one respect: they will orbit red dwarfs, also known as M dwarfs, rather than sunlike stars. M dwarfs are the universe's smallest, coolest stars, but they are also the hottest sites for exoplanet discovery, largely because of their sheer abundance. Although none are visible to the naked eye, they make up more than half of the 140 known stars within 20 light-years of the sun and harbor two thirds of the known exoplanets in that region (*graphic*). Even though M dwarfs are cool stars, planets orbiting close to them would be warm. Earth-like or not, these alien worlds are destined to become the ones we know best.



Worlds Far, Far Away

Projects such as NASA's Transiting Exoplanet Survey Satellite (TESS) are scouting far beyond the sun's neighborhood for other worlds. Slated to launch in March 2018, TESS will survey the entire sky, with a focus on 2.5 million target stars. M dwarfs constitute one fifth of this sample. Because TESS's sensitivity to small, rocky planets is highest for worlds in close orbits around small stars, most of the potentially habitable worlds it finds are likely to come from M dwarfs.