APOLLO 11 50 years SPECIAL REPORT

ANNIVERSARY OF APOLLO 11 | *THE PAST AND FUTURE OF HUMANS ON THE MOON* PAGE 50

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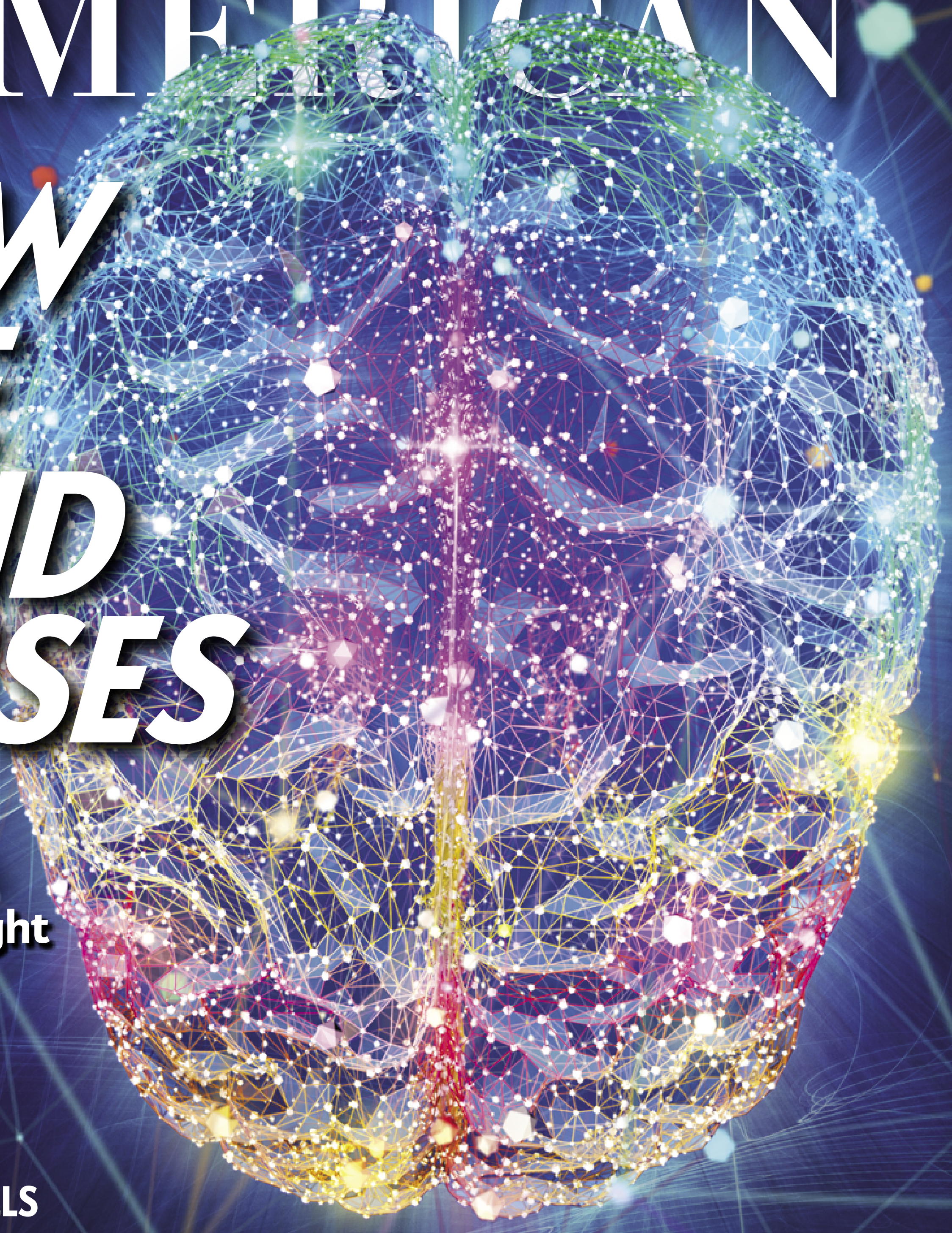


HOW THE MIND ARISES

Network interactions in the brain create thought

PLUS

INVINCIBLE CELLS

Synthetic cells that are impervious to virus attacks PAGE 34

DISASTER IN MADAGASCAR

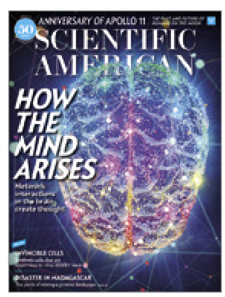
The perils of mining a pristine landscape PAGE 42

JULY 2019
ScientificAmerican.com

JULY 2019

VOLUME 321, NUMBER 1

SCIENTIFIC AMERICAN



ON THE COVER

The frenzied buzzing of networks scattered across the brain somehow produces our ability to sense, think and act. Network neuroscientists are now using sophisticated mathematical tools to model the ungraspable complexity by which the activation of the brain's 100 trillion connections produces what we call the mind. Illustration by Mark Ross Studios.

Photograph by Chris Gunn

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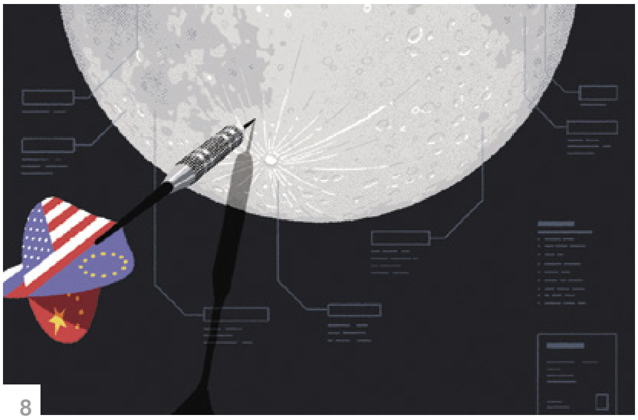
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ON THE WEB

Apollo, 50 Years On
An interactive video and photo album commemorates the 50th anniversary of the *Apollo 11* lunar landing.
Go to www.ScientificAmerican.com/jul2019/apollo-50

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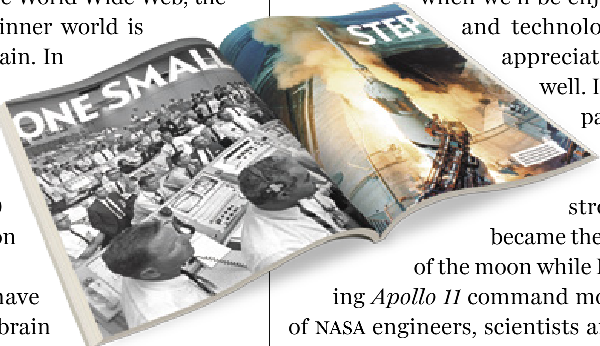
Mariette DiChristina is editor in chief of *Scientific American.* Follow her on Twitter @mdichristina

A Symphony of Science

We live in a world of networks, write University of Pennsylvania physicist and MacArthur Fellow Danielle S. Bassett and Max Bertolero of Bassett's Complex Systems Group in this issue. Consider the interstate highway system, the World Wide Web, the power grid, to name just a few. Our inner world is also networked—specifically, in the brain. In their article, "How Matter Becomes Mind," the authors describe how "what the brain is—and thus who we are as conscious beings—is, in fact, defined by a sprawling network of 100 billion neurons with at least 100 trillion connecting points, or synapses."



Until recently, neuroscientists have looked at the different regions of the brain in relative isolation. Just as an orchestra requires all instruments to play together, Bassett and Bertolero note that "living brains are massive orchestras of neurons that fire together in quite specific patterns." Researchers studying these networks could lead to a clearer picture of cognitive functioning, better diagnoses for psychiatric diseases and new therapeutics. To learn more about them, an allegro tempo to page 26 might be in order.

As I write, unfortunate outbreaks of measles are occurring in several areas of the U.S. and other places where people have chosen not to vaccinate out of misplaced health fears. By training immune systems, however, vaccines have the means to prevent illness as one of the most remarkable and far-reaching medical benefits humanity has ever seen. But what if, asks journalist Rowan Jacobsen, we could create virus-proof cells? Turn to "The Invulnerable Cell," on page 34.

Advances in discoveries often draw our attention to a time when we'll be enjoying the next fruits of science and technology. But there's great value in appreciating the lessons of the past as well. In our special report, starting on page 50, we do just that as we take "One Small Step Back in Time." Half a century ago Neil Armstrong and Edwin "Buzz" Aldrin became the first humans to visit the surface of the moon while Michael Collins piloted the orbiting *Apollo 11* command module—supported by thousands of NASA engineers, scientists and mission controllers back on Earth. Back then, I remember thinking it would be no time at all before we moved on to Mars and beyond. Yet nobody has returned to the lunar surface since the last astronaut left in 1972. The Apollo missions demonstrated the power of big dreams to motivate and unify a nation amid social and political strife. Today we face other challenges. But perhaps, inspired by this past triumph, we might again summon the will to create for ourselves a better, more hopeful future. SA

SCIENTIFIC AMERICAN

Illustration by Nick Higgins

March 2019

> **"Everyday observations strongly support that animals experience emotions similarly to humans."**
> RICHARD FRENKEL *SWAMPSCOTT, MASS.*

CONSPIRACY DRIVERS

Melinda Wenner Moyer's article on "Why We Believe Conspiracy Theories" took me back about a decade to when I was a member of a team of HIV/AIDS researchers and activists battling the denialists who variously argued that HIV did not exist, was not the cause of AIDS or was created in government laboratories for evil purposes. At that time, AIDS denialists influenced national policies on HIV/AIDS in South Africa, costing an estimate of more than 300,000 lives, and manipulated vulnerable individuals worldwide to make health-threatening choices.

Much of what Moyer describes resonates with my experiences (such as threats and smears regularly sent to my university's administration or me) and the collective strategies employed by my colleagues and me. We, too, found that most of the more prominent HIV/AID denialists were also members of other conspiracy groups, whether health-related or more generally.

This link was a weakness we could exploit, particularly for those with academic connections: our pointing out to universities that a faculty member published on, say, the existence of the Loch Ness Monster or how the U.S. faked the moon landing helped to erode that person's intramural credibility while having a positive effect on individuals who believed they were receiving expert advice. And we could reason with and better educate such at-risk people, something that was utterly unproductive with the hard-core naysayers.

The AIDS denialists are still around. Their damaging effects have diminished in recent years, but many of them are now active in the "anti-vaxxer" movement, peddling the lies that compromise vaccine uptake by a significant number of people, with adverse public health outcomes that are all too apparent. Publicly naming and shaming these conspiracy theorists for who and what they really are—and what they also believe—can be an effective tactic. The gloves should come well and truly off.

JOHN P. MOORE *Weill Cornell Medicine and* SCIENTIFIC AMERICAN*'s board of advisers*

No writer on the topic of conspiracy theories can afford to overlook the remarkable 1964 essay "The Paranoid Style in American Politics," by Richard Hofstadter, one of the great scholars of American history, who was active during the 1940s to 1960s. It has been reprinted many times and is currently available on the Internet. Hofstadter traces the recurrent waves of political paranoia in American society going back to the 18th century, listing the targets of those waves, the similarities in how certain groups have responded to those perceived threats, and the important differences between normal fears and concerns and what he terms the "paranoid style." His analysis clearly parallels that proposed in Moyer's article. The targets have changed over the years, but the story and the style of its telling have not.

SYDNEY RUTH KEEGAN *Port Hadlock, Wash.*

Moyer notes that the perceived powerlessness in the face of real and imagined social forces creates susceptibility to conspiracy theories. Many believers in such theories were driven into economic insecurity, despite years of hard work in often highly skilled occupations that did not require college degrees. People who are financially secure and who have an education conducive to seeking out and evaluating evidence are less vulnerable to such notions.

JEFF FREEMAN *Rahway, N.J.*

SHARED FEELINGS

In "The Orca's Sorrow," Barbara J. King presents accumulated observations that suggest that animals grieve. Everyday observations strongly support that animals experience emotions similarly to humans. The reverse would be quite surprising because it would somehow call for the evolution of emotions strictly or separately in our species. Emotions are a key driver of behavior and clearly have deep and adaptive evolutionary roots. Occam's razor and sound science place the burden of proof on those who deny animals have them. A corollary is that cruelty to animals is as intolerable as cruelty to our fellow humans.

RICHARD FRENKEL *Swampscott, Mass.*

KING REPLIES: Emotions have indeed evolved widely in the animal kingdom to guide behavior. Yet denial of this cross-species similarity still happens routinely: In my article, I describe how the orca Tahlequah carried her dead calf for 17 days. In the Guardian, *zoological writer and consultant Jules Howard writes that classifying her behavior as grief means "making a case that rests on faith not on scientific endeavour." Howard has it precisely backward, though; it's good science to recognize visible evidence of animal emotion and of evolutionary continuity. We owe it to animals to see them for who they are.*

MANIA FOR CLASSIFICATION

In "The Undiscovered Illness," Simon Makin states that unipolar mania—mania that does not occur alongside depressive episodes—is not listed as a "distinct and unalloyed condition" in diagnostic systems. But that does not mean it is neglected everywhere. The diagnosis features in clinical practice, perhaps most commonly in countries where formal classification systems, such as the *Diagnostic and Statistical Manual of Mental Disorders* (*DSM*), are used as intended—as general guides rather than checkbox tools.

As a psychiatrist familiar with the *DSM* but not compelled to use it, I used to be annoyed whenever I saw it described as "the psychiatrist's bible." On reflection, though, that is quite a good description because in practice, some psychiatrists (chiefly in the U.S.) consult the *DSM* commonly, others ignore it completely and a great majority draw on it selectively, focusing on the parts that make sense to them and completely ignoring large sections that do not.

Brendan Kelly *Trinity College Dublin*

DECIDING WEATHER

Based on personal experience of the threat of Hurricanes Florence and Michael, Zeynep Tufekci argues in "Big Data and Small Decisions" [The Intersection] that when one is presented with a deluge of data, even a simple binary choice (stay or go, in her case) can be difficult. Unable to make a data-driven decision, she notes that she followed the advice of her neighbors.

Another way to frame this dilemma would be through the decision-making framework proposed by David Snowden, formerly at IBM and now at Cognitive Edge. Rather than ponder "What to do?" he essentially suggested we ask, "What kind of problem is this?"

Some well-structured problems are complicated, with cause and effect reasonably clear, so decision-making may call for experts who can sort through enormous data sets (the domain of "good practice"). But problems where cause and effect are nonlinear and nonproportional and where elements are volatile, uncertain, complex and ambiguous (VUCA) are in the domain of "emergence." An example is a hurricane scenario akin to Tufekci's, for which crowdsourcing via neighbors who, it is hoped, have more knowledge and practical wisdom of the area may be a reasonable way to make the choice of staying or leaving.

Larry M. Starr *Director, Doctor of Management in Strategic Leadership program and Doctor of Philosophy in Complex Systems Leadership program, Thomas Jefferson University*

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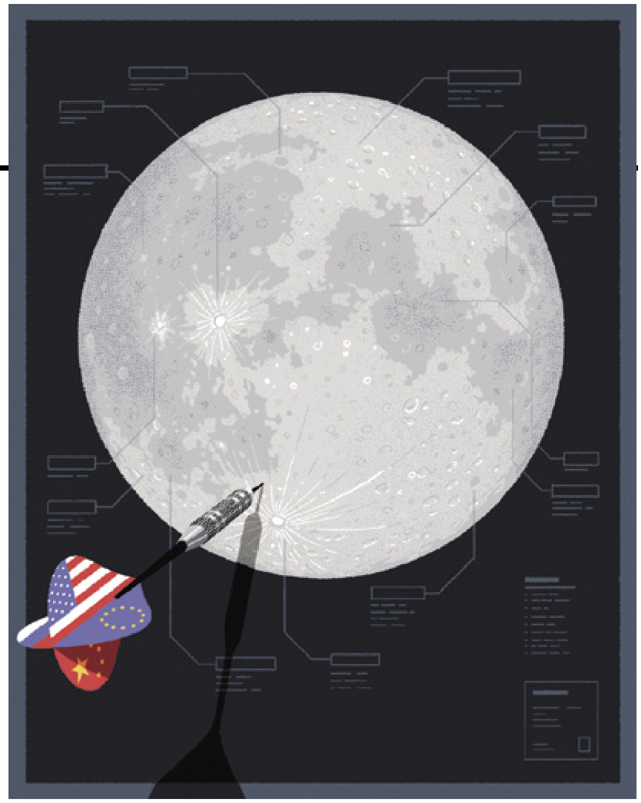
MAGA on the Moon

Do not make the U.S.'s lunar return an international clash

By the Editors



Just in time for the half-century anniversary of the *Apollo 11* lunar landing [see our special report, starting on page 50], the White House has declared the U.S. is going back to the moon within the next five years. "The first woman and the next man on the moon will both be American astronauts, launched by American rockets, from American soil," said Vice President Mike Pence during remarks in late March at the U.S. Space & Rocket Center in Huntsville, Ala.

There are reasons to be skeptical. Chief among them is the potential for Congress to balk at funding what some might consider a political stunt. According to the Trump administration, however, the urgency borders on being existential: China is now poised to "seize the lunar strategic high ground and become the world's preeminent spacefaring nation," Pence said. But such a jingoistic stance carries risks of its own, possibly isolating the U.S. from international collaborations in otherworldly exploration.

China has already achieved a first by landing a rover on the moon's far side this past January. And later this year it is set to conduct its first robotic lunar sample-return mission. Zhang Kejian, head of China's national space agency, confirmed in April that these missions are precursors to human landings perhaps a decade hence. Such missions could support China's plans for a research station near the lunar south pole to study resources such as water ice, which can be used to manufacture rocket fuel, potable water and breathable air. The fear in the White House, it seems, is that China will lay claim to the lunar pole and prevent the U.S. and others from operating there. (This action is essentially prohibited under the United Nations Outer Space Treaty of 1967, to which both China and the U.S. are signatories.)

There are good reasons to treat China as an adversary in space, but these moon plans are not among them. China's use of antisatellite missiles and spacecraft does pose significant threats to strategic U.S. assets (while mirroring decades of similar efforts by the U.S. and Russia). Such concerns do not require framing NASA's planned lunar return as part of a warlike conflict with China. As the crown jewel of the U.S. civil space program, the agency is ostensibly devoted to science and exploration instead of national defense. Although it emerged from the cold war–fueled space race of the late 1950s, NASA has more recently been defined by collaboration, not competition—most notably, in its partnerships with Russia and other nations on the International Space Station, which has served for decades to defuse geopolitical tensions.

The U.S. and China are not the only spacefaring nations with ambitious plans for lunar missions—plans that rely on varying degrees of international collaboration. Europe—a key partner in NASA's exploration efforts—is leading the push for a multinational "Moon Village" and is working with Russia on a lander. India also intends to put a lander and rover (along with a NASA-built instrument) at the lunar south pole. Japan, a regular U.S. partner in space science, is pursuing a lunar lander as well. Israel has already made one landing attempt with help from NASA's deep-space communications network and may soon make another. In the context of a return to the moon, a similar degree of cooperation with China would be valuable—except that Congress has placed severe restrictions on NASA's ability to collaborate with the Chinese.

Sending NASA to the moon to beat China would not be the first time the administration has sought to extend President Donald Trump's signature "Make America Great Again" mantra into outer space. Trump has previously vowed to aggressively develop space-based missile defense systems and to create a "Space Force" as a sixth branch of the U.S. military. Both proposals have been framed as part of an unfolding clash of civilizations in which the U.S. and its allies must act decisively in space to overcome China and other adversaries, such as Russia and North Korea.

In the long term, however, this stance will most likely be self-defeating because it reinforces the impression, eagerly promulgated by China and Russia, that the biggest threat to the peaceful use of outer space is really the U.S. To ensure that our nation's values are enshrined in space governance, the White House and Congress must together reduce needless barriers to engagement with China and other competitors, ideally through reinvigorated U.S. diplomacy within the framework of existing U.N. treaties and committees. Collaboration, not conflict, is the sustainable path forward to the moon.

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Illustration by Matt Harrison Clough

Jonathan N. Stea is a registered and practicing clinical psychologist in Calgary.

Can Cannabis Fix the Opioid Crisis?

Not alone, but it could be part of the solution

By Jonathan N. Stea

Cannabis has been hailed as a potential magic bullet in the fight against all sorts of ills, including chronic pain and depression. But it has also been called the "devil's lettuce," with claims that using it will lead to laziness, insanity and even murder. These polarized views can, in part, be explained by the drug's complexity: cannabis is not a single substance but rather a mixture of more than 500 individual chemicals whose proportions vary from one plant strain to another.

Because cannabis is such a complicated chemical soup, until recently most often prepared for the black market, it has been difficult to draw clear research conclusions about whether the substance harms or helps. This assessment is particularly true in the area of addiction and mental health, where advocates believe that the drug could be the white knight of the opioid epidemic.

Some U.S. states—New York, New Jersey and Pennsylvania—have followed the lead of such advocates and explicitly approved medical cannabis as a treatment for opioid addiction. But critics of these policy decisions have argued there is not yet enough evidence to support and promote cannabis as an effective panacea. And the critics are correct: there have been no randomized controlled trials—the gold standard for testing drug effects—that have evaluated cannabis specifically for treating opioid addiction.

Further, as argued by Keith Humphreys of Stanford University and Richard Saitz of Boston University in *JAMA,* substituting cannabis for opioid addiction therapies could be harmful because it would displace already established treatments, such as methadone and buprenorphine—which could be life-threatening. At this time, offering cannabis as a treatment for opioid addiction is not consistent with the practice of evidence-based medicine.

But such evidence is beginning to emerge. A recent review in *Cannabis and Cannabinoid Research,* for example, shows that cannabis might be able to help with the treatment of opioid symptoms such as withdrawal and cravings. The reason: biologically, the receptor systems in the brain that allow cannabis and opioids to affect us are closely related. If the goal of treatment is to reduce harm, then it makes intuitive sense to offer cannabis in the hope that opioid use will decrease. Cannabis is less dangerous than illicit opioids to both the individual and society at large. While there is a small chance that substituting a less harmful drug for a more harmful one could simply lead to a new addiction, this approach might well be a risk worth taking.

One issue complicates the equation: it's unclear if cannabis can help people who experience opioid addiction *and* chronic pain. Whereas fewer than 8 percent of pain patients become addicted to opioids, people addicted to opioids have higher rates of chronic pain as compared with the general population. The effectiveness of cannabis for pain management is by no means proved: research on this question so far is relatively weak—but that could be said for most work on a drug scientists have been discouraged from studying by the government. The case is by no means closed.

So will cannabis be the cure for the opioid crisis? Not by itself, clearly: the crisis is a multilayered and multicausal problem that demands a multipronged solution. Because opioid addiction develops as the result of many interacting biological, psychological and social factors, effective treatment modalities are needed at each level of analysis. This complexity suggests an approach that incorporates evidence-based psychological and pharmacological treatments, coupled with a system that allows people easy access, whether through family physicians, emergency departments, pain-treatment centers, safe injection sites, or outpatient and residential programs.

Despite the hype, it is absurd to think cannabis can be a remedy for all aspects of the human condition. There is, however, good reason to believe that future research will support a helpful role for it in the treatment of opioid addiction. But we are not there yet. This kind of work, especially in the form of randomized controlled trials, is sorely lacking and urgently needed. Such research should be aggressively pursued so we can say with better certainty whether cannabis belongs in the evidence-based tool kit in the fight against opioid addiction.

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Illustration by Jialun Deng

ADVANCES

New evidence suggests the Dead Sea harbored ancient bacterial life in its sediments.

GETTY IMAGES

MICROBIOLOGY

Dead Sea Life

Evidence of ancient bacteria in the lake's sediments may point to past life on Mars

The Dead Sea is not all dead. Sure, it is one of the most extreme ecosystems on our planet, with a salinity so high that tourists can easily float atop its dense, briny brew. And with no plants, fish or other visible life, swimmers can be excused for assuming that nothing stirs in the deep. But long ago scientists discovered single-celled microorganisms called archaea living in the lake's waters—causing many to wonder whether other simple life could also survive within the sediments below despite the absence of oxygen, light or nutrients.

Now Camille Thomas, a geomicrobiologist at the University of Geneva, and his colleagues have unearthed molecular fossils in Dead Sea sediments that suggest bacteria lived there as recently as 12,000 years ago. It is the first time scientists have discovered a life-form other than archaea in this ecosystem—which hints that such life might exist (or have existed in the past) in similar places across the globe and elsewhere in the solar system, including Mars. The results were published in March in *Geology.*

Thomas and his colleagues were part of an international collaboration that in 2010 drilled 430 meters below the lake bed in an unprecedented opportunity to better assess our climate's past. After several years of analyzing the samples, Thomas's team found archaea buried within the sediment. It was proof that these organisms could survive both within the lake itself and in the sediment below, where conditions are even more hostile. But Thomas still thought it was unlikely that anything other than archaea could survive there. "I was thinking, 'It's an extreme environment, and it's only for the extreme guys,'" he says.

The team's most recent finding upends that notion. Thomas and his colleagues analyzed layers of gypsum (a mineral left behind when saltwater evaporates) that were deposited 12,000, 85,000 and 120,000 years ago. Entombed within them, they discovered wax esters—energy-rich molecules that small organisms create and store when food becomes scarce. Because archaea cannot produce these molecules, and multicellular organisms are very unlikely to survive such hostile conditions, the team concludes that ancient bacteria must have produced the compounds.

But how did these bacteria survive? The wax esters carried traces of archaea cell membranes, so the researchers hypothesize that the bacteria scavenged remains of archaea. That survival mechanism would explain how the community managed to thrive in such seemingly desolate conditions. "Although we know there's a ton of diversity in the microbial biomass, it's always exciting to see what strategies these microbial communities use to survive in different environments," says Yuki Weber, a biochemist at Harvard University, who was not involved in the study. "There's still a lot that has to be learned about the microbial metabolism."

Furthermore, Thomas and his colleagues found tantalizing hints that bacterial life may exist in the Dead Sea ecosystem even today. When they first opened a large vial of contemporary sediments, for example, they smelled rotten eggs—a telltale sign of hydrogen sulfide gas, which is often produced by bacteria. But the gas can also have a nonbiological origin, such as geothermal activity (for which Yellowstone National Park is famous), so the researchers are not certain that bacteria continue to reside below the salty lake.

Even if they do not, bacteria most likely live in similar conditions across Earth's vast underground biosphere, Weber argues. And as scientists continue charting the extreme environments in which life can survive, they will better understand how and where it arises on Earth and other planets, he says.

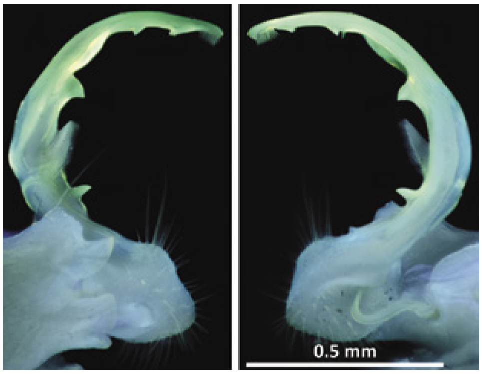
Take Mars—in 2011 NASA's Opportunity rover stumbled on gypsum, the same mineral that Thomas found in the Dead Sea sediments. Its presence suggests that as the Red Planet warmed, its oceans and lakes evaporated. But before they did, these bodies of water probably would have looked a lot like the Dead Sea—maybe even down to the biological processes, says Tomaso Bontognali, a scientist at the Space Exploration Institute in Switzerland, who was not involved in the Dead Sea study. Bontognali works on the European Space Agency's ExoMars rover, which is set to land in 2021 in an ancient ocean bed on Mars. It will analyze sediment cores with a simplified version of the method used by Thomas's team. The Dead Sea evidence "makes the hypothesis that life may have existed on Mars more plausible," Bontognali says. *—Shannon Hall*

ANIMAL PHYSIOLOGY

Glimmering Gonopods

Millipedes' genitalia fluoresce under ultraviolet light

Millipedes are hard to tell apart. Different species of the many-legged creatures often share the same dull colors and tend to blend in with the gloom of the forest floor. But under ultraviolet light, some millipedes display a striking characteristic: their genitals glow brightly.



Genitals of the millipede *Pseudopolydesmus caddo* glow brightly in UV light.

Stephanie Ware, a research assistant at Chicago's Field Museum, and her colleagues have used this strange fluorescence to help identify the leggy arthropods. Ware rigged up a camera with inexpensive UV flashlights to capture images of millipedes' glimmering "gonopods," specialized appendages used for copulation. The camera took multiple pictures that Ware stitched together to create a composite image. In visible-light photographs, "it's really hard to pick out different structures" on the millipedes, she says. "But under UV, there were different patterns and colors that made them really pop out."

This technique makes it easier to distinguish between similar-looking species, according to Petra Sierwald, a zoologist at the Field Museum. She and Ware and their colleagues co-authored a study on the topic, published online in April in the *Zoological Journal of the Linnean Society.* Using the UV technique, the researchers identified eight species—which had previously been miscategorized as 12—within the North American genus *Pseudopolydesmus.* Sierwald says this kind of imaging could have applications in soil science and conservation, helping researchers quickly assess whether certain millipede species are present in a habitat. "Millipedes are very good indicators for soil health because they recycle rotting leaf litter," she says.

Yet scientists still have no idea why these animals' genitals fluoresce. "The order Polydesmida can't even see—they don't have eyes," Sierwald says. M. Gabriela Lagorio, a chemist who studies photobiology at the University of Buenos Aires and was not involved in the study, says the feature may or may not have an evolutionary purpose. She notes that it may be "simply a nonfunctional consequence of the chemical structure of a substance present in the tissue." *—Jim Daley*

STEPHANIE WARE *Field Museum*

ART AND SCIENCE

Cultured Art

A designer uses bacteria to create stunning lamps

1

2

3

Colorful bacterial colonies—such as *Serratia marcescens* and *Escherichia coli* (1 and 2) and other species (3)—add flair to flasklike lamps.

SANDY HAGGART (1, 2); MICHAL MAZUR (3)

Most people think of bacteria as unseen disease carriers and simply want to wash their hands of them. But Stockholm-based industrial designer Jan Klingler is putting them in the spotlight with his colorful lamps. "Every living being and place has its own unique and personal microbiological fingerprint," Klingler says. By capturing such signatures, he aims to bottle memories.

Customers who order one of Klingler's lamps—which will be for sale soon—will get a kit with a sterile swab they can brush on a loved one, pet or object. (Klingler himself swabbed the subway station pillar where he met his partner.) The customer will send the sample back to Klingler, who will culture it in a petri dish.

Bacterial colonies erupt in different colors, which Klingler can customize by varying the species and growth medium. This approach creates flamboyant shapes "growing into each other and melting together in interesting patterns," he says. Klingler and his collaborator Volkan Özenci, a microbiologist at the Karolinska Institute in Sweden, are now experimenting with tuning growth speed and duration. "It is impossible to exactly foresee what will grow," Klingler says.

After the bacteria multiply for a day or two, he encases them in resin, making what he calls "modern fossils." The resin disks are then embedded in blown-glass structures that resemble laboratory equipment. Finally, bright LEDs bring the colors and patterns to life. *—Prachi Patel*

ADVANCES

HUMANS IN SPACE

A Year in Orbit

Astronaut Scott Kelly describes the hardships of life in space

Onboard the International Space Station: NASA astronaut Scott Kelly in July 2015.

GETTY IMAGES

Scott Kelly is the first American to spend almost a year in space. The NASA astronaut lived for a record 340 days onboard the International Space Station (ISS) from 2015 to 2016. Like other astronauts, he endured the stresses of microgravity, cosmic radiation and "headward fluid shift," in which blood and tissue fluid collect in the head. But Kelly's experience was unique in that researchers painstakingly documented his physiology and cognitive performance while in orbit—and simultaneously monitored his identical twin brother, Mark Kelly, as an earthbound control.

The NASA Twins Study, a groundbreaking analysis of the effects of life in space, was published in April in *Science.* It revealed that Kelly underwent changes (which his twin did not experience) in his eyes, carotid artery, DNA expression and cognitive performance during the mission. Most measurements returned to preflight levels after he returned to Earth—although some of his cognitive scores worsened. SCIENTIFIC AMERICAN spoke with Kelly about the study, the difficulties of prolonged spaceflight and the implications for future long-term missions. An edited excerpt follows.

—*Jim Daley*

What were the biggest physiological challenges you faced in orbit?

That headward fluid shift is the worst in the beginning. Your body adjusts to it over time, but it never adjusts completely. I always felt pressure in my head. Another thing that varied from high to too high was the carbon dioxide. When it was at its lowest, it was 10 times what it would be on Earth. When it was at its highest, it was about 30 times what it is on Earth. It would burn your eyes. I was able to tell what the CO_2 level was pretty accurately without having to look at the measurement.

EDITORS' NOTE: According to a 2012 NASA study, the ISS functions at higher than normal concentrations of CO_2 "out of operational necessity," but research supports these levels as safe.

What physical changes did you experience back on Earth?

In the absence of gravity, not only is your heart less fit, but your veins and arteries are also not as strong. And once you get back to Earth, all the blood just wants to pool in your legs. That lasted for weeks. I would stand up, and my legs would swell up like water balloons. I had rashes and hives on my skin whenever it had any pressure on it: on my butt, the back of my legs, my elbows. That was surprising. I was sore.

I was tired for a long time. From a mental state, your schedule is so tightly controlled onboard the ISS—then, when you get back, you don't have anyone telling you what to do anymore. You feel a little lost for a bit. When you don't have that structure, it's kind of hard to be motivated at first.

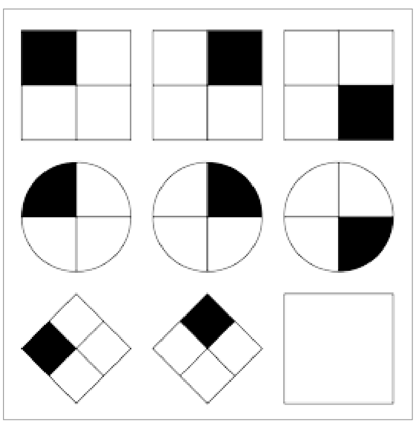
COGNITIVE SCIENCE

Interactive IQ

A "click and drag" intelligence test predicts real-world success

Imagine playing Scrabble without being able to rearrange the tiles on your rack or designing a building without sketching ideas or making models. Such a thought exercise shows the importance of environmental interaction in human thinking. But many cognitive tests meant to predict real-world achievement measure only what people can process inside their head. A new type of IQ test that lets takers "externalize" their problem-solving predicts school grades better than the original version it was based on, a recent study found.

In a common IQ test called Raven's Progressive Matrices, each question shows participants a three-by-three grid of shapes in which one is missing and asks them to select a shape that best completes the overall pattern. In the updated version, they must first arrange the eight other shapes into a coherent pattern by clicking and dragging them on a computer screen.



Question in the style of a static Raven's Progressive Matrices test.

HTTPS://EN.WIKIPEDIA.ORG/WIKI/RAVEN%27S_PROGRESSIVE_MATRICES#/MEDIA/FILE:RAVEN_MATRIX.SVG

The new test's creators gave 495 Dutch university students either the old or new assessment. Their scores on the original test correlated with their exam grades, but scores on the click-and-drag test predicted grades even better—by one measure more than twice as well as the original version, according to the study, which was published in the February issue of *Nature Human Behaviour.*

The researchers also tracked people's movement of shapes during the test and found that those who performed best tended to exhibit flurries of activity, with lulls in between. The study authors suspect that rather than randomly moving shapes until they fit a pattern, successful students were forming ideas, testing them and then pausing to reflect before trying a new one.

Why might your cognitive test scores have declined once you were back on Earth?
When you're up there, and you're doing tests a lot, just like anything else you get better at them. But when I got back, I wasn't feeling great. Imagine showing up to your SAT with the flu: you probably wouldn't do too well. I attribute a lot of my performance on those tests not necessarily to my cognitive ability but more to the other symptoms I had. Even though you might not have a cognitive deficit, the fact that you feel like crap makes it very hard to do those tests.
EDITORS' NOTE: The NASA Twins Study researchers suggested that several factors, including Kelly's hectic postflight schedule, may have contributed to the apparent decline in performance.

What does your experience tell us about longer astronaut missions in the future?
The researchers didn't observe anything that would prevent us from going to Mars. Certainly the radiation is something we've got to deal with, although this wasn't really an experiment on that. But if we're going to go beyond Mars, we are going to have to start thinking about artificial gravity. I flew in space for seven, 13, 154 and then 340 days. The longer you're there, the more symptomatic you are when you return. I couldn't imagine coming back to Earth after being in space for many years.

"This external detour in information processing is precisely what makes it possible for people to come up with serendipitous solutions to difficult problems," says Bruno Bocanegra, a psychologist at Erasmus University Rotterdam in the Netherlands and the paper's lead author.

"The new test could be an asset to test problem-solving in the real world," says Wendy Johnson, a psychologist at the University of Edinburgh, who was not involved in the research. Johnson would like to see a version of the SAT college admissions exam that also tests externalized thinking. "Overall, I think the paper is a great addition to this burgeoning field," says Gaëlle Vallée-Tourangeau, a psychologist at Kingston University in England, who has found that interacting with the physical world helps people with creativity and statistical reasoning. "We still have a lot to learn, but it is time we move away from a dated conception of the mind as merely a computer." —*Matthew Hutson*

Juvenile Murray River turtle (*Emydura macquarii*). Such turtles are growing rarer.

DANITA DELIMONT *Alamy*

CONSERVATION

Slow-Motion Extinction

Turtles' famed longevity can mask their decline—until it is too late

Nearly four decades ago zoologist Michael Thompson, then at the University of Adelaide in Australia, made an alarming discovery: invasive red foxes were gobbling up more than 90 percent of all the turtle eggs laid along the banks of Australia's Murray River. Thompson's surveys also revealed a disproportionate number of older turtles, suggesting that fox predation had already reduced the amount of juveniles in the river. If no one took action, he warned, the formerly abundant turtles would eventually disappear.

Very little was done, and Thompson's prediction now appears to be on its way to coming true. A recent study confirms that several turtle species have either drastically declined or disappeared from various sections of the Murray River. "The problem is that the longevity of turtles gives the perception of persistence," says Ricky Spencer, an ecologist at Western Sydney University and a co-author of the study, which was published in February in *Scientific Reports*. "It's human nature that only when something is gone do we start missing it."

Spencer and his colleagues tallied populations of three once common turtle species—the broad-shelled turtle, the eastern long-necked turtle and the Murray River turtle—at 52 sites along the southern reaches of the river. The researchers inferred the species' population sizes from the number of individuals they trapped in a given amount of time. They found the turtles have been extirpated in places where they were previously abundant, and most of the specimens they managed to capture elsewhere were large—and likely old—adults. Spencer and his colleagues blame the losses on ongoing nest predation by foxes, compounded by other problems, including environmental degradation and severe drought in the 2000s.

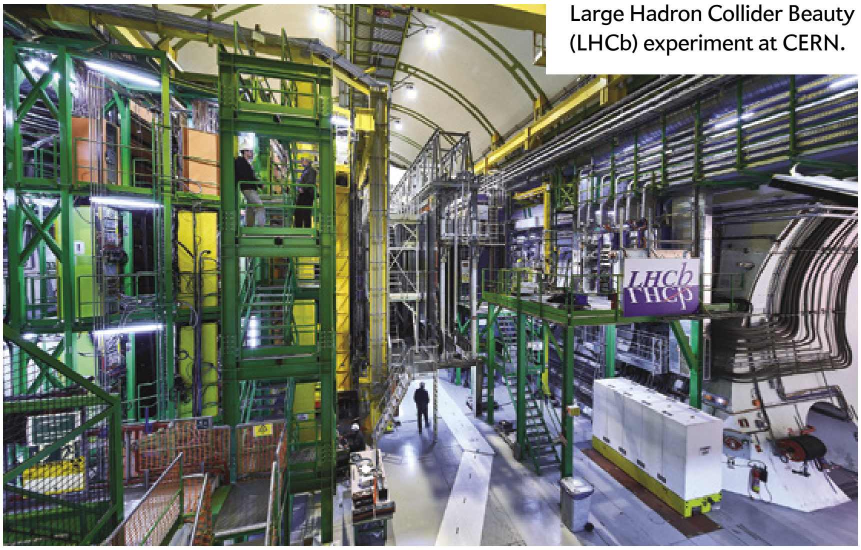
"We have known about [the turtle die-off] for decades, and despite intense media hype in Australia about the 'plight of our rivers,' nothing has been done to reverse that decline," says Rick Shine, a herpetologist at Macquarie University in Sydney, who was not involved in the research. "This paper is a wake-up call that unless we begin to do something about turtle conservation on a landscape scale, we may lose a fascinating component of our native fauna."

The turtles could recover quickly if action is taken to protect nests from foxes and restore habitat, Spencer notes. But governments tend to respond only when losses reach crisis levels, and the Murray River species currently lack federal protection, he says. He and his colleagues have a work-around, however: "Our next step is to start designing community conservation efforts for common turtle species," he explains, "so people can actually do things without having to wait for government funding." —*Rachel Nuwer*

PARTICLE PHYSICS

Lucky Charms

New evidence hints at what happened to the universe's antimatter



Large Hadron Collider Beauty (LHCb) experiment at CERN.

CERN

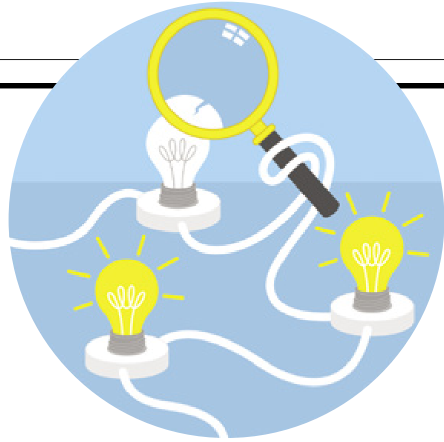
We could have been living in an antimatter universe, but we are not. Antimatter is matter's upside-down twin—every matter particle has a matching antimatter version with the opposite charge. Physicists think the cosmos started out with just as much antimatter as matter, but most of the former got wiped out. Now they may be one step closer to knowing why.

Researchers at the Large Hadron Collider Beauty (LHCb) experiment at CERN near Geneva have discovered antimatter and matter versions of "charm" quarks—one of six types, or flavors, of a class of elementary matter particles—acting differently from one another. In a new study, which was presented in March at the "Rencontres de Moriond" particle physics conference in La Thuile, Italy, the physicists found that unstable particles called D^0 mesons (which contain charm quarks) decayed into more stable particles at a slightly different rate than their antimatter counterparts. Such differences could help explain how an asymmetry arose between matter and antimatter after the big bang, resulting in a universe composed mostly of matter.

Matter and antimatter annihilate each other on contact, and researchers believe such collisions destroyed almost all of the antimatter (and a large chunk of the matter) that initially existed in the cosmos. But they do not understand why a relatively small excess of matter survived to become the stars and planets and the rest of the cosmos. Consequently, physicists have been looking for a kind of matter that behaves so differently from its antimatter version that it would have had time to generate this excess in the early universe.

The newly discovered mismatch in decay rates between charm quarks and antiquarks turns out to be too small to account for the universe's excess of matter. The result, however, "does bring us closer to finding the answer because it shows one of the possible answers may not be the right one," says theoretical physicist Yuval Grossman of Cornell University, who was not involved in the new work. "I am also excited because it's the first time we've ever seen this [phenomenon in charm quarks]."

Physicists previously found similar variations in two other quark flavors, but those were also too tiny to account for our matter-dominated universe. Scientists are holding out hope of finding much larger matter-antimatter differences elsewhere, such as in ghostly particles called neutrinos or reactions involving the Higgs boson—the particle that gives others mass—says LHCb team member Sheldon Stone of Syracuse University: "There are lots of different searches going on." —*Clara Moskowitz*



ENGINEERING

Electricity Detective

A new sensor system warns when an electrical device is about to fail

From the outside, the main diesel engines on the U.S. Coast Guard cutter vessel *Spencer* looked normal. But a newly developed sensor system indicated that a bank of heaters, used to warm up the engines before they rumble into action, had failed. When the crew members removed the heaters' metal cover, they found smoking, corroded wires.

Not only were the heaters incapacitated, "their electrical insulation was starting to fray and crack, on the verge of starting a fire," says Massachusetts Institute of Technology professor Steven Leeb, who was senior author of a study published in March in *IEEE Transactions on Industrial Informatics* describing the new system. "Our power monitor was able to detect the gradual changes over the course of a year and saw a time when it failed severely."

The system relies on a technology called nonintrusive load monitoring (NILM). In ships and buildings alike, many devices are often connected to a single power supply, and each one creates unique changes in the flow of current. A NILM sensor installed at one point in the electrical network can extract these distinct "fingerprints" to determine how much energy each device is using. Although NILM dates back to the 1980s, practical applications have emerged only in the past few years as utilities and independent start-ups began developing smart meters to monitor energy usage in homes and buildings.

The new system processes NILM data and displays the information via dashboards onboard Coast Guard cutters. "The [researchers have] made a usable tool," says David Irwin, an assistant professor of electrical and computer engineering at the University of Massachusetts Amherst, who was not involved in the study. Whereas many academic NILM projects can be esoteric, Irwin says, Leeb's team has focused on real-world use, successfully adapting a sensor for commercial applications.

A similar dashboard interface can warn homeowners of failing appliances—and could be critical in industrial or military settings. "The diagnostics work is directed toward detecting when things break—and even better, prognosticating when they *may* break," Leeb says. Early detection of the *Spencer*'s faulty engine component enabled the Coast Guard to replace it while the vessel was still docked.

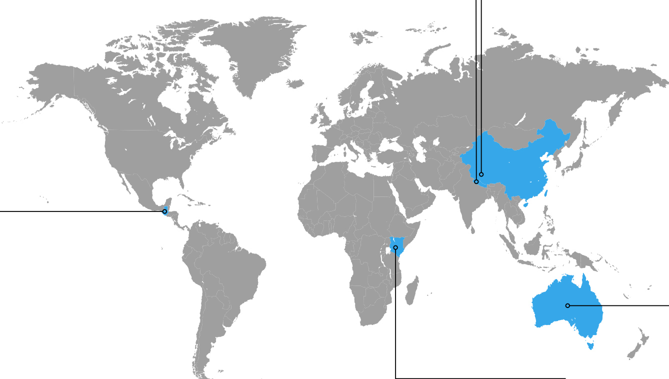
"Almost nobody likes having something be broken," he says, but on cutters—or in refineries, chemical-processing operations, manufacturing plants or commercial buildings—one broken part can take down a much larger system in a so-called mission cripple, causing serious and wide-ranging consequences. —*Sophie Bushwick*

Illustration by Thomas Fuchs

IN THE NEWS

Quick Hits

By Jim Daley



NEPAL
Researchers confirmed the nation's first recorded tornado, which occurred during a devastating storm in March. The team relied on satellite imagery and posts on social media to make the identification.

CHINA
The Large High Altitude Air Shower Observatory on the eastern edge of the Tibetan Plateau began operating in April. Located some 4,400 meters above sea level, the observatory will study high-energy cosmic rays.

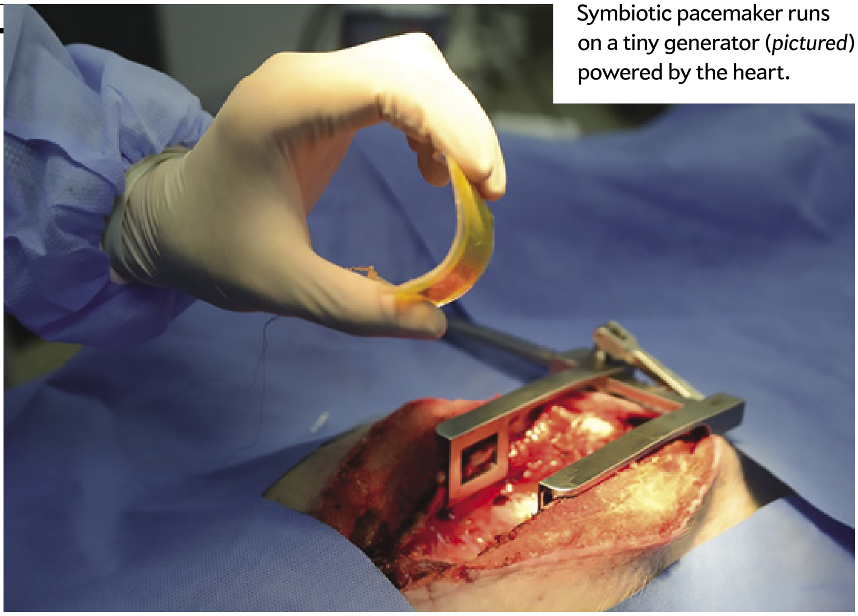
GUATEMALA
Archaeologists unearthed the largest known Mayan figurine factory. The more than 1,000-year-old workshop mass-produced intricate statues that were likely used in diplomacy as gifts to allies.

AUSTRALIA
The government announced it will not regulate gene-editing technology provided it does not introduce new genetic material to target sites in the genome. Editing human embryos used for reproduction is still banned, however.

ANTARCTICA
Emperor penguins have abandoned one of their biggest breeding colonies, possibly because of sea-ice loss. Biologists found that the population, which reached about 25,000 breeding pairs of birds in 2010, collapsed in 2016 and has not rebounded since.

KENYA
Paleontologists have identified a fossil jawbone in the Nairobi National Museum that came from a previously unknown giant carnivore, which roamed Africa 22 million years ago. The predator was likely larger than a polar bear and had banana-sized fangs.

For more details, visit www.ScientificAmerican.com/jul2019/advances



Symbiotic pacemaker runs on a tiny generator (*pictured*) powered by the heart.

FROM "SYMBIOTIC CARDIAC PACEMAKER," BY HAN OUYANG ET AL., IN *NATURE COMMUNICATIONS*, VOL. 10, ARTICLE NO. 1821; 2019

BIOMEDICAL ENGINEERING

The Beat Powers On

An experimental pacemaker runs off energy from a beating heart

Scientists have successfully tested a heartbeat-powered pacemaker in living pigs, whose hearts are similar to humans' in size and function. Researchers say this is an important step toward developing battery-free implantable medical devices. Current pacemaker batteries have a life span of seven to 10 years, and replacing them entails expensive surgery.

The new "symbiotic pacemaker" consists of three components: a wafer-sized generator attached to the heart that converts the organ's mechanical energy into electrical energy; a power-management unit that has a capacitor to store that energy; and the pacemaker itself, which stimulates and regulates the heart muscle.

Zhou Li of the Beijing Institute of Nanoenergy and Nanosystems and Zhong Lin Wang of the Georgia Institute of Technology and their colleagues implanted their device in two adult male pigs. In the first animal (which had a healthy heart), the team tested how well the generator harvested energy; it powered the pacemaker for a total of nearly three and a half hours. The pig's heart generated more than enough energy to power a human version of the pacemaker, the scientists reported in April in *Nature Communications.* In the second pig, they induced an irregular heartbeat (arrhythmia) to test the pacemaker's therapeutic function. When the device—which had been charged by the pig's heart for more than an hour—was turned on, the animal's heartbeats promptly became regular and remained so even after it was turned off.

Human testing is unlikely in the near future because the device's size, safety and efficiency must still be optimized. "The technology described is a significant achievement," says Patrick Wolf, a biomedical engineer at Duke University, who was not involved in the study. But he cautions that the size and efficiency hurdles are significant, and the pacemaker's effectiveness in a less dynamic, diseased heart is yet to be determined.

Another drawback is that the unit must be attached directly to the heart's surface and could interfere with the organ's functions. A group at Dartmouth College and the University of Texas at San Antonio previously designed a pacemaker that instead harnesses kinetic energy from its own lead wire, which moves when the heart pulses. The team is currently testing it in dogs.

"The development of these battery-free technologies will revolutionize implantable devices," says Ramses Martinez, a researcher in industrial and biomedical engineering at Purdue University, who was not involved in either study. "Soon traditional rigid implants will evolve into conformable systems capable of harvesting the energy they need to function from the patient."

—*Harini Barath*

Ify Aniebo is an expert in clinical medicine and infectious diseases. She is a senior research scientist at the Health Strategy and Delivery Foundation and a Takemi Fellow at the Harvard T. H. Chan School of Public Health.

Genomic Surveillance for Malaria

It can flag pathogens long before patients show up in clinics

By Ify Aniebo

In 2018 the World Health Organization proposed a "10+1" initiative for malaria control and elimination that targets 10 African countries plus India, which together host 70 percent of global cases. Although this approach is promising, it is missing an important component: genomic surveillance. Drug resistance threatens all of the progress made so far against malaria, but genomic surveillance can detect resistance years before the first warning signs appear in clinics. It can answer critical questions about how resistance emerges and spreads and can help control the balance of interventions, preserve the useful life of already existing drugs and ensure effective treatment.

I call on the WHO, global health partners and the malaria community to incorporate mandatory genomic surveillance by making it a major intervention in countries that have the highest malaria burden. This genomic information can help malaria-control programs use quality data sets for regular monitoring of drug resistance, provide evidence-based decision-making around malaria policy and assist in managing the spread of resistance.

The countries most affected by malaria all had a first-line drug that ended up becoming resistant. In African countries, toward the end of the 20th century, chloroquine was the drug of choice, but malaria parasites grew resistant to it. That drug was then replaced with a combination of pyrimethamine and sulfadoxine in the early 2000s, and resistance again occurred. Now the parasites are becoming resistant to the current first-line artemisinin-based combination therapies (ACTs). Artemisinin resistance is conferred by the *kelch13* gene, which is located in the propeller region of chromosome 13.

Although mutation in this gene has occurred in Southeast Asia and is spreading around the region, there are fears that it will also spread to Africa, as happened with the drugs before ACTs. The more drugs we use to treat malaria parasites, the more resistant they become as a result of selective pressure, which creates the preconditions for resistance. Because we know this biological response from the parasites is inevitable, we should put in place measures to track down these changes when they arise: doing so would help us prevent the spread of the disease, investigate emergence of resistance and subsequently preserve the efficacy of the current first-line antimalarial treatment.

With advances in genomic technology, scientists have been able to analyze malaria parasites from the patients carrying them and the mosquitoes transmitting them. Such analysis has become a source of relevant information for both drug and insecticide resistance. Research shows that genomic surveillance has helped us understand how different mosquito species arise and transmit malaria to humans, which in turn has led to a better targeting of interventions as vectorial capacity becomes better understood.

Such surveillance has enabled greater knowledge of changing transmission intensity and parasite gene flow, including drug-resistant genes, and has aided in quantifying the risks of importing malaria from a country that is burdened with the disease. But work using genomic surveillance as a tool has mostly transpired within the realm of research, with only a few examples of its application in the field where malaria burden remains high.

Genomic surveillance has been used in countries that have eliminated malaria to prevent its resurgence and in countries that are in a malaria-elimination phase. It should not be any different for the African countries that have the highest malaria burden. Lessons learned from poliomyelitis show that genomic surveillance played a huge role in controlling the infection. Public health officials have been able to use quality data to learn where this virus emerged from, map the transmission network and determine where to direct their vaccination efforts.

It is time for genomic surveillance to move from mainly academic research into the field where malaria deaths occur. I propose that the WHO should incorporate a new "tool kit" that includes malaria genomics in its eradication plans. Such a kit would provide valuable information that would make national programs fighting the disease, especially in the African countries included in the 10+1 initiative, far more effective. As with any public health crisis, the more we know, the better.

Claudia Wallis will return next month.

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

I've Come Around on Nuclear Power

Climate change scares me more than the risk of meltdowns

By Wade Roush

Fifty-four percent of Americans are opponents of nuclear power, according to a 2016 Gallup poll. I can certainly understand why. I used to be one of them. Back in the 1990s, I wrote an entire Ph.D. dissertation about the errors that led to disasters such as Three Mile Island and Chernobyl, and it didn't leave me with much faith in our ability to safely tap fission energy.

But in recent years I've swung around to a different point of view. Today the specter of climate change scares me way more than the risk of future meltdowns. It's time to find ways to enable the nuclear industry's rebirth in the U.S.

The virtue of nuclear plants is that they plug into the existing electrical grid and provide continuous power while emitting zero carbon. Wind and solar are great, too, but we don't yet have the battery technology needed to make them useful as "baseload" power sources.

Without nuclear, it would be much harder to meet the world's growing power needs while limiting the average global temperature increase to 1.5 degrees Celsius, the goal of the 2015 Paris Agreement.

Fortunately, engineers have been rethinking every aspect of reactor design, from the way fuel is packaged [see "Reactor Redo," by Rod McCullum; May 2019] to the way cores are cooled. All three active reactors at Japan's Fukushima Daiichi plant melted down in 2011 because an earthquake and the resulting tsunami destroyed the backup diesel generators meant to power cooling pumps. Several companies, including Washington State–based TerraPower, are working on passive designs that would use plain old convection rather than electric pumps to carry away decay heat.

But TerraPower will likely build its first full-scale reactors outside the U.S., vice chairman of the board Nathan Myhrvold told me in a 2017 interview for Xconomy. "Frankly, if the whole world was like the United States, we might not have ever done this, because [the U.S. has] gotten so risk-averse that we don't want to try anything new," Myhrvold said.

Today the main obstacle to new nuclear power investment in the U.S. isn't safety, it's cost. Two new Westinghouse Electric Company reactors under construction at Georgia's Vogtle nuclear plant are five years behind schedule and $14 billion over budget.

Builders of traditional reactors have failed to follow basic design, fabrication and supply-chain principles proven in other capital-intensive businesses such as pharmaceuticals and jet engine manufacturing, a 2018 report from the M.I.T. Energy Initiative found.

Then there's the energy marketplace, which was turned upside down by the fracking revolution of the 1990s. In the U.S., natural gas is so cheap and abundant that even well-run nuclear plants can't compete.

They can't, that is, unless one accounts for the social cost of carbon, a measure representing the economic damage that will inevitably result from sea-level rise, wildfires and other consequences of carbon dioxide emissions. If electricity from fossil-fuel plants were taxed to reflect this cost, nuclear would suddenly become the more economical option, the M.I.T. report argues.

Because carbon taxes are a political nonstarter, the states of New York and Illinois are going at it from the other direction, forcing coal- and gas-burning utilities to purchase zero-emissions credits from nuclear plant owners. In both states, courts have turned back power generators' legal challenges to zero-emissions credits, and the new revenue has kept open five plants that faced early closure.

We need to scale up these credits nationally to keep our existing nuclear plants operating while removing obstacles to the construction of safer new designs. If we allow ourselves to be unnerved by the nuclear mistakes of the past, we'll never win the paramount race against global warming. SA

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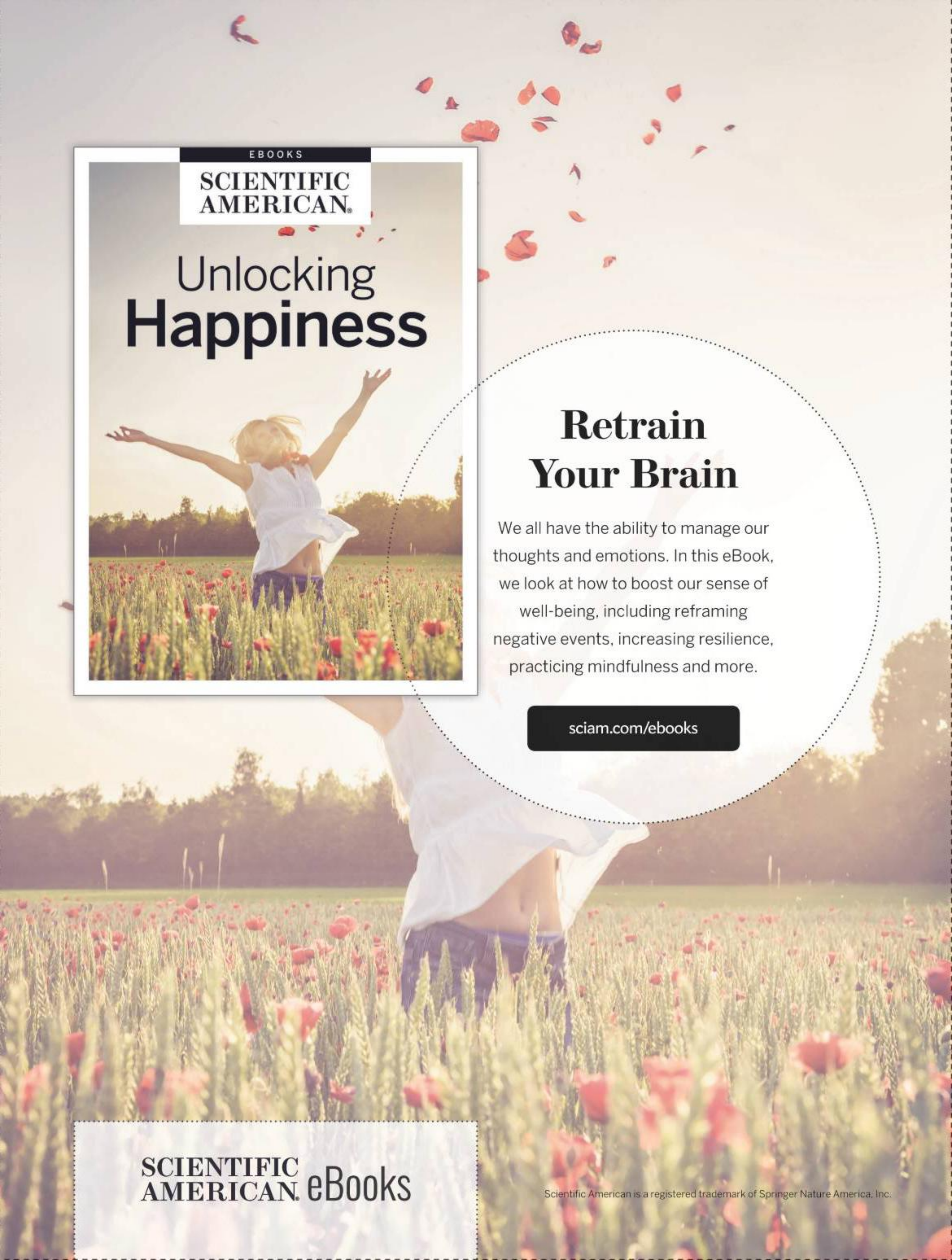
Illustration by Jay Bendt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NEUROSCIENCE

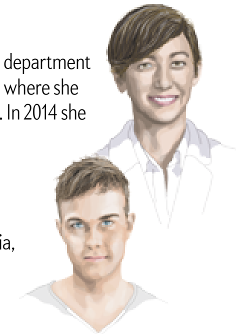
how matter becomes mind

The new discipline of network neuroscience yields a picture of how mental activity arises from carefully orchestrated interactions among different brain areas

By Max Bertolero and Danielle S. Bassett

Illustration by Mark Ross Studios

NETWORKS PERVADE OUR LIVES. EVERY DAY WE USE INTRICATE NETWORKS OF roads, railways, maritime routes and skyways traversed by commercial flights. They exist even beyond our immediate experience. Think of the World Wide Web, the power grid and the universe, of which the Milky Way is an infinitesimal node in a seemingly boundless network of galaxies. Few such systems of interacting connections, however, match the complexity of the one underneath our skull.



Danielle S. Bassett is an associate professor in the department of bioengineering at the University of Pennsylvania, where she studies networks in physical and biological systems. In 2014 she became a MacArthur Fellow.

Max Bertolero is a postdoctoral fellow in Bassett's Complex Systems Group. He received a doctorate in systems neuroscience from the University of California, Berkeley, and undergraduate degrees in philosophy and psychology from Columbia University.

Neuroscience has gained a higher profile in recent years, as many people have grown familiar with splashily colored images that show brain regions "lighting up" during a mental task. There is, for instance, the temporal lobe, the area by your ear, which is involved with memory, and the occipital lobe at the back of your head, which dedicates itself to vision.

What has been missing from this account of human brain function is how all these distinct regions interact to give rise to who we are. Our laboratory and others have borrowed a language from a branch of mathematics called graph theory that allows us to parse, probe and predict complex interactions of the brain that bridge the seemingly vast gap between frenzied neural electrical activity and an array of cognitive tasks—sensing, remembering, making decisions, learning a new skill and initiating movement. This new field of network neuroscience builds on and reinforces the idea that certain regions of the brain carry out defined activities. In the most fundamental sense, what the brain is—and thus who we are as conscious beings—is, in fact, defined by a sprawling network of 100 billion neurons with at least 100 trillion connecting points, or synapses.

Network neuroscience seeks to capture this complexity. We can now model the data supplied by brain imaging as a graph composed of nodes and edges. In a graph, nodes represent the units of the network, such as neurons or, in another context, airports. Edges serve as the connections between nodes—think of one neuron intertwined to the next or contemplate airline flight routes. In our work, the human brain is reduced to a graph of roughly 300 nodes. Diverse areas can be linked together by edges representing the brain's structural connections: thick bundles of tubular wires called white matter tracts that tie together brain regions. This depiction of the brain as a unified network has already furnished a clearer picture of cognitive functioning, along with the practical benefit of enabling better diagnoses and treatment of psychiatric disorders. As we glimpse ahead, an understanding of brain networks may lead to a blueprint for improved artificial intelligence, new medicines and electrical-stimulation technology to alter malfunctioning neural circuitry in depression—and perhaps also the development of genetic therapies to treat mental illness.

THE MUSIC OF THE MIND

TO UNDERSTAND HOW networks underlie our cognitive capabilities, first consider the analogy of an orchestra playing a symphony. Until recently, neuroscientists have largely studied the functioning of individual brain regions in isolation, the neural equivalent of separate brass, percussion, strings and woodwind sections. In the brain, this stratification represents an approach that dates back to Plato—quite simply, it entails carving nature at the joints and then studying the individual components that remain.

Just as it is useful to understand how the amygdala helps to process emotions, it is similarly vital to grasp how a violin produces high-pitched sounds. Still, even a complete list of brain regions and their functions—vision, motor, emotion, and so on—does not tell us how the brain really works. Nor does an inventory of instruments provide a recipe for Beethoven's *Eroica* symphony.

Network neuroscientists have begun to tame these mysteries by examining the way each brain region is embedded in a larger network of such regions and by mapping the connections between regions to study how each is embedded in the large, integrated network that is the brain. There are two major approaches. First, examining structural connectivity captures the instrumentation of the brain's orchestra. It is the physical means of creating the music, and the unique instrumentation of a given musical work constrains what can be played. Instrumentation matters, but it is not the music itself. Put another way, just as a collection of instruments is not music, an assemblage of wires does not represent brain function.

Second, living brains are massive orchestras of neurons that fire together in quite specific patterns. We hear a brain's music by measuring the correlation between the activity of each pair of regions, indicating that they are working in concert. This measure of joint activity is known as functional connectivity, and we colloquially think of it as reflecting the music of the brain. If two regions fire with the same time-varying fluctuations, they are considered to be functionally connected. This music is just as important as the decibels produced by a French horn or viola. The volume of the brain's music can be thought of as the level of activity of electrical signals buzzing about one brain area or another.

At any moment, though, some areas within the three-pound organ are more active than others. We have all heard the saying that people use a small fraction of their brain capacity. In fact, the entire brain is active at any point in time, but a given task modulates the activity of only a portion of the brain from its baseline level of activity.

That arrangement does not mean that you fulfill only half of your cognitive potential. In fact, if your entire brain were

IN BRIEF

How does the brain give rise to who we are? This question has led to the new field of network neuroscience, which uses a branch of mathematics, graph theory, to model the brain connections that let us read, calculate, or simply sit and tap our fingers.

Graph theory, which is also used by chemists, quantum field theorists and linguists, models the physical pathways that build functional networks from which our cognitive capacities emerge, whether for vision, attention or self-control.

By understanding networks at increasing levels of abstraction, researchers have begun to bridge the gap between matter and mind. Practical benefits could entail new ways of diagnosing and treating disorders such as depression.

strongly active at the same time, it would be as if all the orchestra members were playing as loudly as possible—and that scenario would create chaos, not enable communication. The deafening sound would not convey the emotional overtones present in a great musical piece. It is the pitch, rhythms, tempo and strategic pauses that communicate information, both during a symphony and inside your head.

MODULARITY

JUST AS AN ORCHESTRA can be divided into groups of instruments from different families, the brain can be separated into collections of nodes called modules—a description of localized networks. All brains are modular. Even the 302-neuron network of the nematode *Caenorhabditis elegans* has a modular structure. Nodes within a module share stronger connections to one another than to nodes in other modules.

Each module in the brain has a certain function, just as every family of instruments plays a role in the symphony. We recently performed an evaluation of a large number of independent studies—a meta-analysis—that included more than 10,000 functional magnetic resonance imaging (fMRI) experiments of subjects performing 83 different cognitive tasks and discovered that separate tasks map to different brain-network modules. There are modules occupied with attention, memory and introspective thought. Other modules, we found, are dedicated to hearing, motor movement and vision.

These sensory and motor cognitive processes involve single, contiguous modules, most of which are confined to one lobe of the brain. We also found that computations in modules do not spur more activity in other modules—a critical aspect of modular processing. Imagine a scenario in which every musician in an orchestra had to change the notes played every time another musician changed his or her notes. The orchestra would spiral out of control and would certainly not produce aesthetically pleasing sounds. Processing in the brain is similar—each module must be able to function mostly independently. Philosophers as early as Plato and as recent as Jerry Fodor have noted this necessity, and our research confirms it.

Even though brain modules are largely independent, a symphony requires that families of instruments be played in unison. Information generated by one module must eventually be integrated with other modules. Watching a movie with only a brain module for vision—without access to the one for emotions—would detract greatly from the experience.

For that reason, to complete many cognitive tasks, modules must often work together. A short-term memory task—holding a new phone number in your head—requires the cooperation of auditory, attention and memory-processing modules. To integrate and control the activity of multiple modules, the brain uses hubs—nodes where connections from the brain's different modules meet.

Some key modules that control and integrate brain activity are less circumspect than others in their doings. Their connections extend globally to multiple brain lobes. The frontoparietal control module spans the frontal, parietal and temporal lobes. It developed relatively recently on the timescale of evolution. The module is especially large in humans, relative to our closest primate ancestors. It is analogous to an orchestra conductor and becomes active across a large number of cognitive tasks.

The frontoparietal module ensures that the brain's multiple modules function in unison. It is heavily involved in what is called executive function, which encompasses the separate processes of decision-making, short-term memory and cognitive control. The last is the ability to develop complex strategies and inhibit inappropriate behavior.

Another highly interconnected module is the salience module, which hooks up to the frontoparietal control module and contributes to a range of behaviors related to attention and responding to novel stimuli. For example, take a look at two words: blue and red. If you are asked to respond with the color of the word, you will react much faster to the one set in red. The frontoparietal and salience modules activate when responding to the color green because you have to suppress a natural inclination to read the word as "blue."

Finally, the default mode module spans the same lobes as the frontoparietal control network. It contains many hubs and is linked to a variety of cognitive tasks, including introspective thought, learning, memory retrieval, emotional processing, inference of the mental state of others and even gambling. Critically, damage to these hub-rich modules disturbs functional connections throughout the brain and causes widespread cognitive difficulties, just as bad weather at a hub airport delays air traffic all over the country.

PERSONAL CONNECTIONS

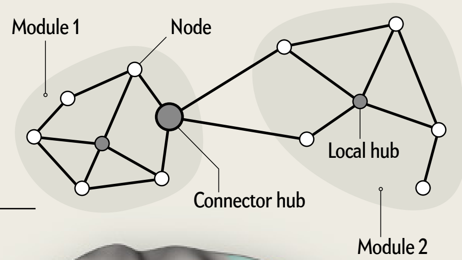
ALTHOUGH OUR BRAINS have certain basic network components—modules interconnected by hubs—each of us shows slight variations in the way our neural circuits are wired. Researchers have recently devoted intense scrutiny to this diversity. In an initial phase of what is called the Human Connectome Project, 1,200 young people have volunteered to participate in a study of brain-network architecture, funded by the National Institutes of Health. (The final goal of the project is to cover the entire life span.) Each individual's structural and functional connectivity networks were probed using fMRI. These data were supplemented by a cognitive battery of testing and questionnaires to analyze 280 behavioral and cognitive traits. Participants provided information about how well they slept, how often they drank alcohol, their language and memory abilities, and their emotional states. Neuroscientists from all over the world have begun to pore over this incredibly rich data set to learn how our brain networks encode who we are.

Using data from hundreds of participants in the Human Connectome Project, our lab and others have demonstrated that brain-connectivity patterns establish a "fingerprint" that distinguishes each individual. People with strong functional connections among certain regions have an extensive vocabulary and exhibit higher fluid intelligence—helpful for solving novel problems—and are able to delay gratification. They tend to have more education and life satisfaction and better memory and attention. Others with weaker functional connections among those same brain areas have lower fluid intelligence, histories of substance abuse, poor sleep and a decreased capacity for concentration.

Inspired by this research, we showed that the findings could be described by particular patterns among the hub connections. If your brain network has strong hubs with many connections across modules, it tends to have modules that are clearly segregated from one another, and you will perform better on a range of tasks, from short-term memory to mathematics, language or social cognition.

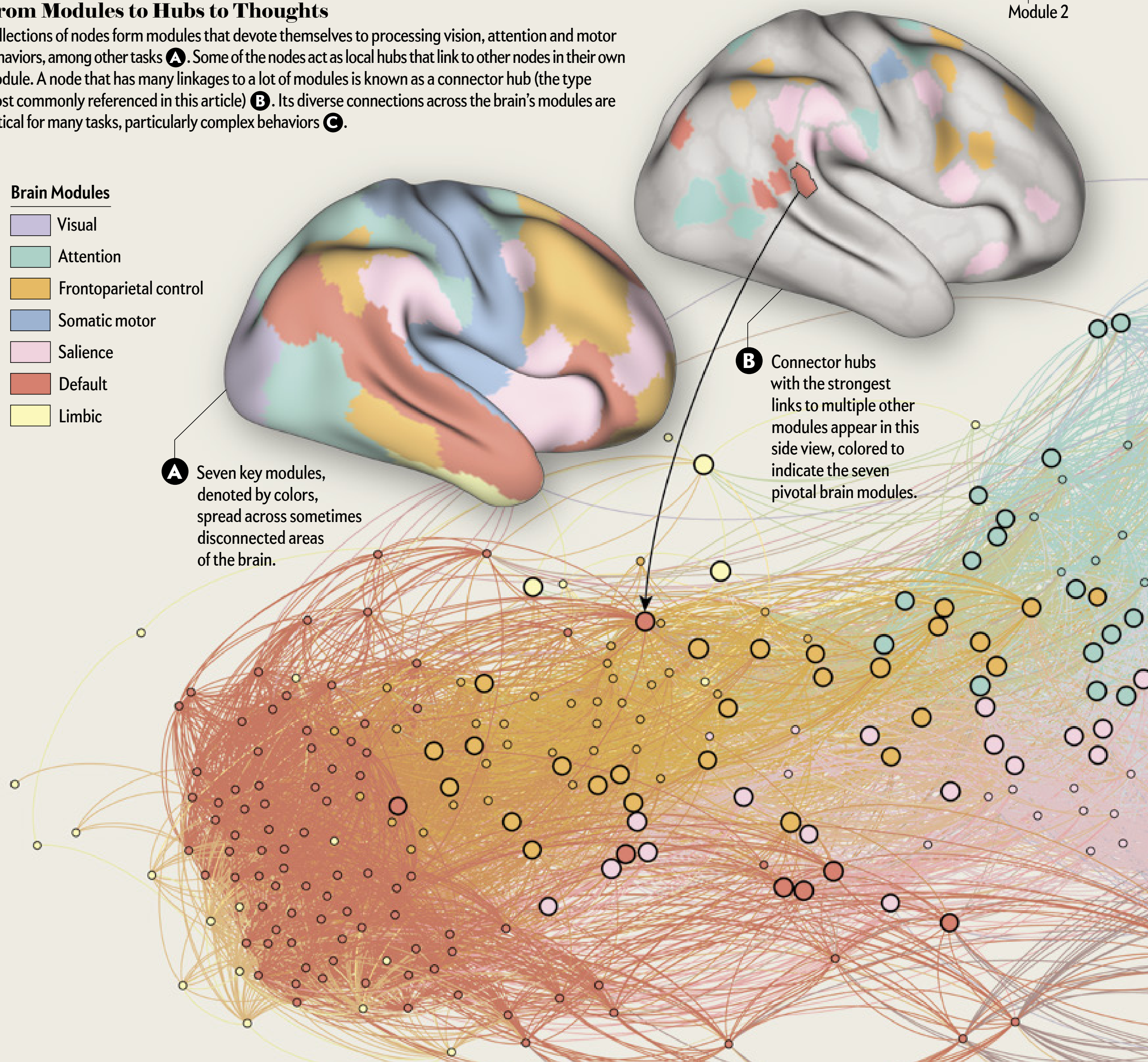
Decoding 100 Trillion Messages

The Milky Way has hundreds of billions of stars—just a fraction of the 100 trillion connections in our brains that enable us to sense, think and act. To unravel this complexity, network neuroscientists create a map, or "graph," consisting of nodes linked by edges that fit into modules, which are tethered to one another with highly connected nodes called hubs.



From Modules to Hubs to Thoughts

Collections of nodes form modules that devote themselves to processing vision, attention and motor behaviors, among other tasks (A). Some of the nodes act as local hubs that link to other nodes in their own module. A node that has many linkages to a lot of modules is known as a connector hub (the type most commonly referenced in this article) (B). Its diverse connections across the brain's modules are critical for many tasks, particularly complex behaviors (C).



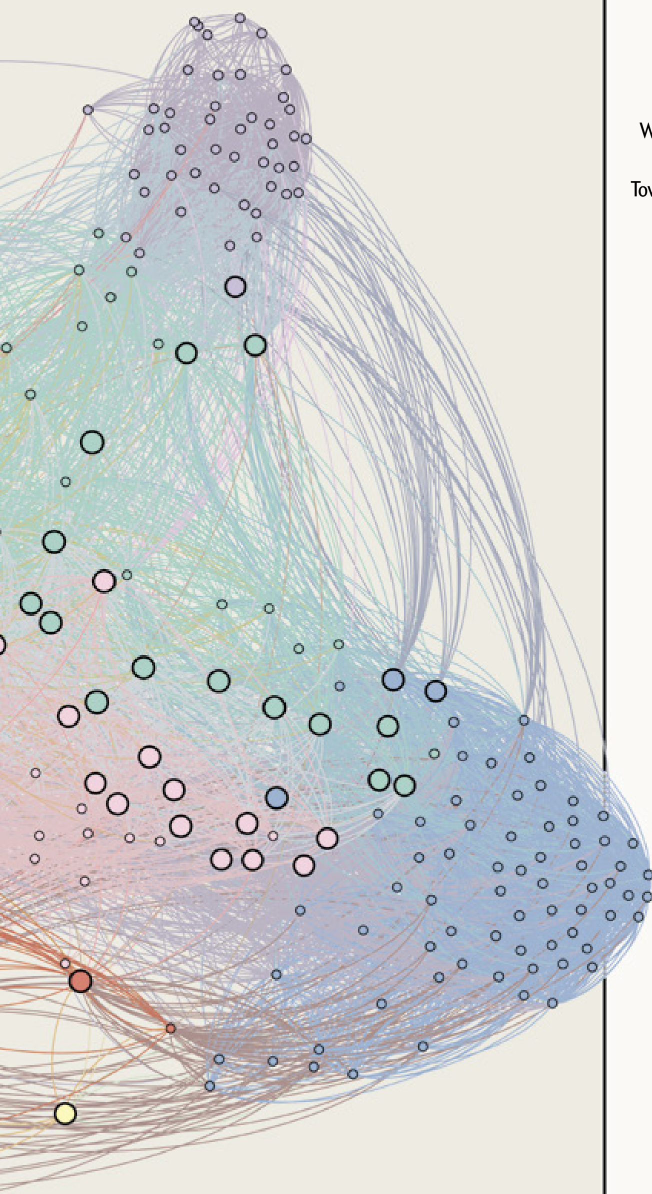
(A) Seven key modules, denoted by colors, spread across sometimes disconnected areas of the brain.

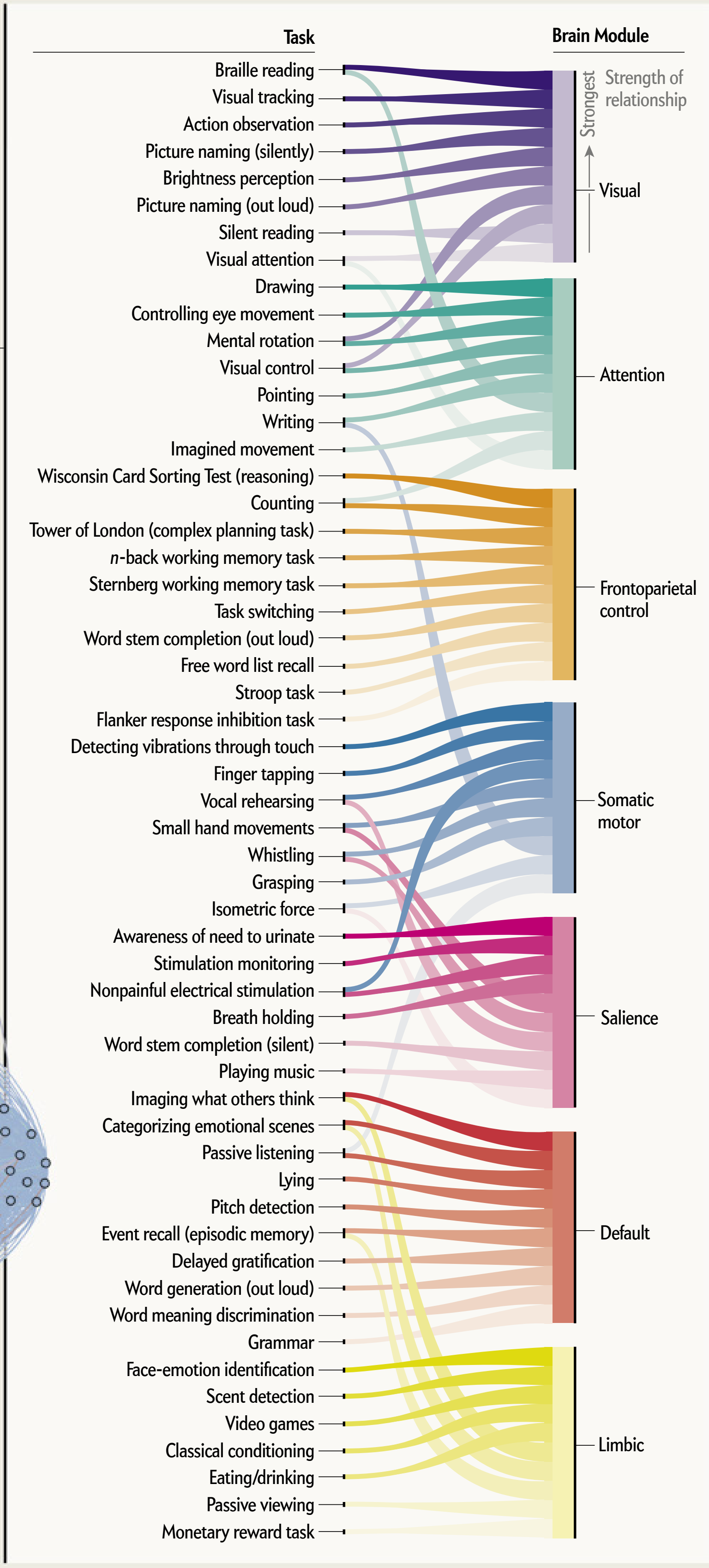
(B) Connector hubs with the strongest links to multiple other modules appear in this side view, colored to indicate the seven pivotal brain modules.

(C) A graph of the human brain's nodes and edges shows the strongest connector hubs represented as large circles. Each node's color represents the module it belongs to. Nodes can be visualized as repelling magnets with edges between nodes acting as springs that hold them together. Tightly connected nodes cluster together. Connector hubs occupy the center because they are well connected to all modules.

Putting It Together

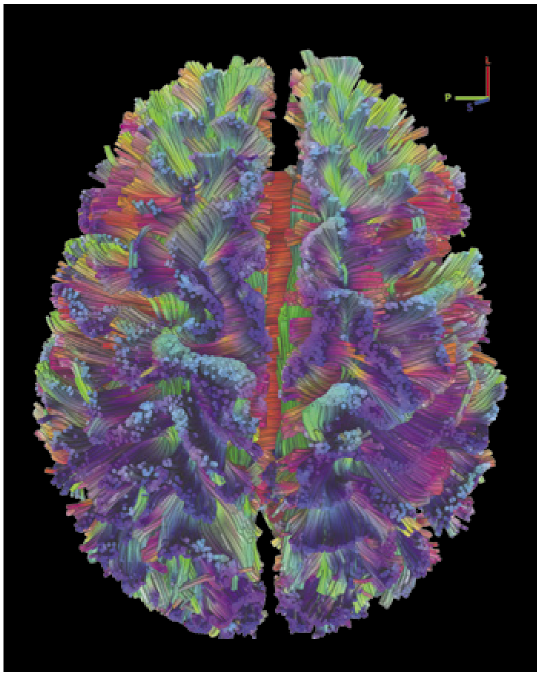
Modules for vision, attention and other cognitive functions are dedicated to specific tasks, often represented here by psychological tests. The most active tasks rise to the top. The visual module, for instance, is involved with naming, reading and observing. Many tasks require multiple modules. For example, a mental rotation task recruits both the visual and the attention modules. Some modules are entrusted with more abstract tasks. The frontoparietal module engages in switching tasks or recalling lists. The default mode module attends to subjective emotional states or passive listening when a person is at rest.





Graphics by Max Bertolero (brains and network diagram) and Jen Christiansen (task chart)

Put simply, your thoughts, feelings, quirks, flaws and mental strengths are all encoded by the specific organization of the brain as a unified, integrated network. In sum, it is the music your brain plays that makes you *you.*



MULTITUDES of white matter connections in this scan are used to model the brain's physical pathways—functional networks use these structural linkages to carry out an array of cognitive tasks.

DANIELLE S. BASSETT AND MATTHEW CIESLAK *University of Pennsylvania*

The brain's synchronized modules both establish your identity and help to retain it over time. The musical compositions they play appear to always be similar. The likeness could be witnessed when participants in two other studies in the Human Connectome Project engaged in various tasks that involved short-term memory, recognition of the emotions of others, gambling, finger tapping, language, mathematics, social reasoning and a self-induced "resting state" in which they let their mind wander.

Fascinatingly, the networks' functional wiring has more similarities than expected across all these activities. Returning to our analogy, it is not as if the brain plays Beethoven when doing math and Tupac when resting. The symphony in our head is the same musician playing the same musical genre. This consistency derives from the fact that the brain's physical pathways, or structural connections, place constraints on the routes over the brain's integrated network that a neural signal can travel. And those pathways delineate how functional connections—the ones, say, for math or language—can be configured. In the musical metaphor, a bass drum cannot play the melodic line of a piano.

Changes in the brain's music inevitably occur, just as new arrangements do for orchestral music. Physical connections undergo alterations over the course of months or years, whereas functional connectivity shifts on the order of seconds, when a person switches between one mental task and the next.

Transformations in both structural and functional connectivity are important during adolescent brain development, when the finishing touches of the brain's wiring diagram are being refined. This period is of critical importance because the first signs of mental disorders often appear in adolescence or early adulthood.

One area our research relates to is understanding how brain networks develop through childhood and adolescence and into adulthood. These processes are driven by underlying physiological changes, but they are also influenced by learning, exposure to new ideas and skills, an individual's socioeconomic status and other experiences.

Brain-network modules emerge very early in life, even in the womb, but their connectivity is refined as we grow up. Consistent strengthening of the structural connections to hubs throughout the course of childhood is associated with an increase in the segregation between modules and an augmentation in the efficiency with which young people perform executive tasks such as complex reasoning and self-regulation. We have also found that the extent to which modules segregate from one another is more rapid in children who have a higher socioeconomic status, highlighting the key impact of their environment.

Although changes in structural connectivity are slow, the reconfiguration of functional connections can occur quickly, in a few seconds or minutes. These rapid shifts are instrumental for moving between tasks and for the massive amount of learning demanded even by a single task. In a set of studies that we published from 2011 to the present, we found that networks with modules that can change readily turn up in individuals who have greater executive function and learning capacity.

To better understand what was happening, we used publicly available data from a landmark study known as MyConnectome, in which Stanford University psychology professor Russell Poldrack personally underwent imaging and cognitive appraisals three times a week for more than a year. Whereas modules are mostly autonomous and segregated, at times the brain will spontaneously reorganize its connections. This property, called functional network flexibility, lets a node with strong functional connections within a module suddenly establish many connections to a different module, changing the flow of information through the network. Using data from this study, we found that the rerouting of a network's connections changes from day to day in a manner that matches positive mood, arousal and fatigue. In healthy individuals, such network flexibility correlates with better cognitive function.

DISSONANT NOTES

THE CONFIGURATION of brain connections also reflects one's mental health. Aberrant connectivity patterns accompany depression, schizophrenia, Alzheimer's, Parkinson's, autism spectrum disorder, attention deficit disorder, dementia and epilepsy.

Most mental illnesses are not confined to one area of the brain. The circuitry affected in schizophrenia extends quite widely across the entire organ. The so-called disconnectivity hypothesis for schizophrenia holds that there is nothing abnormal about the individual modules. Instead the disarray relates to an overabundance of connections between modules.

In a healthy brain, modules are mostly autonomous and segregated, and the ability to bring about flexible changes in network connections is beneficial for cognitive functioning—within certain limits. In our lab, we found that in the brains of people with schizophrenia and their first-degree relatives, there is an overabundance of flexibility in how networks reconfigure themselves. Auditory hallucinations might result when nodes unexpectedly switch links between speech and auditory modules. The uninvited mix can result in what seem to be the utterings of voices in one's head.

Like schizophrenia, major depressive disorder is not caused by a single abnormal brain region. Three specific modules appear to be affected in depression: the frontoparietal control, salience and default mode modules. In fact, the symptoms of depression—emotional disinhibition, altered sensitivity to emotional events and rumination—map to these modules.

As a result, normal communication among the three modules becomes destabilized. Activities from module to module typically tug back and forth to balance the cognitive processing of sensory inputs with more introspective thoughts. In depression, though, the default mode dominates, and the afflicted person lapses into ruminative thought. The music of the brain thus becomes increasingly unbalanced, with one family of instruments governing the symphony. These observations have broadened our understanding of the network properties of depression to the extent that a connectivity pattern in a brain can allow us to diagnose certain subtypes of the disorder and determine which areas should be treated with electrical-stimulation technology.

NETWORKS EVOLVE

BESIDES STUDYING DEVELOPMENT, network neuroscientists have begun to ask why brain networks have taken their present form over tens of thousands of years. The areas identified as hubs are also the locations in the human brain that have expanded the most during evolution, making them up to 30 times the size they are in macaques. Larger brain hubs most likely permit greater integration of processing across modules and so support more complex computations. It is as if evolution increased the number of musicians in a section of the orchestra, fostering more intricate melodies.

Another way neuroscientists have explored these questions is by creating computer-generated networks and subjecting them to evolutionary pressures. In our lab, we have begun to probe the evolutionary origins of hubs. This exercise started with a network in which all edges were placed uniformly at random. Next, the network was rewired, mimicking natural selection to form segregated modules and display a property known in network science as small-worldness, in which paths form to let distant network nodes communicate with surprising ease. Thousands of such networks then evolved, each of which ultimately contained hubs strongly connected to multiple modules but also tightly interconnected to one another, forming what is called a club. Nothing in the selection process explicitly selected for a club of hubs—they simply emerged from this iterative process.

This simulation demonstrates that one potential solution to evolving a brain capable of exchanging information among modules requires hubs with strong connections. Notably, real networks—brains, airports, power grids—also have durable, tightly interconnected hubs, exactly as predicted by evolutionary experiments. That observation does not mean evolution necessarily occurred in the same way as the simulation, but it shows a possible means by which one of nature's tricks might operate.

STATES OF MIND

WHEN NOBEL PRIZE–WINNING PHYSICIST Richard Feynman died in 1988, his blackboard read, "What I cannot create, I do not understand." He created a beautiful aphorism, yet it misses a pivotal idea: it should be revised to "What I cannot create *and control,* I do not understand." Absent such control, we still know enough to enjoy a symphony, even if we do not qualify to be the conductor.

When it comes to the brain, we have a basic understanding of its form and the importance of its network architecture. We know that our brain determines who we are, but we are just beginning to understand how it all happens. To rephrase mathematician Pierre-Simon Laplace's explanation of determinism and mechanics and apply it to the brain, one's present brain, and so one's mental state, can be thought of as a compilation of past states that can be used to predict the future. A neuroscientist who knew all the principles of brain function and everything about someone's brain could predict that person's mental conditions—the future, as well as the past, would be present inside the person's mind.

This knowledge could be used to prevent pain and suffering, given that many mental illnesses are associated with network abnormalities. With enough engineering ingenuity, we may develop implanted devices that alter or even generate new brain networks or edit genomes to prevent the disorganized networks associated with mental disorders from occurring in the first place. Such an achievement would enable us to treat diseases and to restore brain function after stroke or injury and enhance it in healthy individuals.

Before those futuristic scenarios materialize, two major gaps must be filled: we need to know more about how personal genetics, early-life development and environment determine one's brain's structure and how that structure leads to functional capacities. Neuroscientists have some knowledge from the human genome about the structure that gives rise to functional networks but still need to learn precisely how this process occurs. We are starting to grasp the way brain networks develop and are shaped by the environment but are not close to explaining the entire complexity of this process. The brain's wiring, its structural connectivity, constrains how various modules interact with one another, but our knowledge remains limited. As we fill in these gaps, chances improve for interventions to guide brain functioning into healthy trajectories.

What holds us back, for the moment, is our still blurry vision of the brain—it is as if we are outside the concert hall and have seen only sketches of the instruments. Inside each brain region that neuroscientists study are millions of neurons firing every millisecond, and we are able just to indirectly measure their average activity levels every second or so. Thus far we can roughly identify the human brain's structural connections. Luckily, scientists and engineers have taken steps to deliver ever clearer data that will enable a deeper look into perhaps the most complex network in the known universe: your brain. SA

MORE TO EXPLORE

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FROM OUR ARCHIVES

100 Trillion Connections. Carl Zimmer; January 2011.

scientificamerican.com/magazine/sa

BIOLOGY

The Invulnerable Cell

Biologists are building an organism that can shrug off any virus on the planet. Impervious human cells may be next

By Rowan Jacobsen

Illustration by Ellen Weinstein

Journalist **Rowan Jacobsen** wrote "Ghost Flowers," about bringing extinct genes back from the dead, in the February 2019 issue.

THE VIRUS TOUCHES DOWN ON THE CELL LIKE A SPIDER LANDING ON A BALLOON 1,000 TIMES its size. It has six thin legs splayed underneath a body that resembles a syringe with a bulbous head. This is a predator named lambda, and its prey is an *Escherichia coli* bacterium. Having found its victim, lambda now does what uncountable trillions of viruses have done since life first emerged: it latches onto the cell membrane with its legs, attaches its syringelike part to a pore and contracts, injecting its DNA inside.

The DNA contains the instructions for making more viruses, and that is pretty much all a virus is: a protein capsule holding blueprints for building more copies of itself. Viruses do not have the molecular machinery to build new things. Instead they break into cells and hijack cellular equipment, using it to replicate until there are so many viruses, they burst through the cell walls. They can do this because all organisms, from rhinoceroses on African plains to rhinoviruses infecting your nose, use the same coding system, which is based on nucleic acids such as DNA. Feed the code into the cell, and it will use those instructions to build proteins.

IN BRIEF

Viral attacks on cells cost pharma—which uses bacterial cells to make drugs—and other industries billions. They also harm health.

A project to recode the DNA of a bacterial cell is removing all genetic pathways that make it vulnerable.

The redesigned cell should work normally and pave the way for virus-safe human cells.

In the infected bacterium, that process starts. New viral proteins take shape. Things are looking good for lambda. Within minutes the cell will be bursting at the seams with a multitude of brand-new viruses. When they break out, each one will head for another bacterium, aiming to repeat this cycle over and over again.

Then the cellular machinery freezes. It simply cannot read the virus's DNA. In the seemingly eternal duel between virus and cell, this failure has never happened. And now it means lambda is doomed.

The reason for its demise is that this strain of *E. coli* has been reprogrammed to use a DNA operating system that has never existed on earth, and the viral code is incompatible with it. The differences leave lambda as helpless as a Windows computer virus inside a Mac. The same fate will befall other viruses that attack. The people who made this bacterium and its new code believe the feature will make it immune to all viruses. They call it *rE.coli-57*. And they have big plans for it.

rE.coli-57 is being built in a laboratory at Harvard Medical School by a team led by a young biologist named Nili Ostrov. For the past five years Ostrov has obsessed over every detail of the bacterium's genetic reconstruction, putting in grueling hours under the fluorescent lights of the wet lab. It is the most elaborate gene-editing project in history and was the subject of a 2016 landmark paper in *Science* that identified 148,955 DNA changes necessary to make the cell virus-proof. Ostrov's team had completed 63 percent of them, she and her colleagues reported, and the beast was doing fine.

Three years later the rebuilt cell is almost ready. Sometime soon the scene just envisioned will take place with not just one but hundreds of viruses in a petri dish. If *rE.coli-57* survives, it may forever change the relation between viruses and their prey—including us.

Viruses are incredibly abundant, with 800 million of them covering every square meter of this planet. They vex us with illness, but they also torment industries that use cells to manufacture products from yogurt to pharmaceuticals. The biotech giant Genzyme (now part of Sanofi), which uses bacteria to make drug molecules, lost half its market value after a 2009 virus infection in its Allston, Mass., plant sabotaged its production line, triggering critical pharmaceutical shortages. Viruses are also an expensive scourge in the dairy industry, which employs bacteria to ferment cheese and yogurt—these products have to be dumped when the bacteria are hit by viral contamination. A virus-proof bacterium could be a billion-dollar bug.

Such a cell could also open up a new world of designer medicines. "If we want to make fancy antibodies and fancy protein drugs, we need to incorporate different chemistry into them," Ostrov says. "That would be a game changer for drug companies." All natural proteins are built from the same 20 amino acids, but *rE.coli-57*'s altered operating system would allow it to build new proteins using exotic amino acids, just as new LEGO pieces expand what can be built with the basic starter set. Designer proteins could target diseases such as AIDS or cancer with exquisite precision.

More controversially, *rE.coli-57*'s success could be a step toward making human cells virus-proof by rendering their DNA impervious to viral hijacking. That achievement would be invaluable to medical research, which suffers from viral infection of human cell lines in lab dishes that are used to develop and test therapeutic medicines. Skeptics, however, doubt recoded cells would function like "normal" ones, making them unreliable test beds. The idea also alarms those who fear such recoding puts us a little closer to creating human beings with designer DNA. (No one involved in the project has proposed designing people.) Just to recode one human lab-dish cell would be extraordinarily complicated because the human genome is 3.2 billion letters long, 800 times larger than *E. coli*'s. But *rE.coli* is an essential and mind-blowing first step.

CODE BREAKERS

RECODING DEFEATS VIRAL INVADERS because it alters the language a cell employs to make proteins, which are the molecules that all life uses to get anything done in the world. Proteins are made of smaller units known as amino acids, and each amino acid has a three-letter DNA code made of some combination of the four DNA bases: A, C, G and T. For instance, TGG means tryptophan, and CAA means glutamine. These three-letter codes are called codons, and every gene is simply a linear sequence of them.

The protein making happens when that sequence gets sent to cellular factories, ribosomes, where the codons pair up with molecules called transfer RNAs (tRNAs). Each tRNA has one end that binds to a particular codon and another that binds to one and only one kind of amino acid. As the sequence of codons moves through the protein assembly line, the tRNAs string together the amino acids until the protein is complete.

But there is an important peculiarity in this system: it has a lot of redundancy. There are 64 codons because there are 64 three-letter combinations of A, C, G and T. But there are only 20 amino acids. That means there are multiple codes for most of the amino acids. AGG stands for arginine, for example, but so does CGA. Some amino acids have six codons.

Back in 2004, George Church, a Harvard geneticist and Ostrov's boss, began to wonder if all these codons were absolutely necessary. What if every AGG in the *E.coli* genome was changed to CGA? Because both code for arginine, the bacterium would still build all its normal proteins. But—and this is a key point—if the tRNA that pairs with AGG was also eliminated from the cell, then the AGG codon would be a dead end in the protein-building process.

As Church thought about the implications of getting rid of certain tRNAs, he had an epiphany. "I realized that this would make the cells resistant to all viruses," he says, "which would be a potential very big bonus." Viruses such as lambda reproduce by getting a cell to read viral genes and build proteins using those sequences. But if the tRNA for AGG is deleted from the cell, then every viral gene that includes an AGG codon will get stuck awaiting a tRNA that no longer exists, and no viral protein will be completed.

Viruses evolve furiously; Church suspected they would quickly work around a single vanished tRNA. But if enough codons and tRNAs were eliminated, it would be virtually impossible for a virus to spontaneously hit on the right combination of mutations to use the revised code. *E.coli* had seven codons that were relatively rare. They occurred in all 3,548 of its genes, an average of 17 times per gene. If all the corresponding tRNAs were eliminated, a virus would need to develop about

A recoded cell could open up a new world of designer medicines. "That would be a game changer," Ostrov says.

60,000 new sequences, each one calling for the right substitute codon in exactly the right spot. And that was just not going to happen.

In 2004 this scenario was just idle thought. It was hard enough to change a single gene in an organism; editing the thousands of genes necessary to eliminate every instance of certain codons was impossible. But by 2014 technological breakthroughs put doing so just on the edge of imaginable. So Church started looking for someone with the drive and organizational skills to tackle the largest gene-editing project in history.

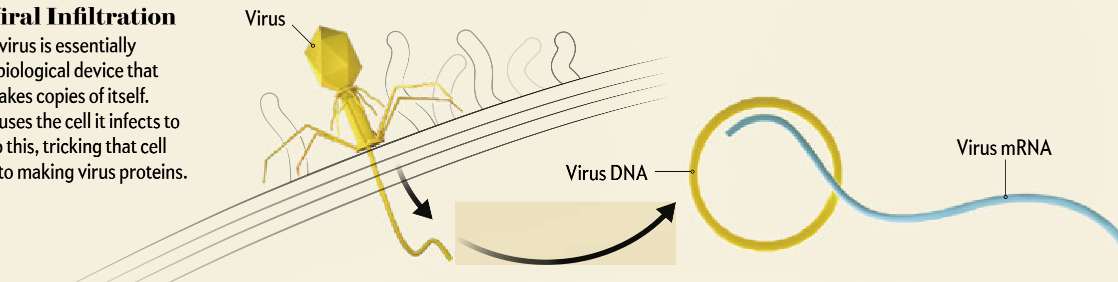
That was when Ostrov arrived in his lab as a postdoctoral researcher. If Church was the architect of *rE.coli-57,* Ostrov became the engineer and general contractor. Ostrov had a lot of molecular construction experience. She grew up in Israel and attended Tel Aviv University, where she modified a protein by adding a few amino acids that bound a metal particle. When several of these modified proteins snapped together, they formed a nanowire that could carry current. "That was awesome," Ostrov recalls. "I thought, wow, we can use biology to make useful things." Later, at Columbia University, she earned her Ph.D. by engineering baker's yeast to produce red pigment when it detected disease-causing microbes; the project earned a Grand Chal-

Virus vs. Cell

There are millions of viruses that infect and take over human and bacterial cells, turning them into virus-making factories. Biologists are now redesigning the DNA of a bacterium, *rE.coli-57,* with genes that let it function as a normal healthy cell but resist all viral assaults.

1 Viral Infiltration

A virus is essentially a biological device that makes copies of itself. It uses the cell it infects to do this, tricking that cell into making virus proteins.



A virus lands on a bacterial cell and injects its own DNA inside. That DNA is made of the same "letters" as bacterium DNA so the cell treats both equally.

The virus DNA is transcribed into a strand called mRNA, which contains instructions to make virus proteins.

2 Hijacking

That virus mRNA moves into the cell's protein assembly plant, or ribosome. There each group of three mRNA letters, known as a codon, pairs with a specific complementary molecule called a tRNA (*blue*). Each one of those is attached to a particular protein building block known as an amino acid (*yellow*).

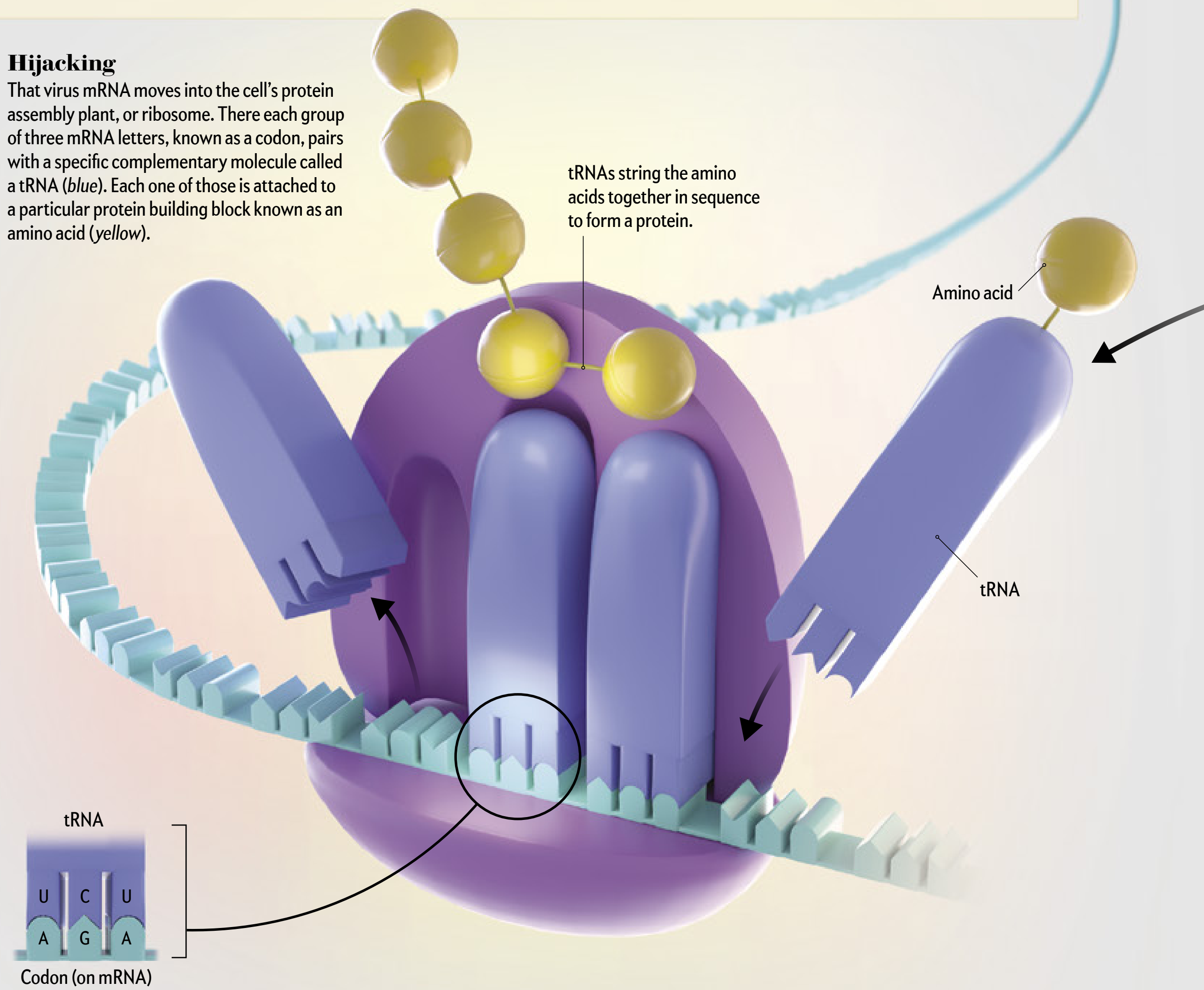
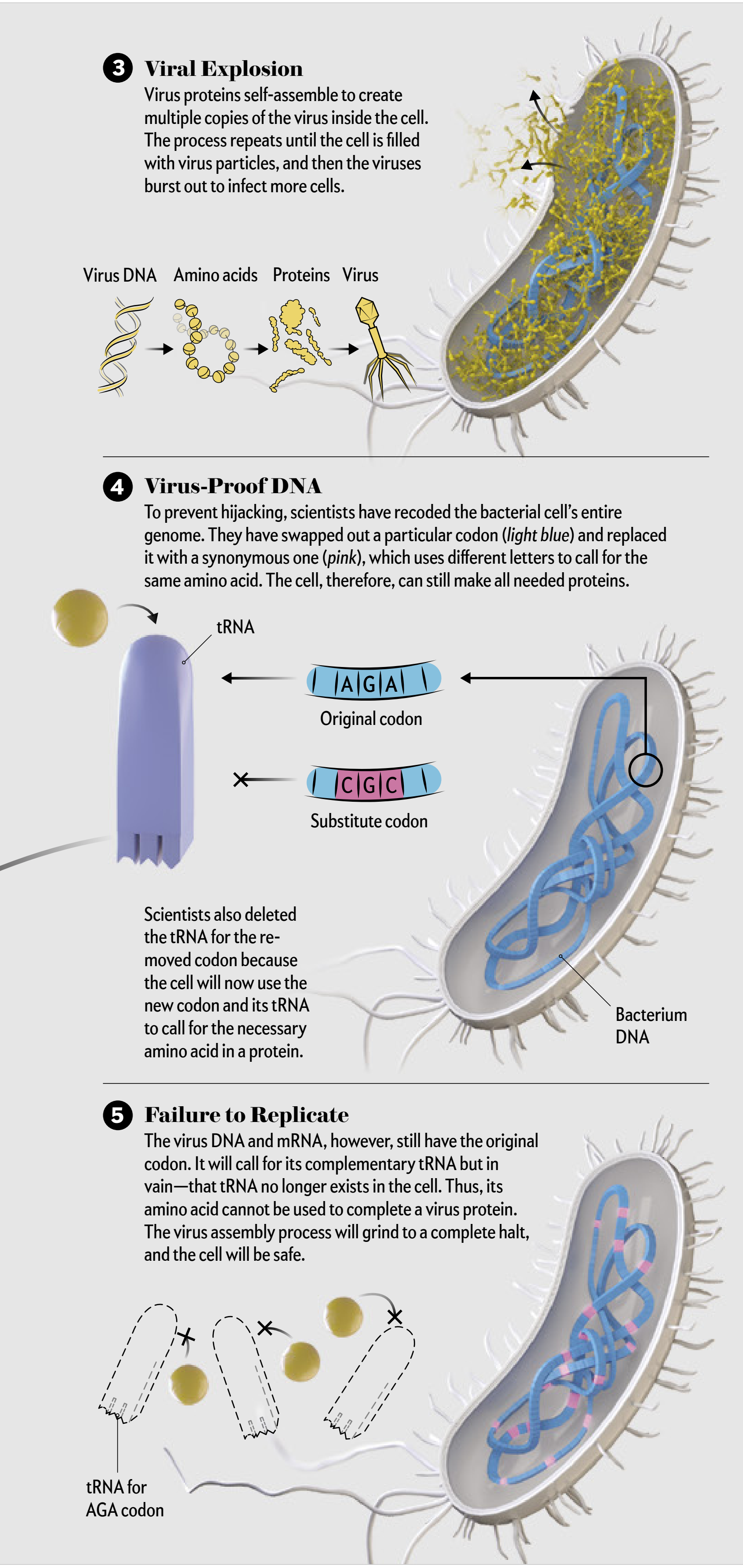


Illustration by Campbell Medical Illustration



lenge Exploration award from the Bill & Melinda Gates Foundation for its use in detecting cholera.

It was an impressive résumé, but Church's project was exponentially more difficult. The seven codons to be eliminated appeared 62,214 times in the *E. coli* genome. Recoding them all required making 148,955 changes to the DNA. There had been a lot of headlines about fast and easy gene editing, but no gene-editing tool was capable of making anywhere near that many changes.

Breakthroughs in DNA synthesis, however, pointed to another solution: build a recoded *E. coli* genome from scratch. DNA can be produced biochemically in special DNA printers, which work like an inkjet printer spraying As, Cs, Gs and Ts. Today's DNA-synthesis companies can reliably make pieces of DNA up to about 4,000 letters long.

Around 2015 Ostrov's team downloaded the standard *E. coli* genome, a long string of four million letters, from a database and put it on a computer. Then the researchers went through the entire sequence, changing all 62,214 instances of the seven rare codons to synonymous ones. (For safety, they also changed genes to make the bacterium dependent on a synthetic amino acid supplied in its nutrient broth. That synthetic molecule does not exist in nature, so the bacterium would die if it ever escaped the lab.) The result was the new *rE.coli-57* genome scrolling across a computer screen. The scientists then divided its four million letters into 4,000-letter pieces with overlapping ends and sent the files to a DNA-synthesis shop. "We cut it on the computer," Ostrov says, "literally like a Word document." The company printed the DNA and sent it back by FedEx. The team assembled those 4,000-letter pieces into 87 large fragments of 50,000 letters each, which is about 40 genes.

Those fragments were just DNA, of course, and DNA is just code. A cell is needed to bring that code to life, and no one knows how to build one of those completely from scratch. Instead Ostrov took a piecework approach. She started with colonies of normal *E. coli* and slowly replaced each piece of their genome with a recoded fragment, one at a time, testing after every transplant to see if the patient survived.

REBUILDING A CELL

ON THE LONG, BLACK BENCHES of the Church lab, amid centrifuges, vortex mixers, racks of pipettes and stacks of petri dishes, Ostrov's team grew 87 colonies of normal *E. coli* in an incubator the size of a dormitory fridge, inserted a different 50,000-letter recoded fragment into groups of microbes, then waited to see if they would live. She did not get her hopes up. Perhaps evolution had chosen its codons for reasons that had escaped human understanding.

Surprisingly, most colonies did well. Only 20 of the revised segments stopped microbes from growing. But that was 20 too many. For *rE.coli-57* to be virus-proof, all the recoded sections had to work. "First, we tried to narrow it down to which specific gene didn't work," Ostrov says. "We broke up the 40-gene segment into two

BIOLOGIST Nili Ostrov and her colleagues at Harvard University have created *rE.coli-57,* an otherwise normal *E. coli* bacterium that has nearly 150,000 DNA changes throughout its genome intended to make it virus-proof.

STEPH STEVENS

20-gene versions and tested those. Then we narrowed it down to four genes that might be the problem. Then one gene. And then we figured out which codon might be the problem."

As it turned out, most of the trouble came from DNA printing errors. In other words, the sequences of DNA Ostrov's team received were not exactly what it had ordered—a common issue in DNA synthesis until very recently. Ostrov went back to the company and got new error-free sequences. After the bad DNA was replaced, more than 99 percent of the redesigned genes worked. Recoding, it seemed, was not a crazy idea.

But there was a handful of remaining problems that seemed to be real issues with protein or DNA function, not quality control at the printer. Ostrov had to figure out what evolution knew that she did not. Why would changing to a synonymous codon, which coded for the exact same amino acid, kill or damage the organism?

Troubleshooting these spots was like blazing a trail through a wilderness for which there was no map. For example, the reproduction rate in bacteria with a recoded section 21 slowed to a crawl. Why? Because there was no scientific literature on these recoded DNA stretches to guide Ostrov—her team was the first to reshape them—she carefully analyzed the performance of all the genes in the section, comparing their products with those in normal bacteria. She found five linked genes that were intact but that, for some reason, were not doing anything.

It turned out to be a problem with the genetic equivalent of an on/off switch. Genes are preceded by sequences of DNA called promoters that control whether the gene is active or not. In higher life-forms, promoters and genes are clearly delineated, with obvious starting and ending points, but sometimes bacterial genes overlap; the DNA sequence at the end of one gene actually doubles as the beginning of the next. Ostrov found that a DNA sequence in a gene called *yceD* was doing double duty as the promoter, the switch, for the five genes that followed. By recoding *yceD,* she had accidentally turned them off. She changed three codons on *yceD* so their DNA more closely matched the design of a known strong promoter. The output of the five genes surged, and the bacteria began reproducing normally.

Ostrov's team had an even tougher challenge with recoded section 44, which had killed its colony entirely. The researchers narrowed the problem area down to a gene called *accD* that bacteria use to make fatty acids. The recoded cells were not making any *accD* protein at all. Ostrov ran a design analysis on the recoded gene and guessed that the problem was right at the beginning of its sequence. In DNA, As and Ts naturally bond, as do Gs and Cs. (In mRNA, the molecule that DNA uses to send code to the protein-making ribosome, a base abbreviated as U substitutes for the T, and it binds to the A with the same specificity.) If the letters are in a certain order—lots of As, say, followed by lots of Ts—the end of the molecule can fold on itself like sticky tape and gum up cellular machinery. On her computer, Ostrov redesigned the gene, revising 10 of its 15 recoded codons to other, synonymous ones that seemed less likely to form sticky folds. When she inserted the new piece of DNA into the bacteria, the colony sprang back to life.

So it has gone, one troubleshooting exercise at a time, the researchers tinkering with biology but thinking like mechanics, always following the design-build-test cycle of the engineer. Remarkably there have been no deal breakers. "So far we haven't hit any impossible spots," Ostrov says. "The code gives us a lot of wiggle room."

VIRUS-PROOF

THIS YEAR, AFTER SHE ADDED working genetic segments from one strain to working segments in another, Ostrov turned the original 87 strains into eight healthy lines, each with one eighth of the fully recoded genome. Every time the scientists combined segments, new incompatibilities arose and had to be troubleshot. But by early spring eight lines were quickly coming together into four, heading toward two. Sometime soon there will be one strain of 100 percent recoded *rE.coli-57.*

Once that strain is up and running, the final step will be to eliminate the tRNAs associated with the missing codons. The cell will be just fine because its genes will use synonymous tRNAs that still exist. But an incoming virus should not be fine at all. Its genes, which have not been reengineered, will have some codons that call for a tRNA that no longer exists. No tRNA means no amino acid at that point in the protein-building sequence, which stops assembly. No new viral protein, no new copies of the virus. The viral DNA remains marooned inside the cell, isolated, alone, unable to replicate and do any harm.

Ostrov plans to test this scenario in a microscopic version of the old film *Mad Max Beyond Thunderdome,* where a hero, trapped in an arena, has to beat a series of attackers. This arena will be a small glass container. The biologists will add lambda to a dish holding a healthy colony of *rE.coli-57.* Then they will step back and let the organisms battle to the death. If *rE.coli* survives, the researchers will add another bacteria-preying virus and, after that, another. It is difficult to envision a way for even the most gifted viruses to crack *rE.coli*'s elaborately altered code. But then again, no virus has ever been forced to try. Two organisms will enter—one will leave.

Ostrov is too cagey to commit to a date for the contest because she does not yet have the single completely recoded strain, but she believes she and her team are close. "Sooner rather than later," she says. "Absolutely." And she hints that a celebration with Brazilian cocktails that she likes may be coming shortly. "When it's done, I won't keep it quiet. I'll call from the beach with one hand holding a caipirinha."

Viral immunity alone will make *rE.coli-57* worth celebrating, but the bacterium will also offer, as Ostrov and her colleagues put it in their *Science* paper, "a unique chassis with expanded synthetic functionality that will be broadly applicable for biotechnology." In other words, the microbe will be a flexible platform for assembling new kinds of proteins.

That could be a boon for drug development. Many cancer and immunotherapy drugs are proteins that break down quickly in the body, but rebuilding them with exotic amino acids could greatly extend their life span. Church has already launched a start-up called GRO Biosciences (the acronym stands for "genomically recoded organism") to design such therapeutics.

ALTERED LIFE

A FEW YEARS FURTHER OUT, the vision of recoded, virus-proof human cells looms. These cells could solve the ongoing problem of viral contamination of cultured human cell lines (such as the famed Henrietta Lacks cancer cells) used throughout medical research. In labs, lines of human cells are regularly employed as test beds to develop new medicines and ideas for therapies. But once viruses infect such cells, they are almost impossible to get rid of, so experiments get tossed out, and scientists have little choice but to start over. If the therapies could be developed faster, they would save lives. The Center of Excellence for Engineering Biology, a global collaborative effort with Church as a founding member, has named recoded human cells as its initial project. *rE.coli-57* would clearly be a stepping-stone on that path.

Not surprisingly, the idea of redesigning the operating system of human cells alarms some critics. For one, the cells might not be reliable mimics of natural cells. And although the center's scientists have never proposed doing anything with the cells beyond cultured cell lines, it might be possible to create a recoded human being who might also be virus-proof.

That would be bad, says Columbia University virologist Vincent Racaniello, who panned the idea on his scientific blog. "Multiple codons exist for a reason—among others they provide a buffer against lethal mutation," he wrote. "Recoding the human genome in this way is not likely to be without serious side effects."

None of the project scientists have suggested recklessly editing the DNA of a baby and seeing what happens, as occurred in China last year. What they do say is that a careful, transparent study of how recoded human cells behave could give us brand-new insights into the

Biologists will add a virus to a dish holding **rE.coli-57.** ***Then they will let the organisms battle to the death.***

relation between us and many of our most injurious diseases. For all of our time on earth, we have been stuck with the 64-codon system—and the illness-causing viruses that take advantage of it. In a few years we may know if we have to accept that situation or not.

Ostrov is not a part of the center's project—"Just to clarify, I do not recode human cells"—but says that it is important to explore the genetic unknown safely, in lab dishes. "Clearly, there's a reason evolution has selected the codons it has. But we know there are other viable options," she says. "By changing them, we get to investigate what happens. We'll see what works and what doesn't, and we'll have a better understanding of the rules." Knowing these principles may offer us a chance to improve some of the organisms that use them. SA

MORE TO EXPLORE

Design, Synthesis, and Testing toward a 57-Codon Genome. Nili Ostrov et al. in *Science,* Vol. 353, pages 819–822; August 19, 2016.

Beyond Editing to Writing Large Genomes. Raj Chari and George M. Church in *Nature Reviews Genetics,* Vol. 18, pages 749–760; December 2017.

FROM OUR ARCHIVES

Engineering Life: Building a FAB for Biology. David Baker et al.; June 2006.

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BROKEN PROMISES

MINING COMPANY RIO TINTO extracts the mineral ilmenite in southeastern Madagascar's coastal forest—a severely threatened ecosystem.

CONSERVATION

Mining giant Rio Tinto made a high-profile pledge to improve the ecology of its ilmenite sites in Madagascar in cooperation with conservation scientists. Then its bottom line began to suffer

By Rowan Moore Gerety

In the forest in Mandena, Madagascar,

Rowan Moore Gerety is a reporter and radio producer in New York City and author of *Go Tell the Crocodiles: Chasing Prosperity in Mozambique* (The New Press, 2018). His reporting trip for this story was paid for with a grant from Mongabay.

BANANA-LEAFED *RAVENALA* TREES CROWD OUT THE sun, their electric blue seed pods dotting the leaf litter and white sand below. When night falls, gray mouse lemurs emerge from tree hollow dens to feed on insects, flowers and fruit. During the rainy season, pools of water form where screw pines' pom-pom-like clusters of long leaves meet their trunks, the base of each leaf forming a reservoir just large enough to nurture small schools of tadpoles to maturity before the puddles dry out every April. There ring-wearing tree frogs—named for the bright-white bands that mark each webby finger—find a perfect spot to nurture their next generation, high above would-be predators. Leopard-spotted and no bigger than a child's thumb, the frogs lay their eggs in a sticky clutch above the water and stand watch for nearly a week, until their offspring drop into the tiny pool and begin to swim.

At close range, this corner of Mandena feels like you could get lost in it. But above the canopy reality looms into view. Forest once stretched to the horizon. What's left of it is now smaller than Brooklyn's Prospect Park—less than a half-hour walk from end to end, sandwiched between a mine on one side and a steadily expanding village on the other.

Madagascar broke free of the land that makes up Africa and India nearly 100 million years ago. Across the eons, evolution in isolation has given the island unparalleled ecological richness: Four out of five plants and animals there are found nowhere else, the sweeping cast of characters in a wide array of highly specialized symbiotic niches. The country's 83 species of screw pine alone serve as breeding grounds for dozens of different reptiles and amphibians. But the ballet between this particular tree and frog is now confined to a tiny collection of forest fragments, like the one in Mandena, that are spread along Madagascar's southeastern coast. Two of the three smatterings of forest where the frog is still found lie inside a concession belonging to Rio Tinto, one of the largest mining companies in the world.

Rio Tinto came to Madagascar in the 1980s, looking for ilmenite, a mineral used to make titanium dioxide, which provides the white pigment found in products ranging from paint and plastics to toothpaste. Test pits hit pay dirt near Tolagnaro (Fort Dauphin), at the southeastern tip of the island. The ilmenite deposits that interest the company lie underneath the remnants of dense evergreen forests that once grew on sand dunes along most of Madagascar's eastern coast, forming a continuous band covering perhaps 465,000 hectares. Since human colonization of the island some 2,000 years ago, these littoral forests, as they are known, have dwindled to at most 10 percent of their original expanse. As such, Rio Tinto's concession weaves through one of the most threatened ecosystems on the planet.

Ordinarily, the discovery of so much buried wealth underneath an already vulnerable ecosystem would spell doom for most of what lives there. But in 2004 executives at Rio Tinto, which is headquartered in London, flew to the International Union for Conservation of Nature's World Conservation Congress in Bangkok, a major gathering of scientists, environmentalists, and government and business leaders, to unveil what amounted to a radical rethinking of mining's relationship with the natural world. Going forward, they pledged, the company would seek not just to limit the environmental damage it caused but to actively improve the ecology of its most sensitive mine sites. And it would start with the mining concession in southeastern Madagascar.

Conservationists met the proposal with enthusiasm. They had reason to be optimistic: Rio Tinto and its predecessor had already been collaborating with scientists from the Missouri Botanical Garden for more than a decade, funding and conducting botanical surveys and studies of the new species discovered throughout

IN BRIEF

In 2004 mining company Rio Tinto vowed to improve the ecology of its most sensitive sites. It would start in Madagascar, where the company was working to extract the mineral ilmenite.

Conservationists working in Madagascar, which is rich in species that are found nowhere else in the world, partnered with Rio Tinto to help the company make good on its pledge.

Eventually Rio Tinto retreated from its promise, raising questions about whether mining companies and conservationists can collaborate effectively on environmental stewardship.

PRECEDING PAGES: ED KASHI *Redux Pictures*

SUN RISES over Tolagnaro (Fort Dauphin), Madagascar. Some 70 million metric tons of ilmenite lie under the littoral forest in this region.

MARTELET CHRISTIAN *Getty Images*

the company's concession. There were few details yet and no hard benchmarks, but if Rio Tinto followed through, the stance had the potential to reverberate throughout the industry, forcing mining companies to compete for permits on the basis of their environmental programs.

As part of this conservation initiative, Rio Tinto had created what the company called a biodiversity committee made up of researchers and nonprofit managers who could help its local subsidiary, QIT Madagascar Minerals (QMM), plan and carry out environmental work on the margins of what promised to be an enormous mine. Madagascar's government would receive a 20 percent stake in QMM—an investment that could generate hundreds of millions of dollars in new revenue for the country over time. For the scientists in the group, joining the committee represented a leap of faith. Their input could prevent the worst and harness Rio Tinto's investment for environmental good. But it also meant they would share the blame for anything that went wrong.

It didn't take long. Within a few years of the committee's inception, its members repeatedly raised concerns that QMM was not on track to meet its biodiversity goals. When ilmenite prices slumped during the Great Recession, Rio Tinto's priorities shifted, and by 2016, the company reneged on its grand conservation promise. Instead it adopted the vague goal of avoiding making things too much worse. Today mining near Mandena is poised to extinguish this biodiversity hotspot. For the people who live there and dozens of endemic species such as the ring-wearing tree frog, destiny now turns on the outcome of this long-running experiment, a test case for industry's role in conservation and the role conservationists can play in the mining industry.

In its natural state, ilmenite accumulates in the deep sediments deposited by rivers and streams that changed course long ago, forming a black sand so heavy it separates from lighter minerals at the surface. To extract the mineral, miners begin by using backhoes and chain saws to remove every scrap of vegetation from each mining tract and pile it into gargantuan mounds of compost. Earth-moving machines dig a trench several stories deep and longer than a football field, which is then filled with water diverted from a nearby river. A dredge stirs up sand from a depth of up to 18 meters and pumps it onto a barge through an oversized straw, where gravity separates some of the ilmenite ore from sand, topsoil and lighter materials. Great "black snakes"—temporary pipelines—crisscross the expanse, conveying the mineral-rich slurry to a gleaming green processing plant near the water. Electrostatic separation is used to extract still more ilmenite before the demineralized sand and soil are spread back out over the landscape.

Rio Tinto discovered ilmenite near Tolagnaro in 1986. At the time, the forests in the region were already heavily fragmented and degraded by human activity. But the company's prospecting soon brought new roads to the area and an influx of people looking for work, hastening the deforestation underway for charcoal production and new farmland to supply the growing city.

Rio Tinto determined that the region around Tolagnaro contained some 70 million metric tons of ilmenite—enough to supply about 10 percent of the global market for a decade or more—and began to make a plan for extracting it. The company set its sights on three mineral-rich areas along the coast encompassing a total of approximately 6,000 hectares. Mining would start at the 2,000-hectare site in Mandena and eventually expand north to Sainte Luce and to Petriky farther south. The extraction would continue for the life of the mine—about 60 years from the date of first production, according to the company's projections. Rio Tinto estimated that in the end the project would result in the loss of 1,665 hectares, or 3.5 percent, of Madagascar's remaining littoral forest.

While Rio Tinto explored the area to gauge the full extent of the ilmenite deposits, it initiated environmental studies. As part of this effort, the company funded one of the first botanical inventories of forests along Madagascar's eastern coast—Rio

Tinto knew it would stand a better chance of securing the requisite mining permits if it could show that it had done due diligence about the extent of environmental damage its mining would bring about. Botanist Pete Lowry worked with a team of his colleagues at the Missouri Botanical Garden to collect and document every plant species they encountered. As the team found dozens of unfamiliar plants, Lowry says, "it sort of dawned on us—there are a lot of species that seem to grow on white sand and nowhere else." The team was tracing the outlines of an ecosystem scarcely known to science. Rio Tinto went on to partner with top-flight researchers from around the world, supporting studies on more than 40 previously undescribed species found in the mining concession.

Despite Rio Tinto's support for ecological research in Madagascar, by the early 2000s the company's global track record had earned it a reputation as an unscrupulous actor in a heavily polluting industry. In Papua New Guinea, where Rio Tinto had developed a giant copper mine in the 1980s, protests brought on by the company's disparate treatment of white foreigners and local workers forced the mine's closure and helped to spark a civil war. Thirty years later Rio Tinto is gone, but pollution from the shuttered Panguna mine will still cost an estimated $1 billion to clean up.

It was against this troubled backdrop that Rio Tinto went to Bangkok in 2004 to announce a pilot conservation initiative in Madagascar. The company called the strategy net positive impact (NPI). It pledged to leave the local ecosystems in Mandena, Sainte Luce and Petriky—all of which have especially high biodiversity—better off *because* of mining than they would have been without it. In 2005 Rio Tinto began to roll out the particulars of its plan. It would avoid mining altogether in well-preserved forest fragments in each of the three sites; undertake unprecedented ecological restoration of areas cleared during mining; and invest in biodiversity offsets at several forest sites elsewhere in the region to compensate for the damage it would do in the mining zone. The biodiversity committee would serve to help the company make good on its promise.

The partnership did not sit well with some conservationists. Barry Ferguson, an environmental researcher then based in Tolagnaro, saw the arrangement as a kind of mutually beneficial "greenwashing" whereby scholars with strong conservation bona fides boosted their research careers with studies funded by QMM. Other observers were skeptical that net positive impact was a target Rio Tinto could ever meet in such an ecologically sensitive area. After all, dozens of plant species are known only from areas within the mining concession. The existence of a particular species of day gecko, *Phelsuma antanosy,* a tiny dart of neon green with red stripes and flashes of turquoise on the males, is even more precarious. Confined to habitat thought to be less than 10 square kilometers, the gecko lays its eggs on a single species of screw pine and forages for insects on the same tree.

Achieving NPI in Madagascar would be an expensive proposition. Rio Tinto calculated that it would have to leave $1.2 billion of ilmenite underground to spare the 624 hectares of forest in the so-called avoidance zones and convert them into protected areas. Restoring ruined forest and creating offsets would cut further into its profits.

Yet in promotional materials, the company often argued the "business case" for NPI, based on a need to show governments and investors that Rio Tinto is the best firm to carry out projects with major social and environmental risks. The way Lowry understood it, "occupying the high ground would give [Rio Tinto] a commercial advantage." He became the biodiversity committee's president in 2006. Early on Lowry hoped the mine in Madagascar, along with two other Rio Tinto pilot sites for NPI in Mongolia and Australia, could help define a new path for the mining industry's relationship with the environment at a time when companies were concerned that social and environmental risks might lock them out of potentially lucrative sites. "The idea was, 'We're a dirty business, everybody knows we're a dirty business,'" he says. "'What do we need to do to gain access in the future?'" Rio Tinto officially began mining operations there in 2008.

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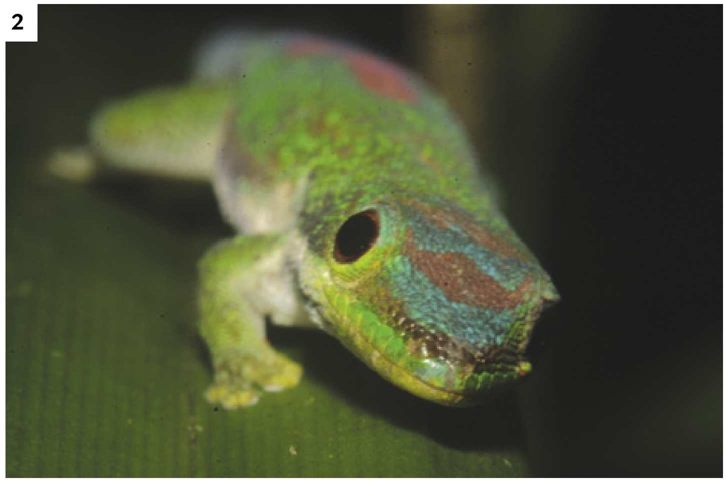


FRANCO ANDREONE

But the business case for NPI soon ran headlong into the business of running a profitable mine. Global financial markets plunged in the months before Mandena was set to enter production in December 2008, and Rio Tinto's stock price tumbled as the company braced for lower demand. The first shipments of ilmenite left Madagascar for processing in Canada in May 2009; by the end of the year demand for the mineral was down 20 percent.

For a while Rio Tinto upheld part of its conservation promise, steering clear of its designated avoidance zones. But simply

RIO TINTO'S MINING SITES in Madagascar are home to a number of imperiled species, including the ring-wearing tree frog (*1*), the Antanosy day gecko (*2*) and the collared brown lemur (*3*). Some species are known only from areas within the company's mining concession.

KONRAD WOTHE *Nature Picture Library*

avoiding these protected areas was not enough—the forests were continuing to degrade from lack of active management and encroaching loggers and charcoal producers. The biodiversity committee grew concerned that the company was not ramping up its conservation work accordingly. "Species extinction is QMM's biggest biodiversity risk," the committee warned in 2010.

The conservation outlook deteriorated from there. Between 2010 and 2012 QMM was supposed to have made substantial progress in adding to forest cover through restoration work. Instead data from the company's own incremental reviews show that deforestation had already claimed an area nearly as large as the protected one in Mandena. One important fragment, in Sainte Luce—home to four of the seven critically endangered species present in QMM's mining footprint—was on pace to dwindle from more than 200 hectares to less than 50 hectares by 2024. The warnings captured in the minutes of the biodiversity committee's meetings grew more urgent: "HUGE RISK FOR ACHIEVING NPI," members wrote in 2012, arguing that QMM was running out of ways to offset future damage done by the mine.

Meanwhile a series of technical snafus in Madagascar and a costly investment blunder in Mozambique, where Rio Tinto overpaid for a stake in a massive new coal mine, ate into the company's bottom line, prompting cost-cutting measures across the enterprise. Although the environmental program's funding was not facing cuts, it seemed to be falling behind any realistic shot at NPI. Months were lost as Rio Tinto pushed for QMM to shoulder more responsibility for funding the work on its own budget.

Even as the mining dredge steadily ate away at the other fragments in Mandena, QMM had successfully curbed deforestation in the protected area to near zero. But Mandena is by far the easiest of the three sites to manage and the least important for biodiversity. By 2015 QMM's Biodiversity Action Plan warned that achieving NPI required immediately stopping degradation and deforestation in both the offset and avoidance zones in Petriky and Sainte Luce and dramatically slowing the loss of forest in the offsets outside the mining area.

Then, in 2016, Rio Tinto officially abandoned NPI as a corporate mandate. A representative met with QMM's biodiversity committee to present a new corporate environmental standard set to replace NPI, one it framed as "minimizing residual impact." What, exactly, did that mean?

"It was totally devoid of anything really substantive," Lowry recalls. The most Rio Tinto will say publicly is that the answer is "site-specific": individual projects can define and pay for their own environmental management—up to and, if they wish, including net positive impact.

Jörg Ganzhorn, an ecologist at the University of Hamburg in Germany who had been collaborating with Rio Tinto and QMM for more than a decade, was stunned. "I would understand if you as a mining company do not claim net positive biodiversity impact. That's not your job," he says. But no one had forced Rio Tinto to tout the standard on its Web site and fly its CEO to environmental conferences around the globe to speak about the company's groundbreaking initiative. To do all that and then abandon NPI? "That's when I decided I had to leave," Ganzhorn says. That October, he, Lowry and the two other remaining scientists advising Rio Tinto in Madagascar released a statement abruptly cutting ties with the company.

Soon afterward, Rio Tinto executives circulated a set of talking points responding to the committee's resignation, portraying its undoing as a mutual agreement "to refresh the objectives and focus of the panel." A new and improved committee would be formed, with former members lending a hand to shape its work, the statement said. Lowry was the only former member still open to being involved going forward. "The stakes are still very high," he says. "If I don't serve on this committee, there will be zero connection to the work that's been done over the past 20 to 25 years."

In July 2017 I rode along with two members of QMM's environmental team on a tour of Mandena, where a patchwork of rolling fields, forest fragments and wetlands is steadily giving way to the hard corners and straight lines of an industrial site. A Madagascar kestrel perched on a fence post. Rows of eucalyptus and acacia saplings formed a grid over the sandy expanse where the mining dredge had passed. Over time QMM hopes these trees will provide a source of wood and charcoal for communities that currently depend on forest fragments that will soon be mined. Just behind the company's headquarters, QMM maintains a nursery that supplies it with acacia and eucalyptus, along with native plants it is using in experiments aimed at restoring some 675 hectares of forest by the end of the mine's life in 2065.

A family of eastern lesser bamboo lemurs (*Hapalemur griseus*) frolicked by an outbuilding, gnawing on bamboo shoots, as Faly Randriatafika, who oversees QMM's environmental work, walked through rows of tiny seedlings arranged in plastic trays. He pointed to an eight-centimeter sapling of *Eligmocarpus cynometroides,* a spindly palm with fist-shaped seeds, represented by about 20 specimens in the wild, all confined to Petriky. "This plant is very hard to germinate: out of 500 fruits, you get maybe only 20 seeds," he said. "Without QMM, without this project, this species would have disappeared completely."

ED KASHI *Redux Pictures*

Lisa Gaylord, then the company's manager of corporate relations, communities and sustainable development, made a similar observation about the fate of the littoral forests around QMM's mine more broadly. At QMM's satellite office in Tolagnaro, she pulled out her laptop to show me an animated slide depicting changes in forest cover around Sainte Luce over the preceding decade. The patches of green shrank from year to year like sandbars disappearing below a high tide. The implication was clear: mine or no mine, charcoal making and farming will soon take over what little forest remains. "We could do nothing, and I could tell you, that entire forest corridor will go," she said. "It will go. That's where Madagascar's going."

Yet there can be no doubt that the mining is taking a grave toll—not only on forests and wildlife but on people. A village lies at the top of a small hill above the mining area in Mandena, along a rutted dirt road known as the old highway, less than half a kilometer inland from the smooth tarmac road QMM built for its own private use. The *chef fokontany,* or local "headman," Francis Maka Teodorik, gathered 10 of his neighbors to talk with me in his home, where we sat on traditional mats made from *mahampy,* a type of reed gathered in wetlands up and down the coast. Woven *mahampy* has long been the dominant source of income for women here, and along with timber for construction, fuel and charcoal making, its supply is shrinking.

QMM has funded a demonstration plot of restored wetlands and training sessions to encourage local women to harvest *mahampy* sustainably by cutting above the roots. But Teodorik and his neighbors said these efforts obscure the real impact of QMM's mine. Helenette Raverosaotra, a mother of four whose two-room house overlooks QMM's processing plant, said it now takes as many as six or seven foraging trips, instead of one, to collect enough reeds to weave a mat that sells for less than $3, as the wetlands around Mandena have been mined one by one. "QMM has already destroyed all the *mahampy* we used for mats," said Fidéline Jine, who now spends her days fishing for shrimp in the river to earn a small fraction of what she once made. "The mines have filled with sand all the places where the *mahampy* grew."

Local farmers, whose land was flooded to create a water source for the mine, had another grievance. For years they protested that they had not received fair compensation for the amount of land they lost. When QMM finally agreed to assess how much farmland it had taken over, the company's own analysis showed the farmers were right—QMM had paid the farmers for the loss of four hectares but had taken more than six times that amount. QMM eventually paid the farmers for the balance.

One missing ingredient from the mining-conservation partnership, everyone seems to agree, is more robust government oversight. Says Jocelyn Rakotomalala, who runs a Tolagnaro-based NGO called Saha, which works with QMM on social and community projects in the area: "Mining companies could conserve more if only the state were more demanding."

Rio Tinto has often credited its commitment to NPI as a crucial factor in gaining approval for the project, but as Heritiana Ravelojaona, the provincial director of mining in the region, points out, the agreement it signed with the Malagasy government does not require anything like NPI. "Take the case of the offsets," he says. "Those are voluntary commitments." And in Sainte Luce, where villagers have repeatedly protested their loss of access to the small protected areas created by the project, he says, "it's no longer QMM's business. It's up to the state, if it decides to protect the area, to come up with a way to help satisfy the demands of the community after restricting access."

Frank Hawkins, who now runs the Washington, D.C., office of the International Union for Conservation of Nature, was one of the first scientists to become involved with QMM. He now feels that QMM has been a "dismal failure" in terms of social and environmental outcomes. But Hawkins says he would still get involved if the process started over again today because the probable alternative to Rio Tinto is not no mines but mines built with woefully inadequate environmental protections. The planet is already littered with examples. In Butte, Mont., in 2016 thousands of snow geese were killed when a storm drove them into a toxic reservoir left behind by an open-pit copper mine that had ceased operations decades earlier. In the Niger River delta, oil exploration has brought the equivalent of an *Exxon Valdez*

WOMEN HARVEST *MAHAMPY,* a type of reed that grows in wetlands along the coast. The *mahampy* is coated with clay and dried before it is woven. For villagers near Mandena, one of Rio Tinto's mine sites, woven *mahampy* has long been a key source of income. But the supply of the reed has dwindled as wetlands there fill with sand from mining.

spill every single year for 50 years. "The sad truth is that the mining sector finds it very easy to negotiate big deals because you're always talking about lots of money," Hawkins explains.

In Ampasindava, a peninsula in northwestern Madagascar, high-level Malagasy officials have appeared eager to grant approval to a rare-earth mining venture under investigation for financial misdealings, after it successfully lobbied to shrink an adjacent protected area. In southwestern Madagascar, an Australian firm is in the beginning stages of developing another large ilmenite mine, one that is likely to exacerbate water shortages in an arid ecosystem already straining under the pressures of drought and deforestation.

Few believe that the Malagasy government has the political will to extract more meaningful concessions from interested mine operators on the front end. Hawkins says he would like to see mining contracts negotiated in the context of broader regional development plans, so that tourism operators or conservation organizations might provide a counterweight and advocate for a broader vision of development.

For his part, Lowry is dismayed that Rio Tinto's gambit on net positive impact does not seem to have spurred a new wave of competition among mining companies on environmental management. Indeed, the most hopeful signs of boosting industry's environmental record in Africa have come the old-fashioned way, through government action. Chad, Sudan, Niger and Gabon, for instance, have all recently taken punitive action against SINOPEC and China National Petroleum Corporation, two state-owned Chinese oil giants, for pollution and exploitative management practices. Zambia got tough with coal-mining operations largely in response to local protests over labor conditions and pollution. Shortly after my visit in 2017, Malagasy officials made a fact-finding trip to a remote part of Rio Tinto's concession to investigate community protests against the company—far more of a government reaction than the biodiversity committee got with its resignation letter.

Whether that reaction leads to any meaningful enforcement is a different question. Rio Tinto has acknowledged that mining in Mandena had encroached on a "buffer zone" around a lake that provides both *mahampy* and drinking water for communities nearby, increasing the risk that radioactive tailings left over from ilmenite extraction could seep into the water supply. The admission came only after two years of prodding by a British charity that works in the area, the Andrew Lees Trust, which had to commission a study by an independent geophysicist to prove the point. But it turns out that Madagascar's environmental regulator—the National Office for the Environment, funded with fees from mining permits such as QMM's—had known about the breach for at least a year. The office decided not to take any regulatory action.

The most reliable commitments from large mining projects seem to be those that come with money attached: In Mongolia, where the International Finance Corporation (IFC) owns a slice of the Rio Tinto project, net positive impact is still on the table—largely because it is attached to the IFC's own performance standard on environmental stewardship. Elsewhere in Madagascar, some of the most successful environmental partnerships between the private sector and local communities are in the seafood industry, where there is a clearer link between end consumers in Europe and the ecological stakes of their purchasing decisions.

Still, Lowry does not regret his decision to work with Rio Tinto, even after seeing NPI collapse as a company-wide model. "I think where QMM is today is a whole lot better than where it would have been, in terms of environmental and social responsibility, if there had never been a committee," he says. In 2018 Lowry chose to join QMM's newly minted biodiversity and natural resources management committee to try and preserve some continuity with the previous group's work. In a way, he was persuaded by Rio Tinto's retreat. With QMM, at least, decisions about conservation won't be made in London. From its offices in Tolagnaro, the forests are not an abstraction. SA

MORE TO EXPLORE

Conservation Status of Vascular Plant Species from the QMM/Rio Tinto Mining Area at Mandena, Tolagnaro (Fort Dauphin) Region, Southeast Madagascar. Porter P. Lowry II et al. in *Madagascar Conservation & Development,* Vol. 3, No. 1, pages 55–63; December 2008.

Madagascar: Rio Tinto Mine Breaches Sensitive Wetland. Edward Carver in Mongabay. Published online April 9, 2019. https://news.mongabay.com/2019/04/madagascar-rio-tinto-mine-breaches-sensitive-wetland

FROM OUR ARCHIVES

Saving Eden. Rachel Nuwer; May 2016.

scientificamerican.com/magazine/sa

ONE SMALL

STEP

▲ *APOLLO 11* blasts off on its Saturn V rocket. The Kennedy Space Center firing room during the launch (*opposite page*).

BACK

HALF A CENTURY AFTER *APOLLO 11,* WE REMEMBER HOW WE ACHIEVED THE IMPOSSIBLE AND WHY WE NEED TO DO IT AGAIN

▲ BUZZ ALDRIN stands next to the Solar Wind Composition Experiment. A record of his boot print (*opposite page*).

IN TIME

APOLLO 11
1969 50 years 2019
ANNIVERSARY

PRECEDING PAGES: NASA (*firing room*); ALAMY (*launch*); THIS PAGE: NASA (*Aldrin on lunar surface*); GETTY IMAGES (*footprint*)

Neil Armstrong thought he had a 50–50 shot at pulling it off. “There are so many unknowns,” the first man to set foot on the moon said in a 2011 interview with an Australian accounting firm. “There was a big chance that there was something in there we didn’t understand properly and we [would have] to abort and come back to Earth without landing.” That he, Edwin “Buzz” Aldrin and Michael Collins—with the help of thousands of NASA engineers, scientists and mission controllers on Earth—did pull off a moon landing remains one of humanity’s most incredible achievements.

Consider that 50 years ago this month a 36-story-tall Saturn V rocket weighing as much as 400 elephants climbed away from Earth atop an explosion more powerful than the output of 85 Hoover Dams. Once in

◀ ALDRIN hops down the ladder of the *Apollo 11* lunar module *Eagle* to step on the moon's surface for the first time.

▶ NEIL ARMSTRONG'S shadow is visible in this photo he took of the lunar module in the distance.

▲ GEORGE M. LOW, manager of the Apollo Spacecraft Program Office, and other mission controllers monitor their consoles at the Mission Operations Control Room.

▶ ARMSTRONG waves as he and his crewmates head to the launchpad on July 16, 1969.

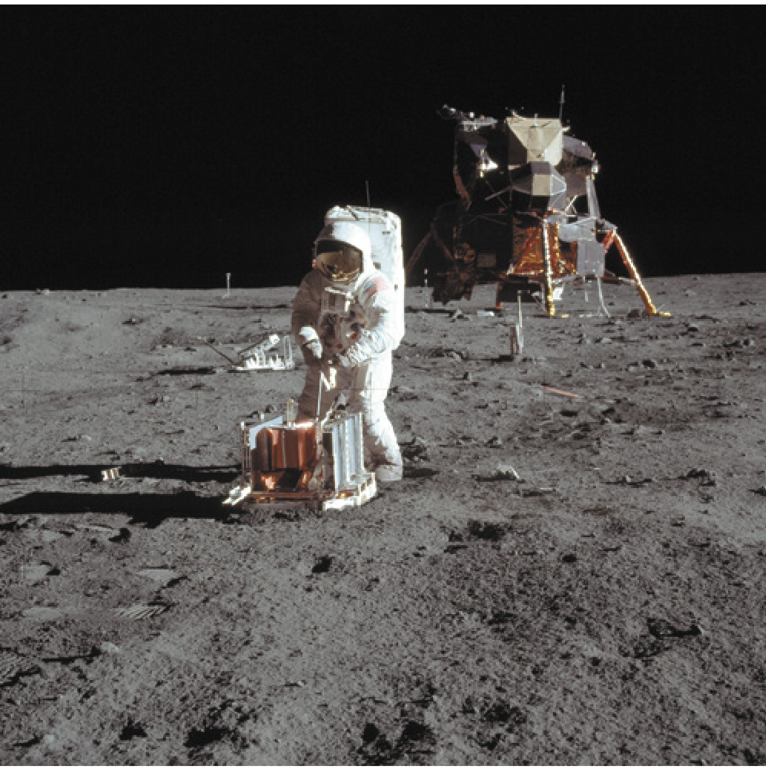
space, the astronauts escaped Earth orbit, traveled to lunar orbit, then undocked part of their spacecraft and steered it down for a soft impact on an alien land. Perhaps even more impressive, after taking a walk around, they climbed back in their lunar lander, launched off the surface of another planetary body (another first), rejoined the command module orbiting roughly 60 miles above the lunar surface, and then flew back to Earth, splashing down safely in the Pacific Ocean two days later.

After that heady feat, dreamers worldwide imagined it would be only a hop, skip and jump to colonies on the moon and vacations on Mars. Yet no human has been back to the lunar surface since the last Apollo astronaut left it in 1972, and plans to put people on Mars or anywhere else in the solar system are barely more defined than they were back then. It seems that every subsequent president promises to send another crew to the moon, but by now those calls have begun to sound like fanciful, unfeasible optimism. When Vice President Mike Pence announced in March that the Trump administration wants to land astronauts on the

CLOCKWISE FROM TOP LEFT: NASA (*Aldrin; lunar module and Armstrong; crewmates*); GETTY IMAGES (*mission control*)

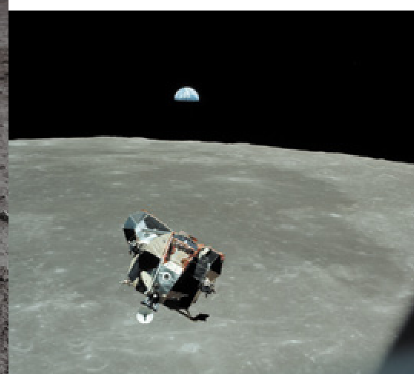
▲ MEMBERS OF THE PRESS watch *Apollo 11*'s liftoff from the Kennedy Space Center.

▲ JUST AFTER coming inside the lunar module after their moon walk, Aldrin took this photo of an elated Armstrong.



◀ ALDRIN deploys the Passive Seismic Experiment on the moon.

▲ ONBOARD THE LUNAR MODULE, Aldrin listens in on his headset.



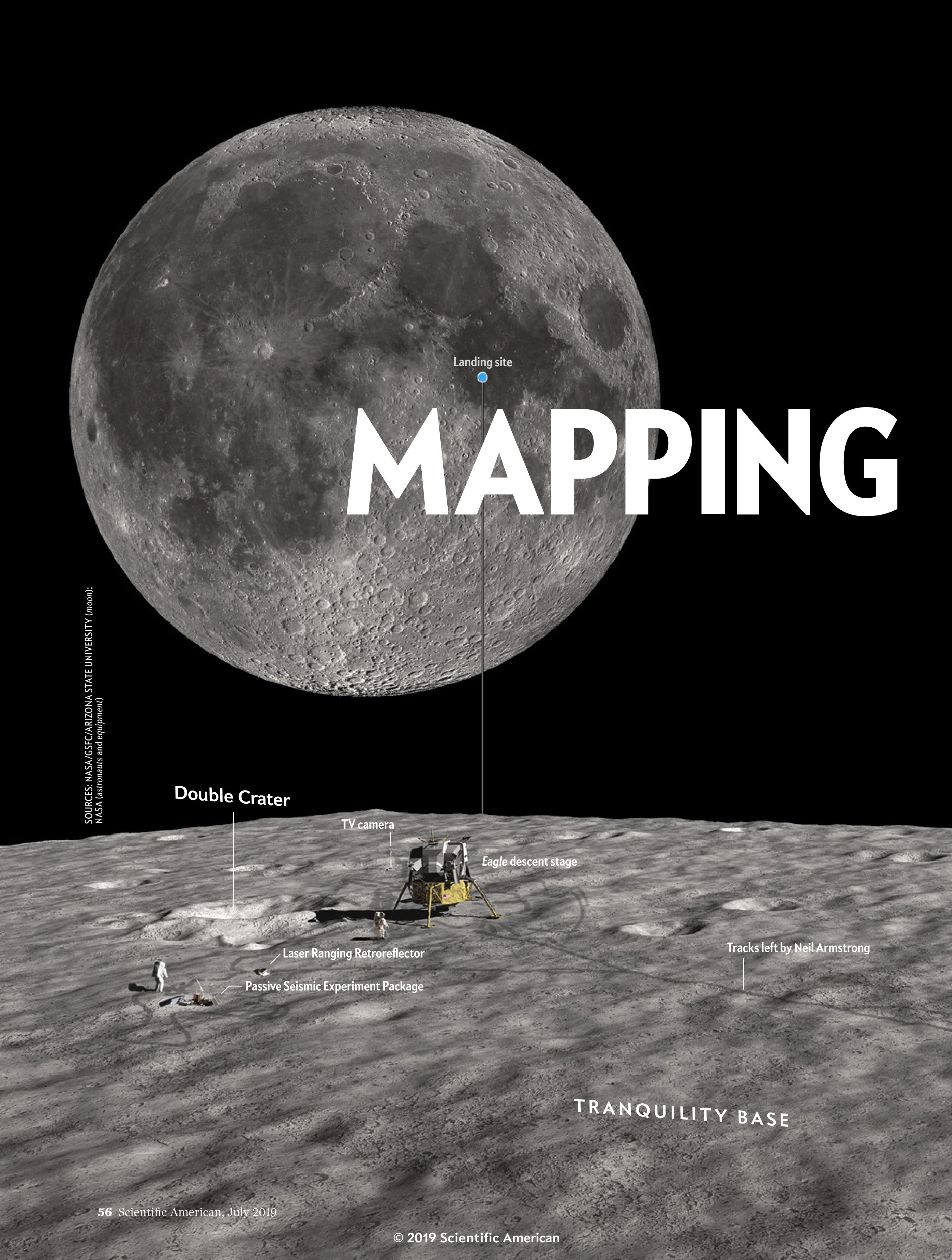
◀ EARTH hangs over the moon as the lunar module flies over the surface.

lunar surface by 2024, the public reaction was incredulity. But the 50th anniversary of *Apollo 11* reminds us that this laughably ambitious goal has in fact already been proved doable—on a short deadline, at a time when computers were the size of rooms, the U.S. was losing the war in Vietnam, women were marching in the streets for equality, and African-Americans were fighting, often sacrificing their lives, for the right to be treated as full human beings.

People often remember the time of the moon landing as one of the country's finest moments, an age when things were simpler, better, more hopeful. Yet *Apollo 11* was not the embodiment of a grand era—it was a testament to the fact that we can do great things in terrible times. That even when we are struggling, when our country is divided and our world is scary, we should chase big dreams. *Apollo 11* showed us, just when we needed it, the best of humanity. Now, when our planet is facing similar strife, we could really use another moon shot, whether we go back to the moon or not. —*Clara Moskowitz*

CLOCKWISE FROM TOP LEFT: MARIO DE BIASI *Getty Images (press corps)*; NASA *(Armstrong)*; GETTY IMAGES *(Aldrin onboard)*; NASA *(lunar module in orbit)*; ALAMY *(Aldrin on lunar surface)*

MAPPING



SOURCES: NASA/GSFC/ARIZONA STATE UNIVERSITY (*moon*); NASA (*astronauts and equipment*)

MODERN SATELLITE IMAGERY AND 3-D MODELING GIVE US A NEW VIEW OF HOW *APOLLO 11* PLAYED OUT

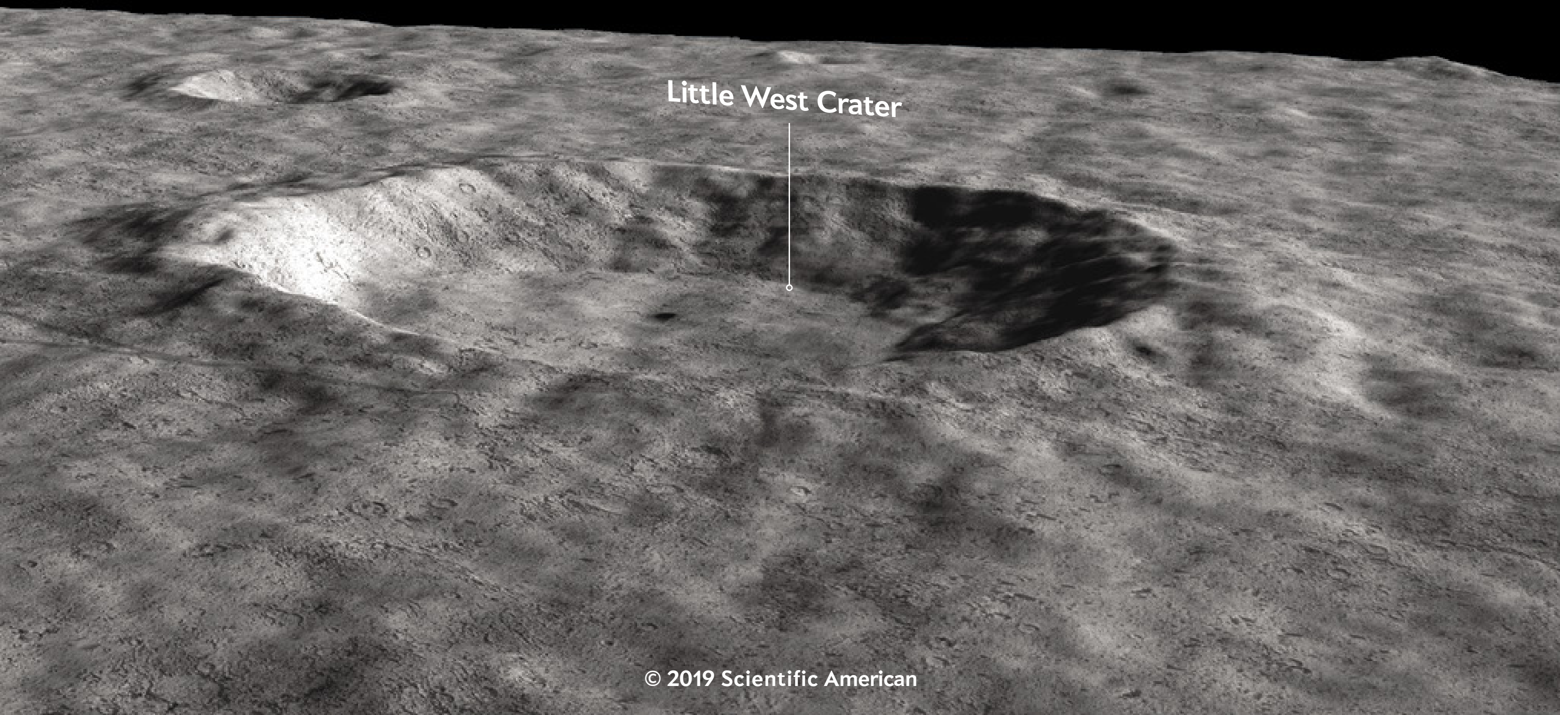
Text and graphics by Edward Bell

APOLLO 11 1969 50 years 2019 ANNIVERSARY

THE MISSION

When *Apollo 11* happened in real time, people back home could follow along with grainy, though exhilarating, video footage. Yet they had little sense of where on the moon the action was happening and how far the astronauts explored. Now three-dimensional computer models based on recent satellite imagery can re-create each step of the mission and the terrain it covered. Based on a 2012 photograph of the landing site from NASA's Lunar Reconnaissance Orbiter (LRO), a height map of the surface shows the contours of the moon where Neil Armstrong and Buzz Aldrin traveled, as well as the positions of the lander, the experiments and even the astronauts' footpaths.

Satellite imagery helps to preserve details of the mission that will ultimately be lost to time: extreme temperatures, solar radiation and the unrelenting bombardment of micrometeorites on the lunar surface are eroding the footprints and will eventually wipe out even the machinery. Little by little, Tranquility Base is disappearing.



THE FINAL MINUTES

The carefully choreographed mission hit a few snags as the *Eagle* descended for landing. This map, created using the same 3-D-modeling techniques as were used for the map on the preceding pages, shows the lander's altitude during the nail-biting moments in which Armstrong navigated past the intended landing spot—which turned out to be littered with dangerous boulders—and found a new target literally on the fly.

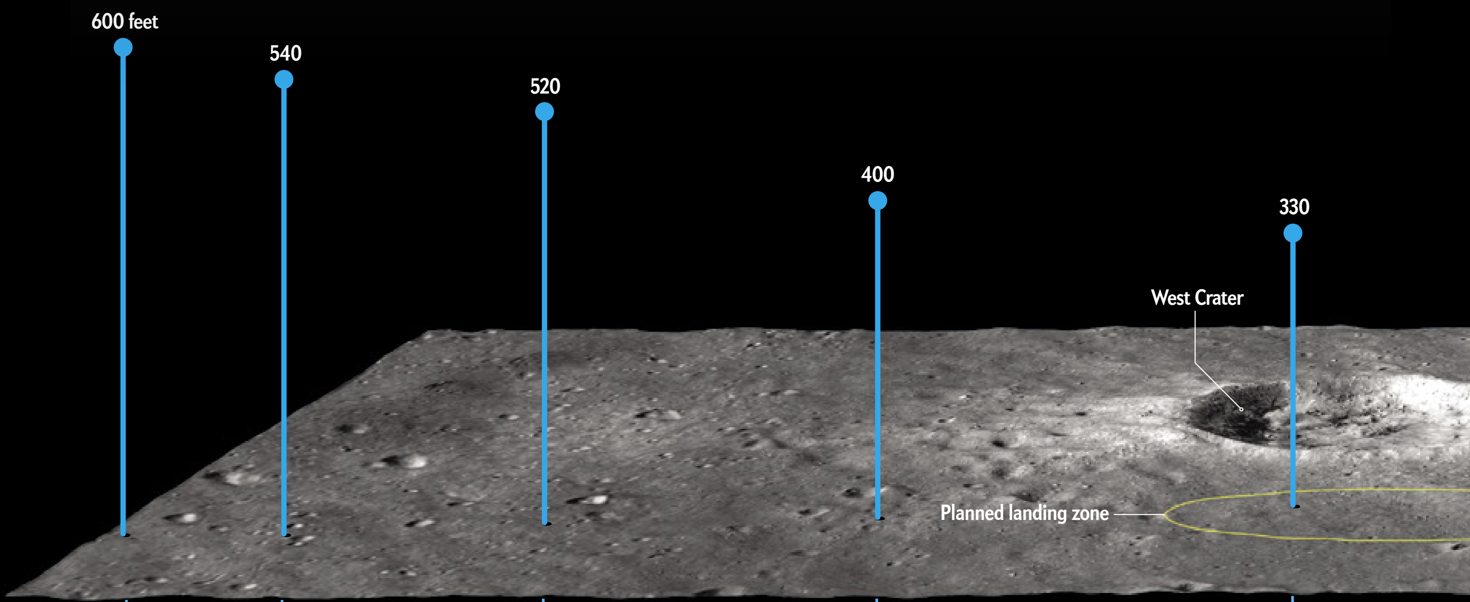
The trouble began at an altitude of about 33,000 feet, when a warning light labeled "1202 program alarm" began flashing on the *Eagle*'s dashboard. "What is it?" Armstrong asked Aldrin as the light blinked and a bell rang at irregular intervals. Neither recognized the alarm from any of their flight simulations. Eventually mission controllers radioed that it could be safely ignored, but trying to determine its cause wasted precious time.

As the lander's fuel reserves dwindled, the *Eagle* became increasingly difficult to maneuver. When the propellant in its tank sank below 50 percent, the fuel started sloshing wildly, jerking the vehicle in all directions. The issue also caused the lander's low-fuel-level alarm to go off between 30 to 45 seconds early, making it seem like the astronauts had less time than they did to safely reach the ground.

Edward Bell is a contributing art director at *Scientific American* and an animator specializing in planetary science. He is author of the award-winning iPad book *Journey to the Exoplanets*.

Finally, with the *Eagle* at around 2,000 feet, Armstrong looked out of his window to examine the proposed landing site. (He should have done this several minutes earlier, but as he said later in a debriefing, "our attention was directed toward clearing the program alarms, keeping the machine flying, and assuring ourselves that control was adequate to continue without requiring an abort. Most of the attention was directed inside the cockpit during this time.") He didn't like what he saw. As he described it in the debriefing, the landing site was a "large rocky crater surrounded with the large boulder field with very large rocks covering a high percentage of the surface."

Running out of fuel and time, Armstrong took over steering the spacecraft from the onboard computer at around 540 feet. Just under the wire, he guided the *Eagle* past the boulder field to a safe landing on relatively flat ground.



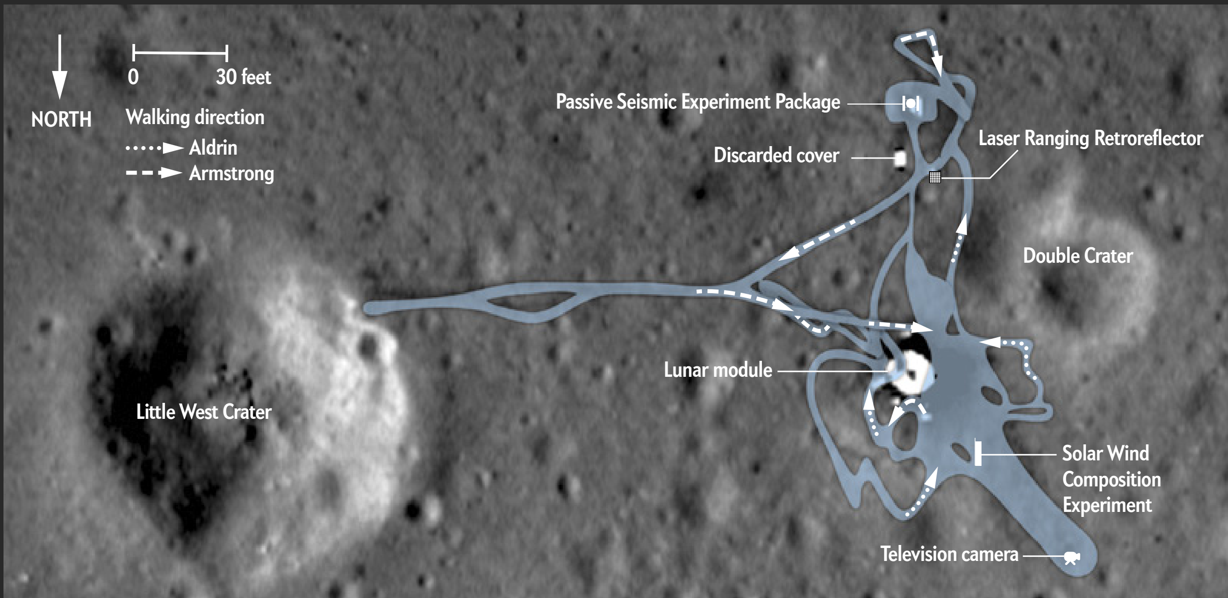
The onboard LPD (Landing Point Designator) is steering the lander toward a boulder field north of West Crater.

Armstrong assumes attitude control of the lander from the onboard computer.

Armstrong repositions (pitches forward) the *Eagle* to maintain ground speed and fly past the boulder field.

The *Eagle* approaches the boulder field.

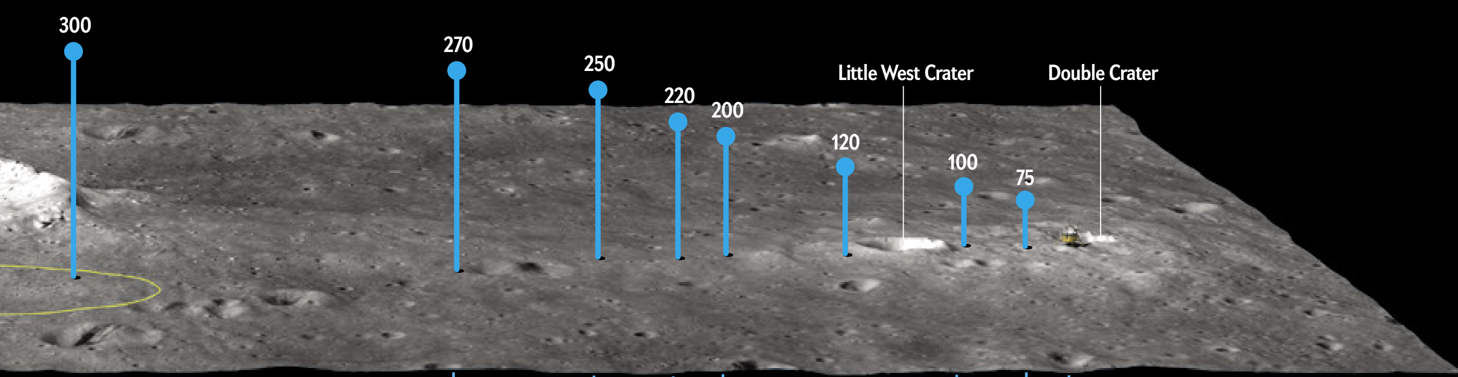
The lunar lander flies over the West Crater boulder field.



SOURCES: NASA (*West Crater and boulder field*); NASA'S GODDARD SPACE FLIGHT CENTER (*base map*); THOMAS SCHWAGMEIER AND ERIC M. JONES (*footpath reference*)

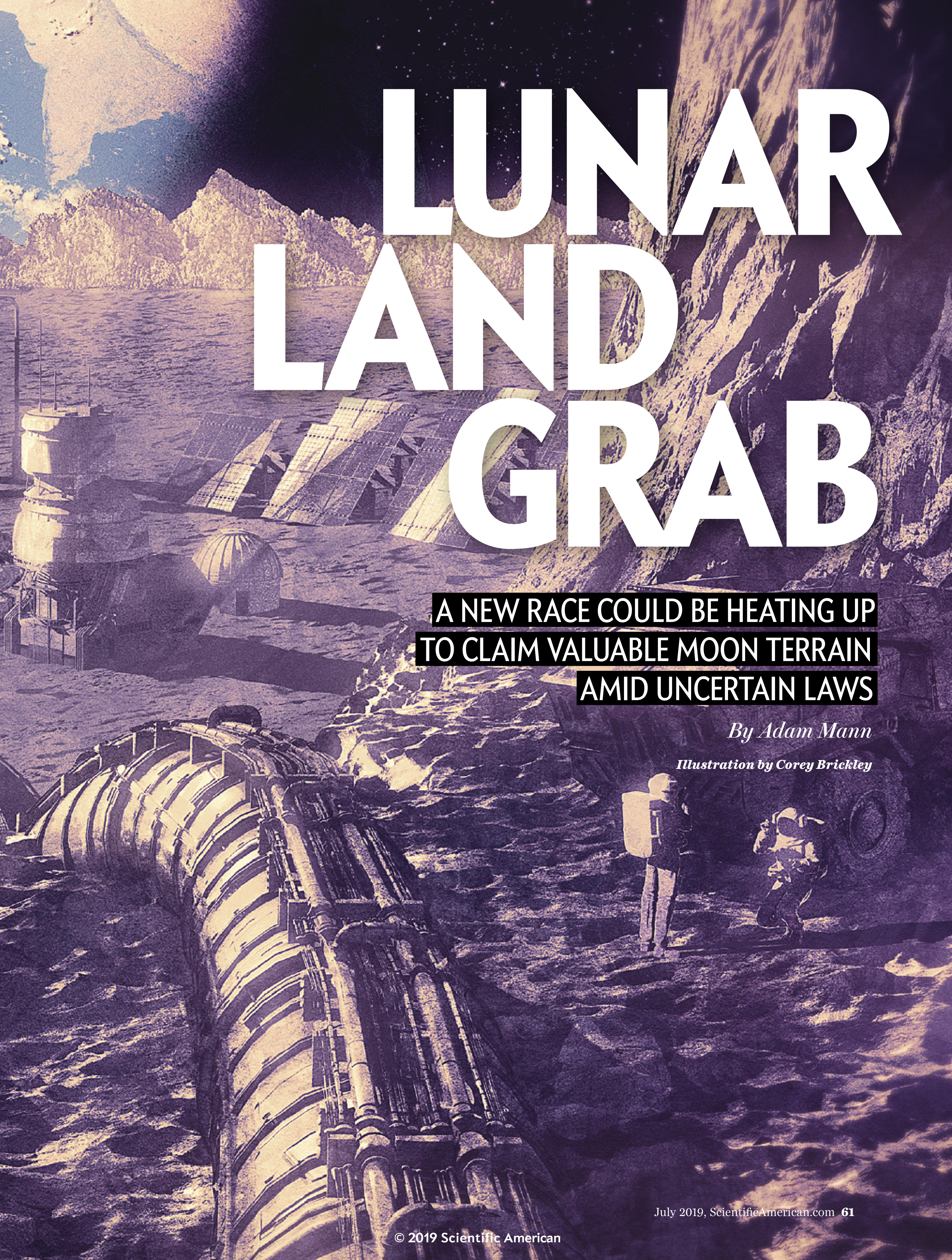
TRACKING THE ASTRONAUTS

Armstrong's "one small step for man" was followed by many more as he and Aldrin set up equipment and explored the lunar surface. High-resolution imagery from the LRO Camera (LROC), displayed here with tracing for emphasis, shows the disturbed moon dust that the two astronauts stirred up during the two and a half hours they moved about Tranquility Base. Much of their travel involved setting up scientific experiments, including the Passive Seismic Experiment to detect lunar "moonquakes," the Solar Wind Composition Experiment, which collected samples of the solar wind for later analysis, and the Laser Ranging Retroreflector, which measured the moon's orbit and variations in its distance from Earth. The farthest trip from the *Eagle* was an unplanned jaunt that Armstrong took to the edge of Little West Crater, a distance of roughly 200 feet.



Graphics by Edward Bell (landing path) and Eléonore Dixon-Roche (footpath)


APOLLO 11
1969
50
years
2019
ANNIVERSARY



LUNAR LAND GRAB

A NEW RACE COULD BE HEATING UP TO CLAIM VALUABLE MOON TERRAIN AMID UNCERTAIN LAWS

By Adam Mann

Illustration by Corey Brickley

Adam Mann is a journalist specializing in astronomy and physics. His work has appeared in *National Geographic,* the *Wall Street Journal, Wired* and elsewhere.

A GRAINY BLACK-AND-WHITE IMAGE PLAYS ACROSS THE SCREEN IN ONE OF BOB Richards's earliest memories—spacesuits, a lander and astronauts Neil Armstrong and Buzz Aldrin taking their historic first steps across the lunar surface. Richards, who was barely out of his toddler years at the time, recalls sitting in his family living room north of Toronto while his dad futzed with the rabbit-ear antenna, trying to improve the broadcast streaming over from Buffalo, N.Y. "*Apollo 11* was a defining moment for humanity," says the founder and CEO of Moon Express, a company that hopes to sell transportation to our natural satellite and eventually mine materials there. "The inspiration of Apollo is very prominent in what's happening today in space."

Back in the 1960s, it seemed like just a matter of time before humanity would slip the bonds of Earth and begin a slow crawl out into the universe. Although it has taken longer than many expected, something like that moment may soon arrive. Around half a dozen governments, as well as a handful of private companies, all have moon missions planned for the near future—a situation ripe for conflict.

The Outer Space Treaty, which the U.S., the U.K. and the Soviet Union signed less than two years before *Apollo 11* (and which now has 109 countries party to it), stipulates that space exploration must be conducted peacefully and for the benefit of all nations. It also holds that no one can claim territory on a celestial body. But lower down in the treaty is a loophole: two "noninterference clauses," which require all signatories to avoid causing harm to another's probes or outposts—for instance, by landing near or on top of them. This sounds reasonable enough, but it also creates an opening for a nation or private entity to monopolize a desirable spot simply by arriving there first.

Should one nation or entity try to stake a claim, it "might trigger a 'scramble for the Moon' comparable in some respects to the 'scramble for Africa' which began with the identification of mineral resources in the Congo in the 1880s," wrote astrophysicist Martin Elvis of the Center for Astrophysics at Harvard University and the Smithsonian Institution and his coauthors in a 2016 paper in the journal *Space Policy.*

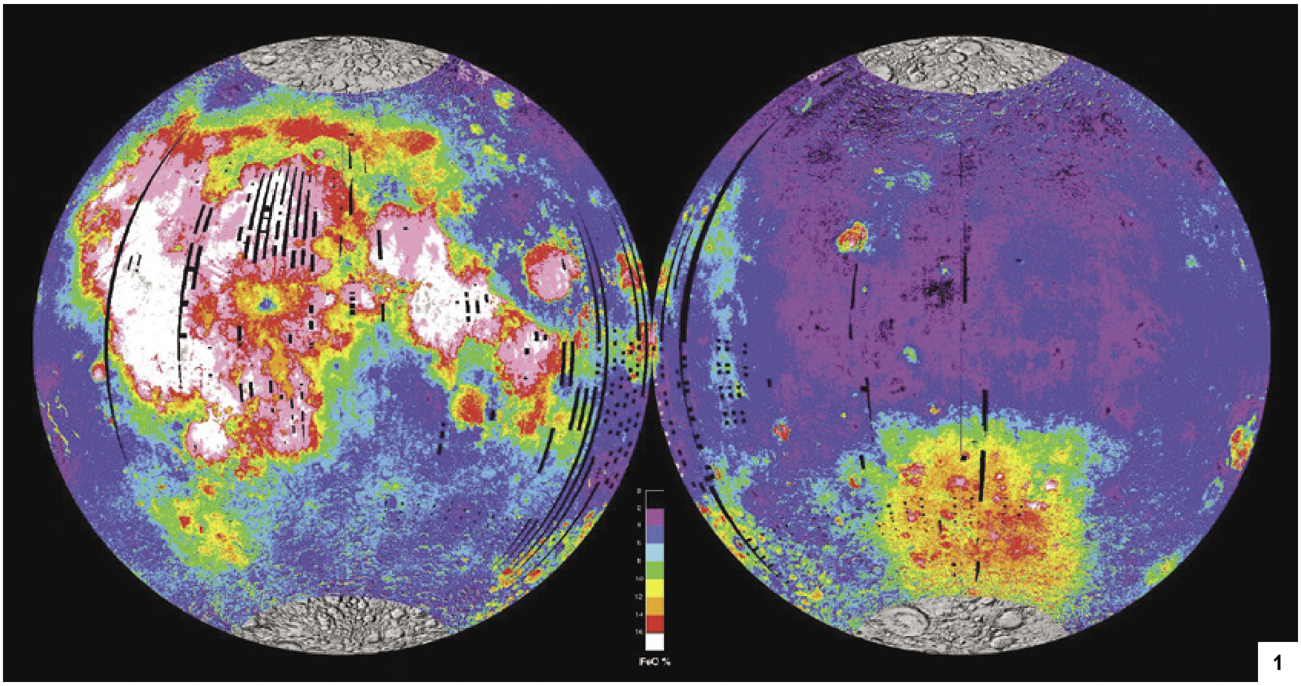
Sure enough, several missions scheduled to take place in the next few years all target the same terri-

IN BRIEF

A large number of countries and private companies are aiming to launch missions to the moon in the coming decade.

International law says no one can own property in space—yet it also says that once an entity has landed somewhere, others should avoid disturbing that site.

This loophole creates the potential for a race to stake claims on some of the moon's highest-value real estate.



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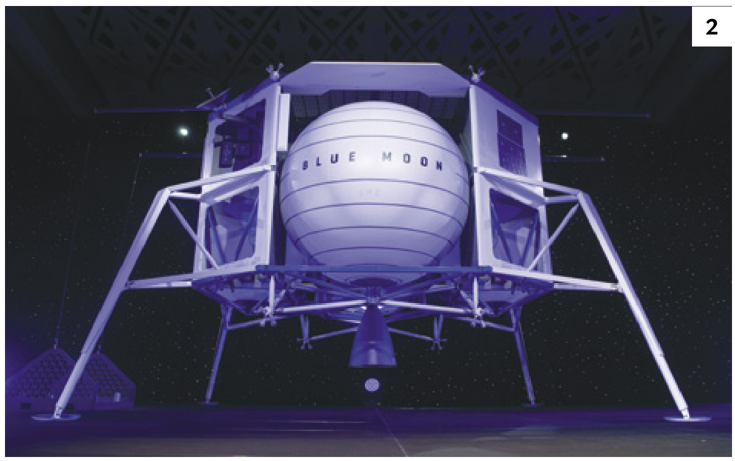


2

IRON concentration on the moon (*1*), as mapped by the Clementine spacecraft in 1994. A mockup (*2*) of the *Blue Moon* lunar lander being developed by Blue Origin.

tory. India's Chandrayaan-2 mission, due to launch in July, will aim for the lunar poles. The China National Space Administration has said that at least its next three probes will head to the poles as well. The Russian space agency Roscosmos is developing its Luna-Glob program, which would touch down near the Boguslawsky crater near the south pole perhaps as early as 2021. That same year Japan intends to launch the Smart Lander for Investigating Moon, or SLIM, which could demonstrate extremely high landing accuracy on small lunar features. NASA, the European Space Agency and more private interests are looking moonward as well. In May, Amazon CEO Jeff Bezos, who founded the spaceflight company Blue Origin, unveiled plans for its *Blue Moon* lunar lander, which, he said, could be ready to carry crews within the next five years.

Moon Express aims to land at the lunar south pole in 2021. And if its spacecraft arrives before anyone else, Richards says, the company wants it to count for something. "One of our drivers is to get there first," he says. "And we expect our rights of noninterference will be respected."

THE OIL OF SPACE

THERE IS PLENTY OF REAL ESTATE on the moon to go around—the total surface area is about the size of Africa—but the resources there are unevenly distributed. Iron and titanium, which could be useful for building moon habitats and technologies, are abundant in different regions of the lunar surface. The helium 3 deposits common in areas of the top layer of lunar regolith could power fusion reactors. And "resources" are not limited to extractable materials. Some landforms, such as certain crater pits, could offer radiation protection to astronauts, and sites on the lunar far side that are shielded from Earth's radio noise would be especially well suited to hosting telescopes.

In the near term, the most desirable resource of all is water. Astronauts can drink water, or they can break it into its constituent elements and transform them into rocket fuel. For the first off-planet explorers, water has been called the oil of space.

Some of the most promising sites for water extraction are the so-called Peaks of Eternal Light at the north and south lunar poles. These are crater peaks, geographical features that often form at or near the edges of impact craters when an asteroid strikes the surface and pushes material to the side, where it rises up to form a ridge at the rim. Because of the moon's orbital mechanics, the sun shines almost perpetually at these peaks, offering a nearly constant source of

NASA (*1*); SAUL LOEB *Getty Images* (*2*) energy to solar panels. Astronauts could stage bases here to extract the water sitting conveniently nearby at the bottom of these craters, where permanently shadowed regions have allowed ice to accumulate.

Each pole contains roughly half a dozen of these Peaks of Eternal Light, which are roughly a few hundred meters across apiece. Given this relative scarcity, it is easy to see why the principle of noninterference could be a useful way for nations to claim territory. "They're so small no one else can land on one without risking damage to a spacecraft that's already there," says Ian Crawford, a planetary scientist at Birkbeck, University of London, who has studied lunar resources. "The first companies or nations that land on these peaks, regardless of the legal niceties, will de facto have ownership."

LEGAL LOOPHOLES

THE OUTER SPACE TREATY was written half a century ago, mainly by two countries—the U.S. and U.S.S.R.—that at the time were the only ones that could even dream of reaching the moon. Legal scholars have debated the treaty's implications ever since, and recent developments, such as the rise of commercial spaceflight, have raised issues that were not on anyone's radar back then.

The Outer Space Treaty was written half a century ago, mainly by two countries—the U.S. and U.S.S.R.—that at the time were the only ones that could even dream of reaching the moon.

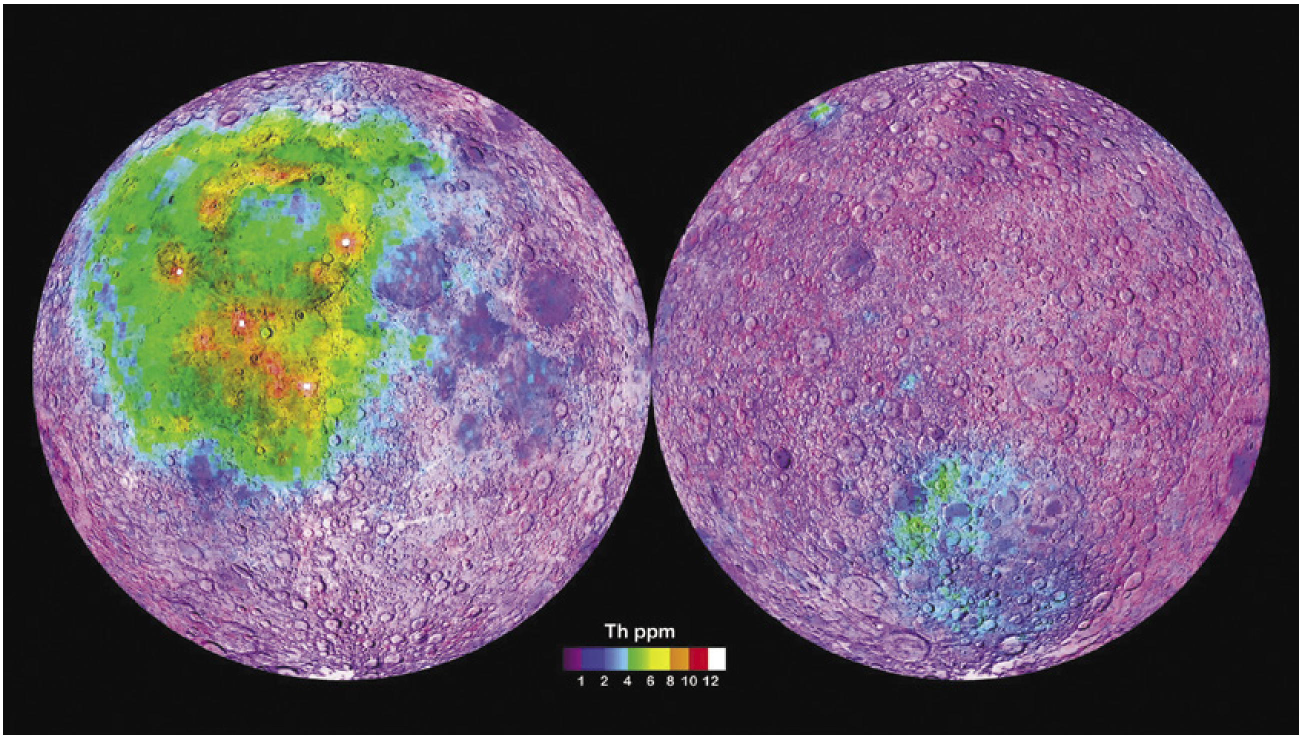
In 2015 Congress sparked an international disagreement by passing the U.S. Commercial Space Launch Competitiveness Act, which specified that although no one can claim property on a celestial body, any material extracted from one is legally owned by the entity that did the mining and can therefore be sold for profit. Representatives from Russia, Brazil and elsewhere subsequently made an uproar at a March 2017 meeting of the United Nations Committee on the Peaceful Uses of Outer Space (COPUOS), stating that off-world mining was a type of de facto appropriation and that a global consortium was needed to regulate extraction operations.

Other countries have sided with the U.S.—including nations such as Luxembourg, which would like to be a major player in space-based resources—in its more laissez-faire interpretation of the law. Chinese delegates at COPUOS have mostly threaded the needle between the two sides, appearing to wait and see which reading will eventually prevail. "International law is made by the states collectively," says Frans von der Dunk, a law professor specializing in space at the University of Nebraska–Lincoln. "If one says this is legal and another says this requires an international regime and licensing, then you have a big problem on your hands."

As things stand today, highly desirable areas of the moon are likely to be acquired on a first-come-first-served basis, rewarding the wealthy countries and companies that can get there soon. Less affluent nations could store up animosity toward those that stake claims, stoking tensions much like in the situation now in the South China Sea, Crawford says. At the moment there is no way to ensure that scientifically interesting regions remain pristine. We should confront these conundrums before exploitation begins in earnest, says Tony Milligan, an ethicist at King's College London and Elvis's co-author. "Once you have a regular presence on the moon, the law begins to look very different, and the colossal loopholes that you can drive spaceships through suddenly stand out in much sharper relief," he observes.

To many, the Chinese space program, with its political will and technological capabilities, appears to have a leg up on the competition. Chinese engineers have suggested that they can place a craft on the surface of the moon with centimeter-scale accuracy. Their upcoming set of Chang'e lunar missions intends to bring back samples and survey the poles in high detail. It might be in the best interests of other countries to begin working on rules that could rein in potential rivals, even if it means giving up some autonomy, von der Dunk says.

Some groups are already trying. A few years ago Tanja Masson-Zwaan, a space law expert at Leiden University in the Netherlands, co-founded the Hague International Space Resources Governance Working Group, an organization that has brought together government, industry and academia, among others, to come up with recommendations for off-world mining. In 2017 the group produced the building blocks for a legal framework of principles that aim to balance the interests of various stakeholders in accordance with international law. Masson-Zwaan recommends establishing something akin to the International Telecommunication Union, an agency at the U.N. that allocates satellite orbits and slices of the radio spectrum among nations for moon mining.



DATA FROM NASA'S Lunar Prospector mission shows the concentration of thorium on the lunar surface. This metal has been suggested as a possible fuel for use in nuclear reactors, making it a potential target for mining.

NASA

RISKS AND REWARDS

ALTHOUGH PLANS are afoot to grab lunar real estate, extracting resources such as rare elements and shipping them back to Earth is a long-term goal. Some would even say it is a fantasy. Given the incredible cost and technological hurdles involved in simply getting to space, let alone landing on the lunar surface, it is hard to imagine that transporting materials back to Earth would be profitable any time soon. Deep Space Industries and Planetary Resources, two private businesses that were set up in the early part of the 21st century to pursue asteroid mining, both failed to attract enough investment to attempt any deep-space resource extraction; they were eventually acquired by a satellite manufacturer and a cryptocurrency company, respectively. "It's different than the gold rush days, when anybody with a mule or a pickax could go and try to find gold," says George Sowers, a space resources expert at the Colorado School of Mines.

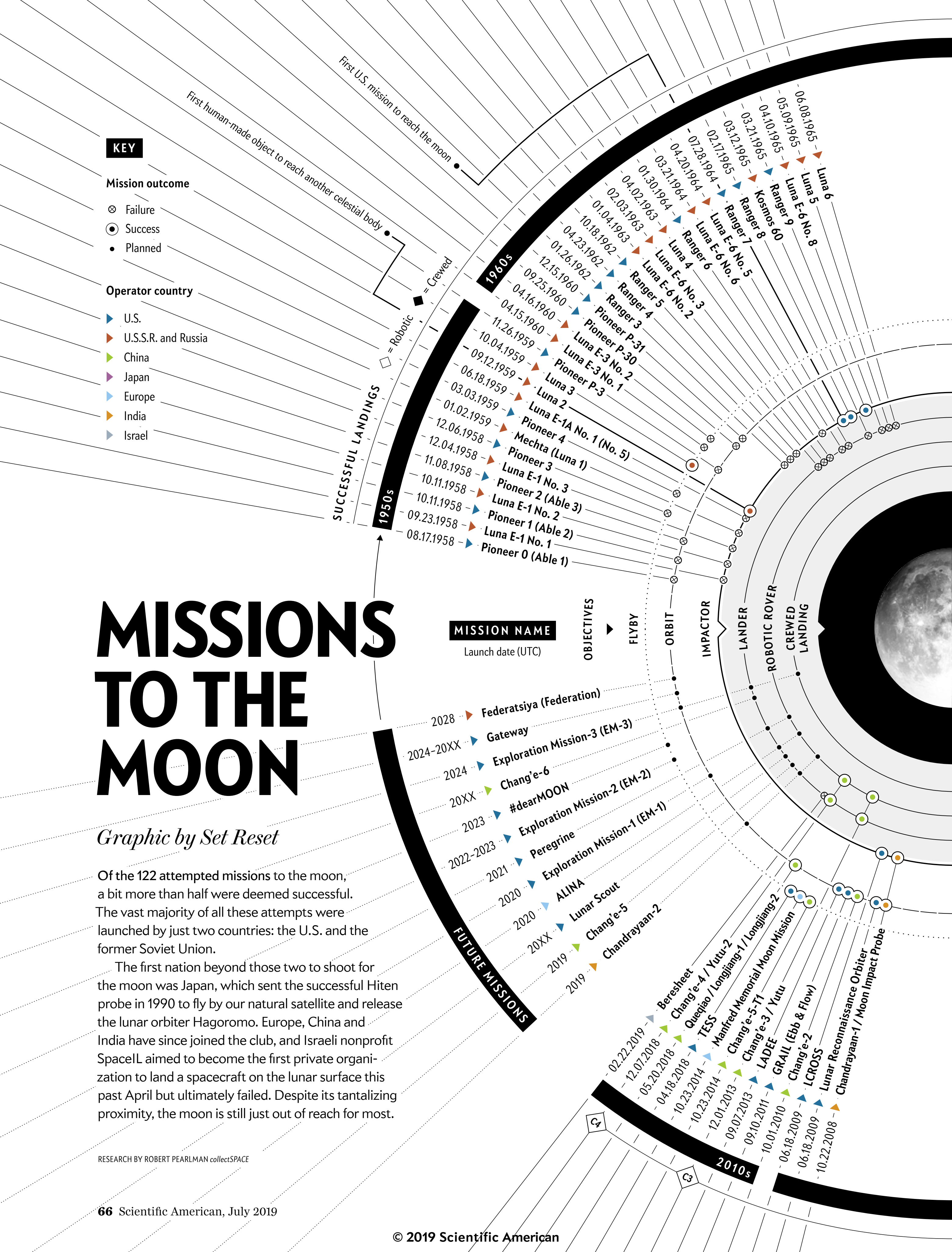
Still, if economic activities in space take off, mining could follow, experts say. Elvis points to private rocket companies, such as Elon Musk's SpaceX, that are driving down the cost of launching vehicles into orbit. The cheaper and easier it is to get to space, the more common missions will become. Demand for fuel and other resources could follow, and launching materials from the relatively low gravity of the moon would be more cost-effective than from the deep gravitational well of our own planet.

Richards is eager to play his part in bringing the moon within Earth's economic sphere. Yet so far even he has struggled to get above the atmosphere. When Richards co-founded Moon Express in 2010, the company was one of 16 teams competing for the Google Lunar XPRIZE, which challenged a privately funded robotic spacecraft to land on the moon, drive around, and send back pictures and data. The original 2012 deadline was extended several times, ultimately to March 2018, but in January of that year the XPRIZE Foundation admitted that no one would be able to claim the $30-million purse.

Moon Express now plans to send its first vehicle into lunar orbit in 2020. It remains to be seen, however, whether its business model—offering space agencies and private companies payload rides to the moon—will be viable in the long run. When asked if he sees any conflict between his desire to stake a claim and the need for an equitable solution for everyone, Richards turns philosophical. The tensions in the Outer Space Treaty reflect the tensions between the belief systems of the two countries that wrote it, he says. The Communist Soviets saw the world from a collective perspective in which goods should be equally distributed, whereas the capitalist Americans believed in greater personal freedom and an unfettered private sector. "That's why the treaty is open to interpretation," he says. "I think we have a chance as a species to conquer these new frontiers without having to conquer each other." SA

MISSIONS TO THE MOON

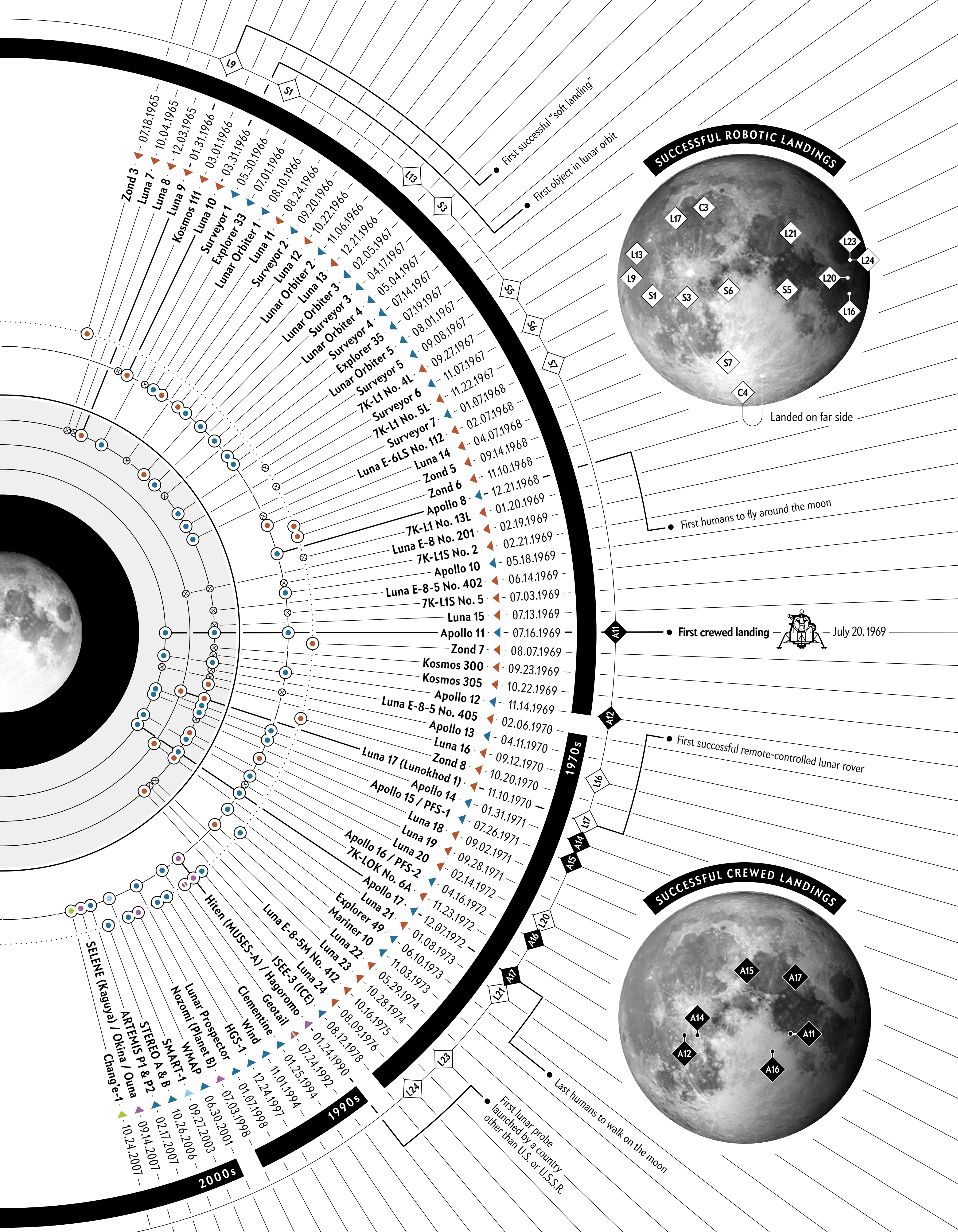
Graphic by Set Reset



Of the 122 attempted missions to the moon, a bit more than half were deemed successful. The vast majority of all these attempts were launched by just two countries: the U.S. and the former Soviet Union.

The first nation beyond those two to shoot for the moon was Japan, which sent the successful Hiten probe in 1990 to fly by our natural satellite and release the lunar orbiter Hagoromo. Europe, China and India have since joined the club, and Israeli nonprofit SpaceIL aimed to become the first private organization to land a spacecraft on the lunar surface this past April but ultimately failed. Despite its tantalizing proximity, the moon is still just out of reach for most.

RESEARCH BY ROBERT PEARLMAN *collectSPACE*



Zond 3 – 07.18.1965
Luna 7 – 10.04.1965
Luna 8 – 12.03.1965
Luna 9 – 01.31.1966
Kosmos 111 – 03.01.1966
Luna 10 – 03.31.1966
Surveyor 1 – 05.30.1966
Explorer 33 – 07.01.1966
Lunar Orbiter 1 – 08.10.1966
Luna 11 – 08.24.1966
Surveyor 2 – 09.20.1966
Luna 12 – 10.22.1966
Lunar Orbiter 2 – 11.06.1966
Luna 13 – 12.21.1966
Lunar Orbiter 3 – 02.05.1967
Surveyor 3 – 04.17.1967
Lunar Orbiter 4 – 05.04.1967
Surveyor 4 – 07.14.1967
Explorer 35 – 07.19.1967
Lunar Orbiter 5 – 08.01.1967
Surveyor 5 – 09.08.1967
7K-L1 No. 4L – 09.27.1967
Surveyor 6 – 11.07.1967
7K-L1 No. 5L – 11.22.1967
Surveyor 7 – 01.07.1968
Luna E-6LS No. 112 – 02.07.1968
Luna 14 – 04.07.1968
Zond 5 – 09.14.1968
Zond 6 – 11.10.1968
Apollo 8 – 12.21.1968
7K-L1 No. 13L – 01.20.1969
Luna E-8 No. 201 – 02.19.1969
7K-L1S No. 2 – 02.21.1969
Apollo 10 – 05.18.1969
Luna E-8-5 No. 402 – 06.14.1969
7K-L1S No. 5 – 07.03.1969
Luna 15 – 07.13.1969
Apollo 11 – 07.16.1969
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Kosmos 300 – 09.23.1969
Kosmos 305 – 10.22.1969
Apollo 12 – 11.14.1969
Luna E-8-5 No. 405 – 02.06.1970
Apollo 13 – 04.11.1970
Luna 16 – 09.12.1970
Zond 8 – 10.20.1970
Luna 17 (Lunokhod 1) – 11.10.1970
Apollo 14 – 01.31.1971
Apollo 15 / PFS-1 – 07.26.1971
Luna 18 – 09.02.1971
Luna 19 – 09.28.1971
Luna 20 – 02.14.1972
Apollo 16 / PFS-2 – 04.16.1972
7K-LOK No. 6A – 11.23.1972
Apollo 17 – 12.07.1972
Luna 21 – 01.08.1973
Explorer 49 – 06.10.1973
Mariner 10 – 11.03.1973
Luna 22 – 05.29.1974
Luna 23 – 10.28.1974
Luna E-8-5M No. 412 – 10.16.1975
Luna 24 – 08.09.1976
ISEE-3 (ICE) – 08.12.1978
Hiten (MUSES-A) / Hagoromo – 01.24.1990
Geotail – 07.24.1992
Clementine – 01.25.1994
Wind – 11.01.1994
HGS-1 – 12.24.1997
Lunar Prospector – 01.07.1998
Nozomi (Planet B) – 07.03.1998
WMAP – 06.30.2001
SMART-1 – 09.27.2003
STEREO A & B – 10.26.2006
ARTEMIS P1 & P2 – 02.17.2007
SELENE (Kaguya) / Okina / Ouna – 09.14.2007
Chang'e-1 – 10.24.2007
1970s
1990s
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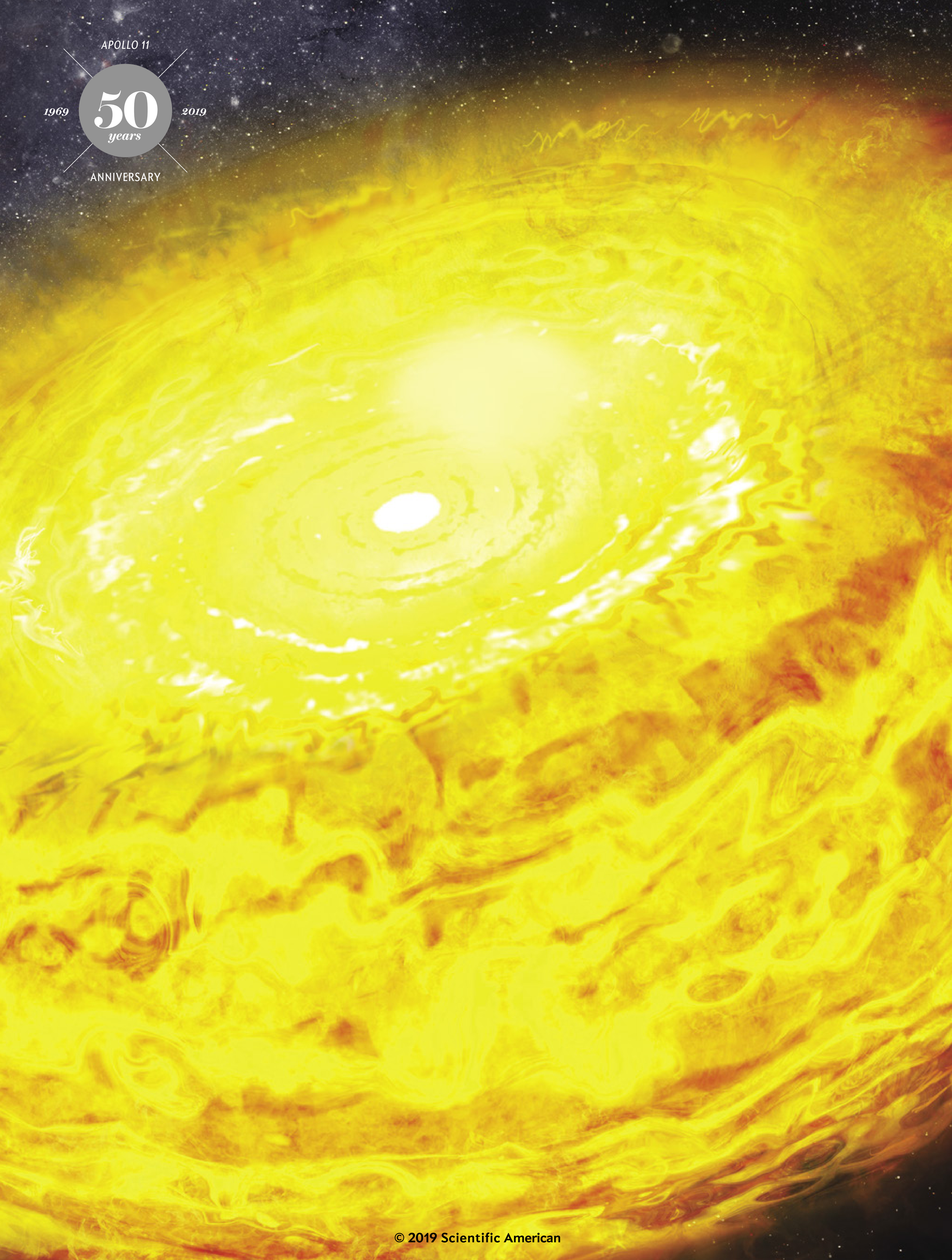
L24
First successful "soft landing"
First object in lunar orbit
SUCCESSFUL ROBOTIC LANDINGS
C3
L17
L21
L23
L24
L13
L9
S1
S3
S6
S5
L20
L16
S7
C4
Landed on far side
First humans to fly around the moon
First crewed landing
July 20, 1969
First successful remote-controlled lunar rover
SUCCESSFUL CREWED LANDINGS
A15
A17
A14
A11
A12
A16
Last humans to walk on the moon
First lunar probe launched by a country other than U.S. or U.S.S.R.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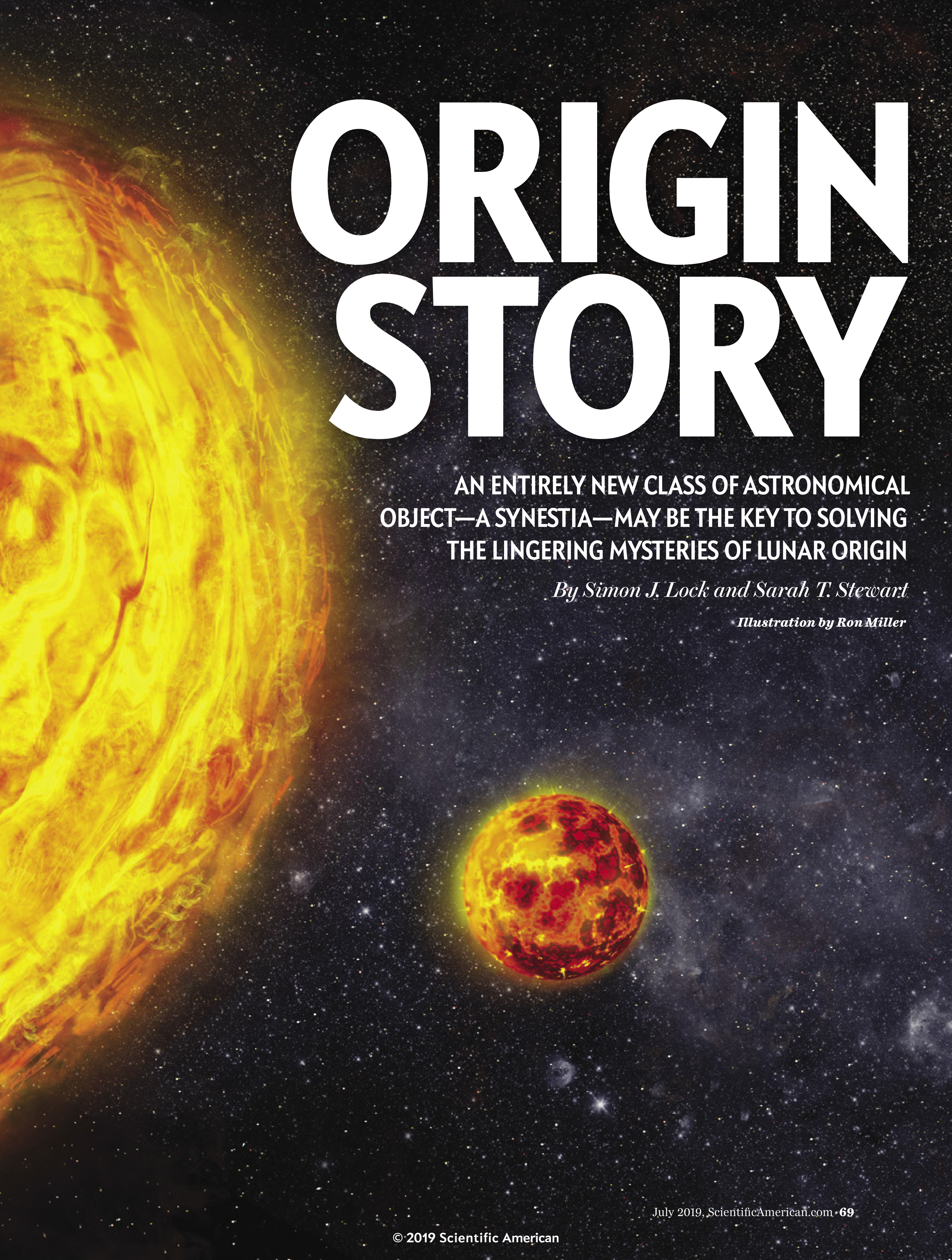


ORIGIN STORY

AN ENTIRELY NEW CLASS OF ASTRONOMICAL OBJECT—A SYNESTIA—MAY BE THE KEY TO SOLVING THE LINGERING MYSTERIES OF LUNAR ORIGIN

By Simon J. Lock and Sarah T. Stewart

Illustration by Ron Miller

Simon J. Lock is a planetary scientist and postdoctoral researcher at the California Institute of Technology.

Sarah T. Stewart is a professor of planetary science and geophysics at the University of California, Davis. In 2018 the MacArthur Foundation awarded her a "genius" grant for her work on synestias.

ON AUGUST 1, 1971, WHILE EXPLORING THE EASTERN EDGE OF THE LAVA PLAIN known as Mare Imbrium on the silent, serene lunar surface, *Apollo 15* astronauts David Scott and James Irwin found something remarkable: a profoundly old piece of lunar crust, a relic more than four billion years old that carried clues to the moon's formation. Seeing the glint of ancient crystals embedded in what would later be called the Genesis rock, Scott immediately knew its potential importance for solving the mystery of how the moon was made. "I think we found what we came for," he radioed to mission control as he and Irwin retrieved the rock and placed it in a bag. It would become a key part of what is the Apollo program's greatest scientific legacy.

Studies of the Genesis Rock and the nearly 400 kilograms of other samples hauled back to Earth by the Apollo astronauts overturned our understanding of lunar history. In what amounted to a scientific reboot, these precious samples nullified the then prevailing theories—that the moon had been gravitationally captured by Earth or had formed alongside it—while revealing important new details, such as the fact that the newborn satellite had been covered by a magma ocean.

The immense energy required to form the moon's magma ocean pointed to a radical new idea for lunar origin: the notion that Earth's closest companion had formed from a giant impact, a collision between the proto-Earth and another planetary body. The concept built on calculations showing that growing planets would collide with one another, as well as the curious fact that the moon's composition is uncannily similar to that of Earth's rocky mantle. Some researchers even proposed that such an impact had set the young Earth's spin, establishing what would become our planet's 24-hour cycle of day and night. The canonical giant impact hypothesis that emerged from these early studies proposes that a glancing collision with a Mars-size body created a hot disk of rocky debris around Earth. The moon then coalesced from the disk—a scenario that can explain the moon's large mass and dearth of water and other volatiles.

Yet the giant impact hypothesis is not without flaws. Chief among them is the astounding chemical relationship between Earth and the moon. These two bodies are made from the same source material, as if they are planetary twins, whereas the canonical hypothesis predicts the moon should mostly be made of its Mars-size progenitor. That progenitor should differ in composition from the proto-Earth because planets growing from the disk of gas and dust around the young sun would each incorporate distinctive mixes of building blocks based on their orbital location. Scientists can discern these differences by making very precise measurements of the relative abundances of isotopes in rocks, yielding unique "isotopic fingerprints" for every planetary body in the solar system—except for Earth and the moon, which, bizarrely, appear to be almost the same.

This isotopic crisis has haunted the giant impact hypothesis for decades, but no better explanation has emerged for the lunar origin. Now, however, in another scientific reboot we have discovered that most giant impacts do not make a planet surrounded by a debris disk. In fact, most giant impacts do not make a planet at all. Instead they make an entirely new class of astronomical object, a transient hybrid between planet and disk called a synestia that could explain many of the moon's most mysterious features.

HIDING IN PLAIN SIGHT

THE DISCOVERY OF SYNESTIAS traces back to a few years ago, when we (Lock and Stewart) were puzzling over whether or not a giant moon-forming impact had set the length of Earth's day. That

IN BRIEF

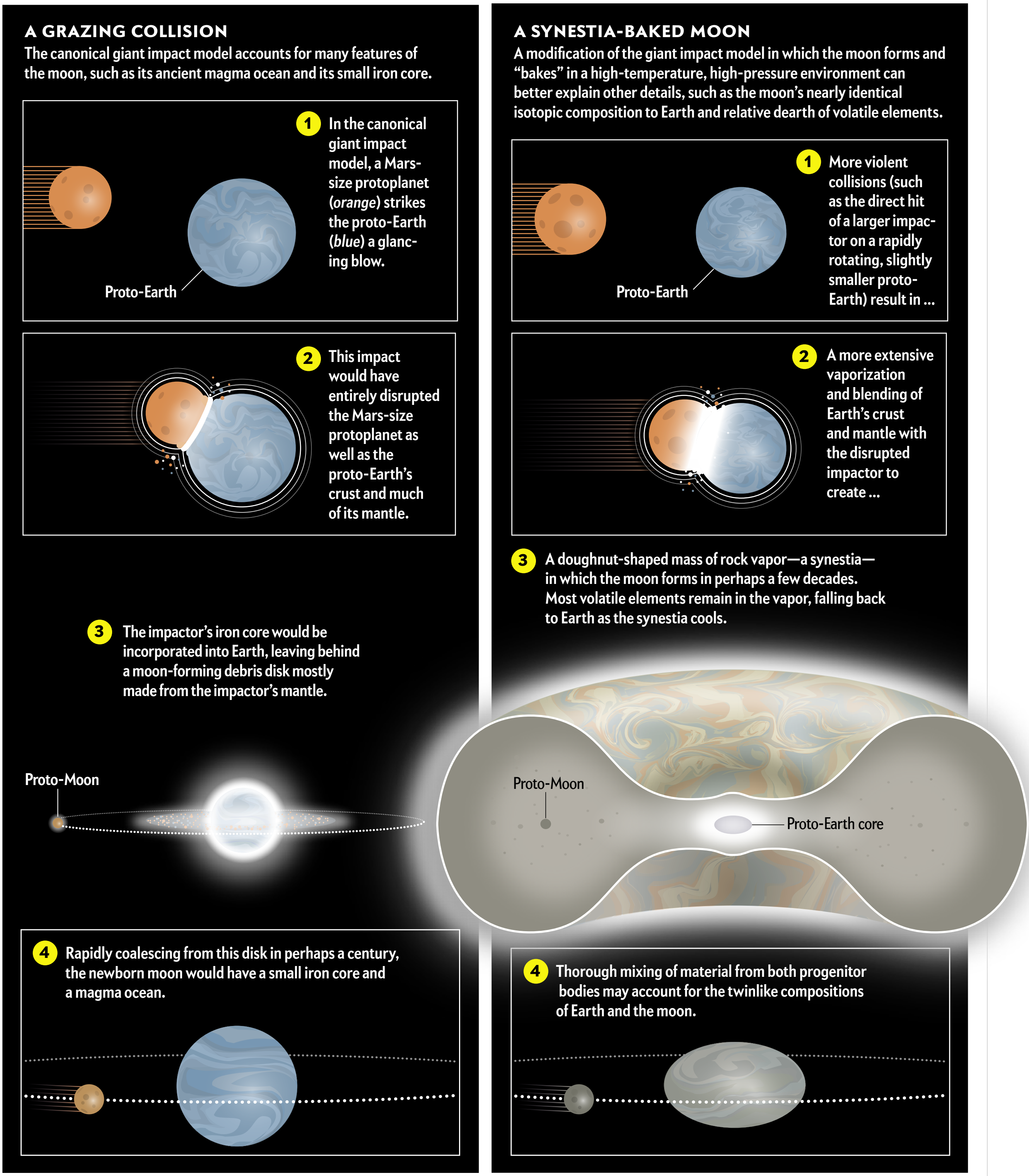
Earth's moon formed nearly 4.5 billion years ago, in the aftermath of a cataclysmic collision between the proto-Earth and another protoplanet.

The giant impact hypothesis has dominated scientific discussions of lunar origins for decades, in part because it neatly explains the moon's large size and lack of water. But the current theory cannot easily account for other lunar properties, such as its uncanny resemblance to Earth in terms of composition.

A synestia—an impact-generated hybrid between a planet and a disk—is an entirely new class of astronomical object proposed to explain the moon's birth and curious compositional similarity to Earth. Synestias may be regular outcomes of the planet-formation process throughout the cosmos.

Making the Moon

Evidence strongly suggests the moon formed some 4.5 billion years ago from a collision between the proto-Earth and another protoplanet. But certain aspects—such as the moon's relative depletion in volatile elements compared with Earth—could be better explained by lunar formation from a synestia, a transient object produced in the aftermath of a giant impact.



diurnal cycle is linked to the giant impact by a fundamental law of physics, the conservation of angular momentum. Going back in time, the moon was closer to Earth, and to conserve angular momentum, Earth spun faster—*much* faster: it would have had a five-hour day. Other scientists had found that a grazing giant impact by a Mars-size body could set the total angular momentum of Earth and the moon. But if something else had set Earth's length of day, then the moon-forming event could have had more (or less) angular momentum, opening the door for a much wider array of possible impact scenarios. And a giant impact with more angular momentum and more energy could, in very rare cases, lead to an equitable mix of material from the two colliding bodies, potentially explaining Earth and the moon's status as isotopic twins.

Examining this problem in simulations of about 100 different scenarios for a high-energy, high-angular-momentum, giant moon-forming impact, we were confronted by seemingly nonsensical results. Our plots of each postimpact scenario did not show the tidy division between "planet" and "disk" that we had expected. The postimpact planets were hot and huge, their rocky mantles partially vaporized and puffed up to more than 100 times Earth's present-day volume, so swollen that they became connected to the encircling disk. The resulting objects did not look like normal planets or disks anymore but instead something in between. In a flash of insight, we realized that these giant impacts were making something new. But we could not immediately understand what it was. We did not know what to call it at the time, but we had seen our first synestia.

We are still learning from the samples collected by the Apollo missions, but they are a limited resource with enormous gaps.

To understand what we were seeing, we went back to first principles, reexamining fundamentals such as the working definition for a "planet." A planet is defined in part by its spheroidal shape, which comes from the body's self-gravity being strong enough to deform the rock as if it were a fluid. And planets rotate around together, with only small variations arising from any internal dynamics. We used a fluid dynamics code to calculate what happens to an Earth-like planet as its rocky mantle is slowly heated, watching as our models showed the planet swelling up as its rocks began to vaporize. At the extreme temperatures after a giant impact, the body resembles a gas giant—hot enough that it lacks a true surface, just a thick rock vapor atmosphere that becomes denser with depth. If such a world rotates with a five-hour day, it maintains a roughly spheroidal shape even as it balloons in size as the temperatures rise.

But if the planet is rotating even faster, as it heats up, something surprising happens. As the planet's equator expands, it reaches a point at which the equator rotates as fast as if it were in orbit. We call this point the corotation limit. With just a little more heat, material will then flow from the planet's equator into orbit. Suddenly, a fin of vapor protrudes from its equator, and the planet becomes something else. Unlike a planet, it is no longer a simple spheroid. Furthermore, unlike a planet, it no longer rotates cohesively, instead featuring an inner corotating region and an outer region that rotates more slowly. After some thought, we chose to name this new celestial creature a synestia, after Hestia, the Greek goddess of the hearth and home—because we believe Earth used to be one of these fiery objects. (The "syn" emphasizes the synergy that exists between all the interconnected material in the planet and the disk.) A synestia is what a planet turns into when heat and spin force it to exceed the limit of a spheroidal shape.

Soon we were manufacturing synestias by the hundreds in our computer models, heating spinning planets beyond the corotation limit. Synestias can have a wide range of shapes and sizes, depending on how mass, energy and angular momentum are distributed throughout the body. The properties of a synestia depend on how it was made. Gently heating a planet makes a synestia that looks like a squat flying saucer, but giant impacts make huge puffy synestias shaped more like doughnuts or cream-filled pastries. Armed with a better understanding of how these objects arise and manifest, we began digging through all our previous simulations of giant impacts and finding synestias there, too. It turned out that we had been making synestias by accident for years. In fact, most scientists working on giant impacts unknowingly had synestias sitting in their modeling data, just waiting to be recognized as strange objects new to science.

The fact that no one had noticed them earlier had been a matter of misplaced expectations. In the range of possible moon-forming giant impacts, the energy and angular momentum of a canonical Mars-size impact are too low to produce a synestia. By focusing on the Mars-size impactor, the entire field—generations of scientists—had been misled into thinking that a planet and disk were the standard outcome of giant impacts.

For us, the next obvious step was modeling how often synestias should emerge from the complex process of planet formation. We developed techniques to map out which impacts could transform planets into synestias. By comparing these results with models of growing planets, we have found that synestias are not extremely rare oddballs but are actually a very common but transient feature of young planetary systems. Indeed, our simulations suggest that most of the universe's rocky planets may have transformed into synestias one or more times during their formation. We now believe that most giant impacts forming an Earth-mass body will also make a synestia. In a flash, we had discovered a missing piece in the cosmic history of planets.

BACK TO THE MOON

AND YET THE MOTIVATING QUESTION remains: Could a synestia explain our moon's unique relation to Earth? A synestia is a very different environment for lunar accretion than a traditional circumplanetary disk. We have found that forming the moon from a synestia offers solutions to many of the issues that have plagued the giant impact model for lunar origin.

A synestia's surface temperature is set by the boiling point of rock, which is about 2,300 kelvins (nearly 3,700 degrees Fahrenheit) at its low-pressure outer edge. There, cooled by radiating heat to space, rock vapor from the moon-forming synestia would have condensed to droplets of magma that rained down into its interior. The rate of the magma rain would have been 10 times that of the most intense rainfall ever measured on Earth. In this scenario, the moon would begin as a small orb of molten rock and metal—some of the material that was not vaporized in the initial impact. Dwarfed by the synestia's immensity, the nascent moon would, in fact, have orbited within the synestia's glowing, vaporous depths, surrounded by vast quantities of high-pressure gaseous rock, growing with each absorbed droplet of falling magma rain. The synestia would shrink as it cooled, so that after tens of years, it would have sufficiently contracted for its outer edge to recede within the orbit of the moon. In that moment, the moon would emerge, born from the dying synestia.

This story may explain why Earth and the moon are isotopic twins because the synestia formed from the vaporized and well-mixed material derived from the two colliding bodies. Furthermore, the synestia's torrential magma rains and turbulent vapors would have driven even more mixing throughout a large fraction of the body. If the synestia was sufficiently well mixed, the moon would have acquired the same isotopic ratios as Earth.

A synestia can also explain several other lunar mysteries that the canonical giant impact hypothesis does not. For example, although the moon has the same isotopic fingerprint as Earth, it does not have exactly the same chemical composition. The moon has lower abundances of extremely volatile elements, such as hydrogen and nitrogen, and moderately volatile elements, such as sodium and potassium, as compared with Earth. These peculiar features are not definitively explained by the canonical hypothesis. Yet they arise naturally from "baking" a growing moon at a few thousand degrees in the "oven" of a synestia.

More volatile elements would have preferentially stayed in the vapor of the synestia, so the moon would never have acquired Earth-like abundances of these elements. The volatile elements that stayed in the vapor would be carried inward with the shrinking synestia to become part of Earth. With help from our colleagues Misha Petaev and Stein Jacobsen, both at Harvard University, we demonstrated that the pattern and abundance of moderately volatile lunar elements can be explained by the moon coming into chemical equilibrium with the vaporized elements inside the synestia. Simply put, being born in a synestia naturally explains why the moon has a similar composition to Earth but has a lower abundance of volatile elements. Our simple recipe for making the moon's chemistry is as follows: vaporize two colliding planetary bodies, mix well and bake at 4,000 degrees Celsius (more than 7,000 degrees F) in a convection oven for 10 to 100 years.

Finally, synestias may explain otherwise mysterious quirks in the moon's orbit. Strangely, the moon does not orbit Earth in the same plane in which Earth orbits the sun, which is called the ecliptic plane. Instead the moon's orbit is inclined to the ecliptic plane by about five degrees. The tilt of the orbit is why we do not have total lunar eclipses every month but only on the rare occasions when Earth, the moon and the sun align. Yet after a giant impact, if the moon formed from a circumplanetary disk or a synestia, the naive expectation would be that it should be orbiting in the ecliptic plane. So why is the lunar orbit inclined?

A new model for how the orbit of the moon changes with time by SETI Institute theorist Matija Ćuk and his colleagues can explain both the inclination of the lunar orbit and the length of Earth's day. The giant impact may have knocked the proto-Earth on its side and produced a synestia with its rotation axis tilted close to the ecliptic plane. The moon would have formed in the plane of Earth's equator, with its orbit also tilted far from the ecliptic. Over time, resonant interactions with the sun would have pulled the rotation axis of Earth more upright to its present-day 23-degree tilt. Earth's spin would have been slowed in the process, with our planet being pushed slightly farther away from the sun to conserve angular momentum. As the moon dissipated its orbital energy by raising tides on Earth, it would slowly move away from the planet, decreasing the lunar inclination to the ecliptic to its present orientation. Thus, a single giant impact that created a tilted synestia could explain many of the key dynamical characteristics of Earth and its satellite.

In sum, the synestia's natural elegance and explanatory power have rescued the giant impact hypothesis—and permanently changed the playing field for studies of the origin of the moon.

FULFILLING APOLLO'S LEGACY

WITHOUT THE DATA FROM THE ROCKS collected by the Apollo astronauts, we could have been satisfied with an incomplete, or even erroneous, idea for how the moon was created. The challenge of explaining the data led to the discovery of synestias. Now our new challenge is to further develop our understanding of synestias and their role in planet formation. We are only at the beginning of this quest.

Our model of a moon-forming synestia can be tested by improving its chemical and isotopic predictions for lunar composition. We are still learning from the samples collected by the Apollo missions—half a century of progress in instrumentation is allowing the extraction of more accurate and detailed data. But the Apollo samples are a limited resource with enormous gaps in coverage and completeness. More than ever, we need rocks from the lunar mantle to build better chemical models for the moon's bulk composition. Returning to the moon to obtain samples from the mantle, parts of which should be exposed in and around massive impact craters, will let us make fresh predictions for that vital measurement. Meanwhile rocks right here on Earth may provide additional important clues for lunar origins. It has recently been realized that the deepest regions of Earth's mantle contain traces of material that survived the moon-forming giant impact. Whatever process formed the moon could not have erased these chemical records. By combining data from Earth and the moon, we hope to piece together our view of the synestia that made both bodies.

Help in understanding synestias may also come from beyond our solar system. So far we have seen them only as mathematical objects on our computer screens, but synestias may not remain a purely theoretical notion much longer. Many telescopes, in space and on the ground, are staring at the heavens in search of exoplanets silhouetted against the bright faces of their stars. Because their shapes are very different from a spherical planet, synestias would cast unusual shadows on our telescopes. Other new and emerging facilities are snapping baby pictures of planets around very young stars that may still be in the giant impact stage of formation. Perhaps some of those snapshots will reveal a puffy, glowing doughnut of rock vapor where a planet used to be. Soon we may glimpse our first natural synestia and witness a near replay of the creative destruction that led to the formation of our own Earth and moon. SA

APOLLO'S BOUNTY

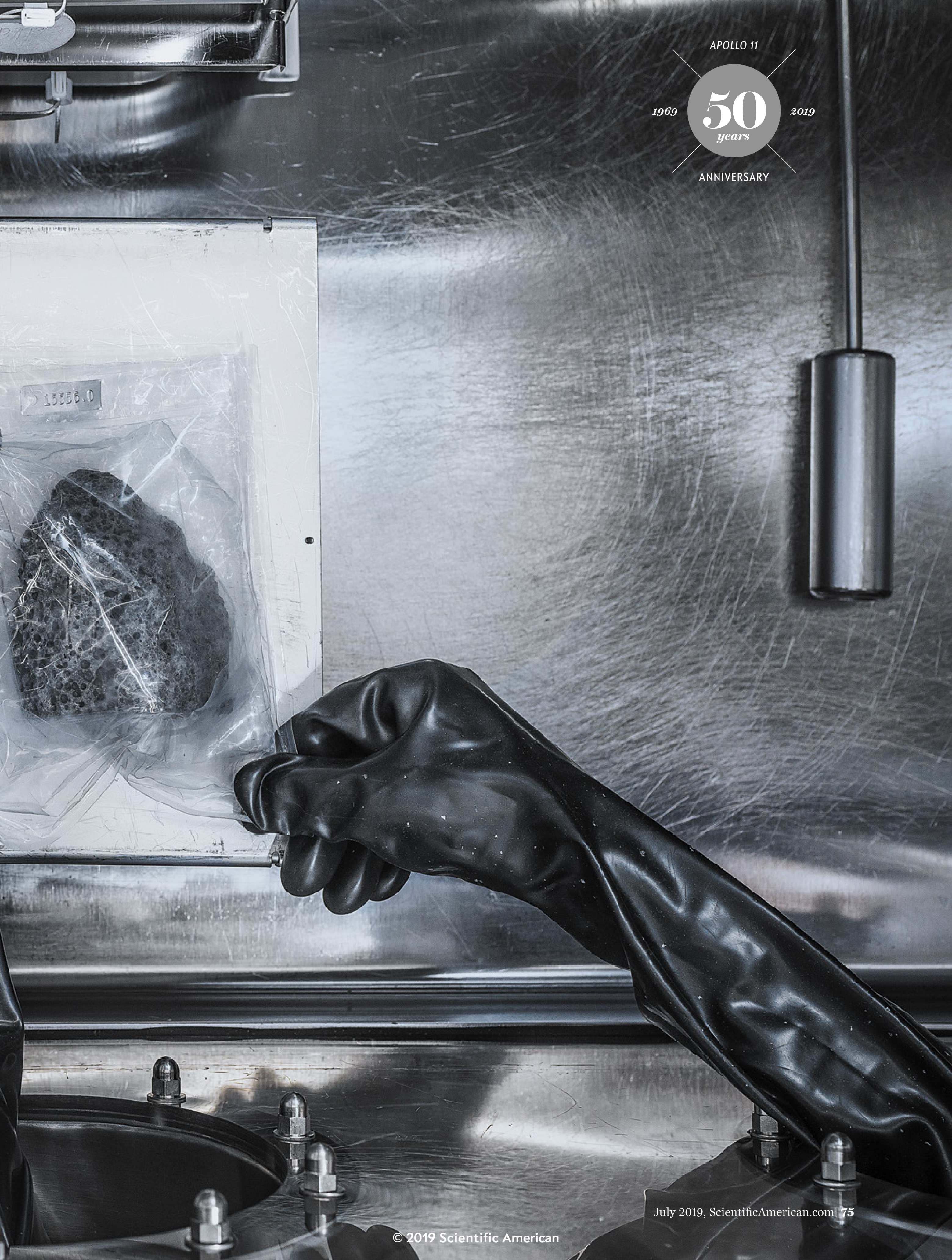
THE LUNAR ROCKS BROUGHT HOME BY APOLLO ASTRONAUTS RESHAPED OUR UNDERSTANDING OF THE MOON AND THE ENTIRE SOLAR SYSTEM. GATHERING MORE OF THEM IS ONE OF THE MOST IMPORTANT REASONS TO GO BACK

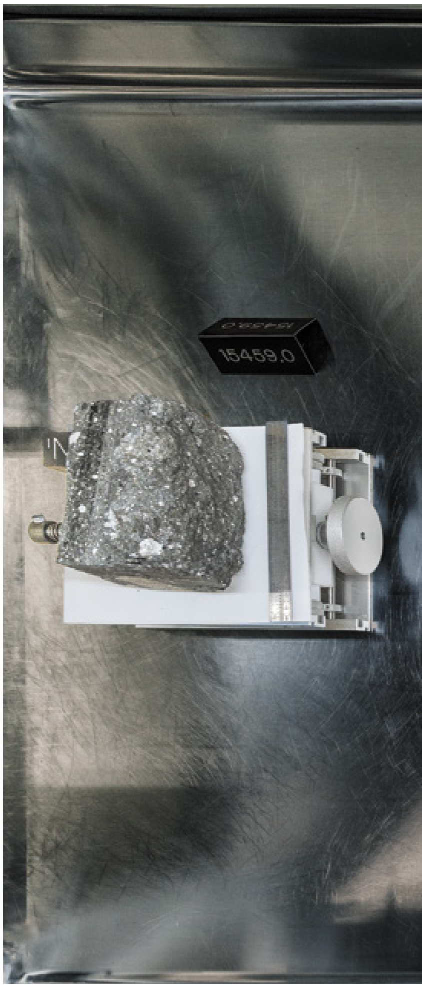
By Erica Jawin

INSIDE a Teflon bag within a nitrogen-filled storage cabinet at the Apollo Sample Vault at NASA's Johnson Space Center is the largest remaining piece of the *Apollo 15* moon rock sample 15556.

Photographs by Chris Gunn

APOLLO 11 1969 50 years 2019 ANNIVERSARY





THE APOLLO MISSIONS ARE MOST CELEBRATED FOR putting human footprints on the moon, but their biggest contribution to science was the collection of rocks the astronauts brought home with them. To call these 382 kilograms of stone and regolith (the thick layer of crushed rock and dust that covers the surface of the moon and other planetary bodies) a treasure trove does not do them justice. Studying these samples in laboratories on Earth helped to establish the modern field of planetary science and gave us crucial insights into geologic processes that operate on all planetary bodies.

I was born too late to witness *Apollo 11,* but my life and career as a planetary scientist have been directly shaped by the samples brought back by the six missions that landed on the moon. For instance, some of my research concerns explosive volcanic deposits on the lunar surface. The data that I have used come from samples that were scooped directly off the surface by astronauts during *Apollo 15* and *17.* Other data were gathered by orbiting spacecraft that scientists built and sent to the moon as a direct result of the scientific and technical knowledge gained through the Apollo missions.

In the past 50 years NASA has received 3,190 unique lunar sample requests from more than 500 scientists in more than 15 countries, according to Ryan Zeigler, NASA's Apollo sample curator. Over the decades, he says, the agency has distributed more than 50,000 unique lunar samples, and currently 145 scientists are studying more than 8,000 samples in diverse fields, including astronomy, biology, chemistry, engineering, materials science, medicine and geology. Above all, the moon rocks have revolutionized our understanding of three major subjects: the nature of the lunar surface, the origin of the moon and the evolution of our solar system.

IN BRIEF

Moon samples gathered by Apollo astronauts have profoundly influenced planetary science.

By analyzing them in labs on Earth, scientists clarified the origin of the moon and the evolution of the solar system.

New samples from different parts of the moon could teach us much more.

ANCIENT SURFACE

BEFORE WE SENT SPACECRAFT and humans to the moon, our knowledge of Earth's natural satellite was largely speculative, limited to observations that could be made from Earth.

These studies had suggested that the surface of the moon is extremely old because it is saturated with impact craters that must have taken billions of years to accumulate. When we finally landed on the moon, we knew for sure. After lunar rocks arrived on Earth, geochemists analyzed them for isotopes that decay over well-understood timescales and found that the moon samples were far older than most terrestrial rocks—between three billion and 4.5 billion years old.

Planetary scientists then made a connection that would affect virtually all subsequent studies of the moon and the other planetary bodies: they compared the first measured ages of lunar samples from the *Apollo 11* landing site with the number of impact craters in the region where each was collected. Then they used this information to develop a model for how quickly impact craters form on the surface of the moon. Through this model, the Apollo sample sites serve as a kind of Rosetta stone, enabling scientists to estimate the age of any location on the moon (and

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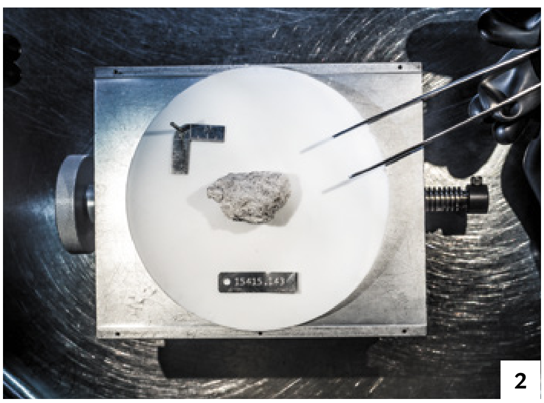


2

FIVE SAMPLES collected during the *Apollo 15, 16* and *17* missions (*1*), as well as the *Apollo 15* sample 15415 (*2*), known as the Genesis rock, which helped scientists develop the leading theory of how the moon formed.

even other planetary bodies) without visiting them.

At about 4.5 billion years old, the oldest sample is essentially the same age as the moon itself. Most rocks on Earth are much younger than four billion years because of the constant recycling of the crust by plate tectonics—a process that does not occur on the moon. Thus, lunar samples provide an important glimpse of ancient rocks from the early days of the solar system. They could even tell us about the young Earth. This March, researchers analyzing an *Apollo 14* breccia (a rock type composed of other rock fragments welded together) determined that one of those pieces might not be a moon rock at all. Instead it may represent the first terrestrial meteorite—a rock that was ejected from Earth four billion years ago and then landed on the moon. After billions of years astronaut Alan Shepard picked it up and brought it home.

LUNAR ORIGINS

BEFORE APOLLO, scientists had several competing ideas for how the moon and other planetary satellites formed. Perhaps Earth captured another body that passed too close. Maybe in its early days our planet spun so fast that a blob separated from the main body. Or maybe Earth and the moon may have formed at the same time from the original "protoplanetary disk" that gave rise to all the planets in our solar system. After the Apollo missions, however, we gained an entirely different picture.

Today the favored theory of the moon's origin is called the giant impact hypothesis. This idea, based on

Erica Jawin is a postdoctoral research geologist at the Smithsonian National Museum of Natural History.

CURATION processors transfer an *Apollo 15* sample out of an airlock in its stainless-steel storage cabinet.

evidence collected during the Apollo program, is that some 4.5 billion years ago, a body about the size of Mars (referred to as Theia) hit Earth, fragmenting itself and ejecting part of Earth's crust and mantle into space. Eventually the ejected terrestrial material mixed with the remnants of Theia, accumulating into a satellite that cooled and became the moon.

This model has been influenced by many observations from the Apollo samples and surface experiments, which include:

IRON: The moon has surprisingly little iron. Surface geophysics experiments deployed by Apollo missions showed that compared with the terrestrial planets, the moon's core comprises a very small portion of its volume compared with the terrestrial planets—just 25 percent of its total radius. The relative lack of iron suggested by the moon's small core is evidence that Earth had already formed an iron-rich center when the giant impact occurred, leaving little iron to form the moon.

DRYNESS: The lunar samples proved to be extremely dry and almost entirely depleted of volatiles—elements or molecules with low boiling points that easily evaporate, such as water, carbon dioxide, nitrogen and hydrogen. To explain this depletion, scientists suggest the massive amount of energy and heat generated from the giant impact may have driven volatiles from the fragments of the proto-moon.

MAGMA OCEAN: One of the most influential hypotheses to come from the lunar samples is the idea that there was an ocean of magma on the early moon. *Apollo 11* samples showed that the lunar highlands (bright, high-standing regions as opposed to the dark lunar maria in low-lying areas) contain high concentrations of the mineral plagioclase. The texture of the rocks containing this mineral suggested that it formed from a large body of molten rock that cooled, and the light plagioclase crystals floated to the top. Because similar rocks had been found by previous robotic missions at other locations, and the lunar highlands are widespread, the layer of magma must have covered most, or all, of the moon's surface. Two independent groups proposed the idea of this early magma ocean in 1970, just six months after the return of the first Apollo samples. Several additional lines of evidence from geochemistry and geophysics support the magma ocean model, which is still being developed today.

One piece of evidence that complicates the giant impact model is the concentration of various isotopes—atoms of an element that have a different mass from the "regular" atoms—in Apollo samples. Using a process called laser fluorination, in 2001 and 2012 researchers found that the compositions of both oxygen and titanium isotopes are almost identical between the moon and Earth. If the moon formed from a mixture of Theia and Earth materials, why does it have an Earth-like isotopic composition? This evidence has inspired new ideas, such as the "synestia" model that planetary scientists Simon J. Lock and Sarah T. Stewart describe in "Origin Story," on page 68.

THE STORY OF THE SOLAR SYSTEM

STUDIES OF LUNAR SAMPLES have also informed us about other planetary bodies. Perhaps the most significant result is the Nice model (so named because it was created in Nice, France) of the evolution of the solar system. According to this model, the giant planets of the outer solar system initially formed close together. After several hundred million years, their orbits became unstable, causing Saturn, Uranus and Neptune to rapidly migrate to their present-day orbits, which are much farther away from the sun. The movement of the giant planets pulled material from the outer solar system—the Kuiper belt—inward, where it collided with planets and moons and caused general chaos throughout the solar system.

This model may sound far-fetched, but it elegantly explains a number of seemingly unrelated observations about our cosmic neighborhood. For instance, by dating Apollo samples and analyzing impact craters, scientists concluded that there was a cataclysmic spike in impacts on the moon about 700 million years after the planets formed, referred to as the "late heavy bombardment." Initially there was no easy explanation for why the number of impacts would have suddenly jumped at this time. Yet the chaotic period of impacts predicted in the Nice model provides a source of impactors during the exact era in question.

In addition to telling us about the evolution of the solar system, the lunar samples have also allowed scientists to investigate the chemical evolution of planetary surfaces. "Space weathering" is a process that describes the physical and chemical erosion on bodies with no atmosphere. Studies of Apollo soils scooped from the surface showed that they contain agglutinates, welded glass and mineral fragments created by the impact of microscopic grains of dust. These agglutinates accumulate over time and can make up 60 to 70 percent of mature regolith samples. Tiny spheres of elemental iron called nanophase iron are also produced by space weathering and build up on the outer rims of certain soil grains, causing surfaces to become darker over time. We now know that solar radiation, large temperature fluctuations and the constant bombardment by tiny micrometeorites are some of the sources of space weathering.

SAMPLES FOR THE FUTURE

THIS IS AN EXCITING TIME in lunar science: this year caches of samples will be released that have remained unopened since they were collected almost 50 years ago on the moon. When the rocks were collected, NASA intentionally left a portion sealed to wait for technology to advance beyond the capabilities of the Apollo era. In March the Apollo Next Generation Sample Analysis (ANGSA) program selected nine research teams to receive unopened, vacuum-sealed samples from *Apollo 15, 16* and *17.* The opportunity to study "new" lunar samples will likely lead to more fundamental discoveries about the formation and evolution of our natural satellite.

As much as we have learned from the Apollo samples and surface experiments and as much as we will undoubtedly learn from the new caches, we desperately need more samples. For instance, we have no recognized samples from the lunar far side, the polar regions or the deep interior. Two samples I would particularly like to have are material from the South Pole–Aitken Basin, on the lunar far side, and ice from a polar crater. The South Pole–Aitken Basin is the largest recognized impact basin on the moon—and one of the largest in the solar system—and its interior could contain material from the moon's lower crust and even its mantle. Studying the South Pole–Aitken Basin would also help us understand how extremely large basins shape the surfaces and interiors of planetary bodies. Returning a sample of lunar polar ice would tell us about the age and origin of lunar water—which, in turn, could clarify where Earth's water originated.

This year caches of samples will be released that have remained unopened since they were collected almost 50 years ago.

These wish-list specimens could come from human exploration or robotic missions: there is no consensus among planetary scientists that either is best. Many experts argue, rightly, that robotic missions are cheaper, safer and can last longer than human missions. On the other hand, humans are more likely than robots to pick out a wider variety of unusual specimens, as evidenced by the diversity of the Apollo sample suite (rock, scooped and sieved soils, boulder chips, drill cores), sample volume and sample geology (composition, rock type, age).

The Apollo missions represent a singular accomplishment that fundamentally altered our view of the solar system. While we celebrate the 50th anniversary of humanity's giant leap, no human has set foot on another planetary body since Harrison "Jack" Schmitt and the late Gene Cernan departed from the lunar surface, during the *Apollo 17* mission, on December 14, 1972. As a scientist deeply inspired by those missions, I am actively working toward creating my generation's Apollo moment: to see humans (people of color and of all genders) land on the surface of the moon, fueled by ingenuity, perseverance and a drive to explore the unknown. SA

APOLLO 11

1969 50 years 2019

ANNIVERSARY

COME ONE, COME ALL

HUMANITY FIRST WENT TO THE MOON TO MAKE A POINT. NOW IT'S TIME TO OVERCOME RIVALRIES AND PITCH IN TOGETHER

By Clara Moskowitz

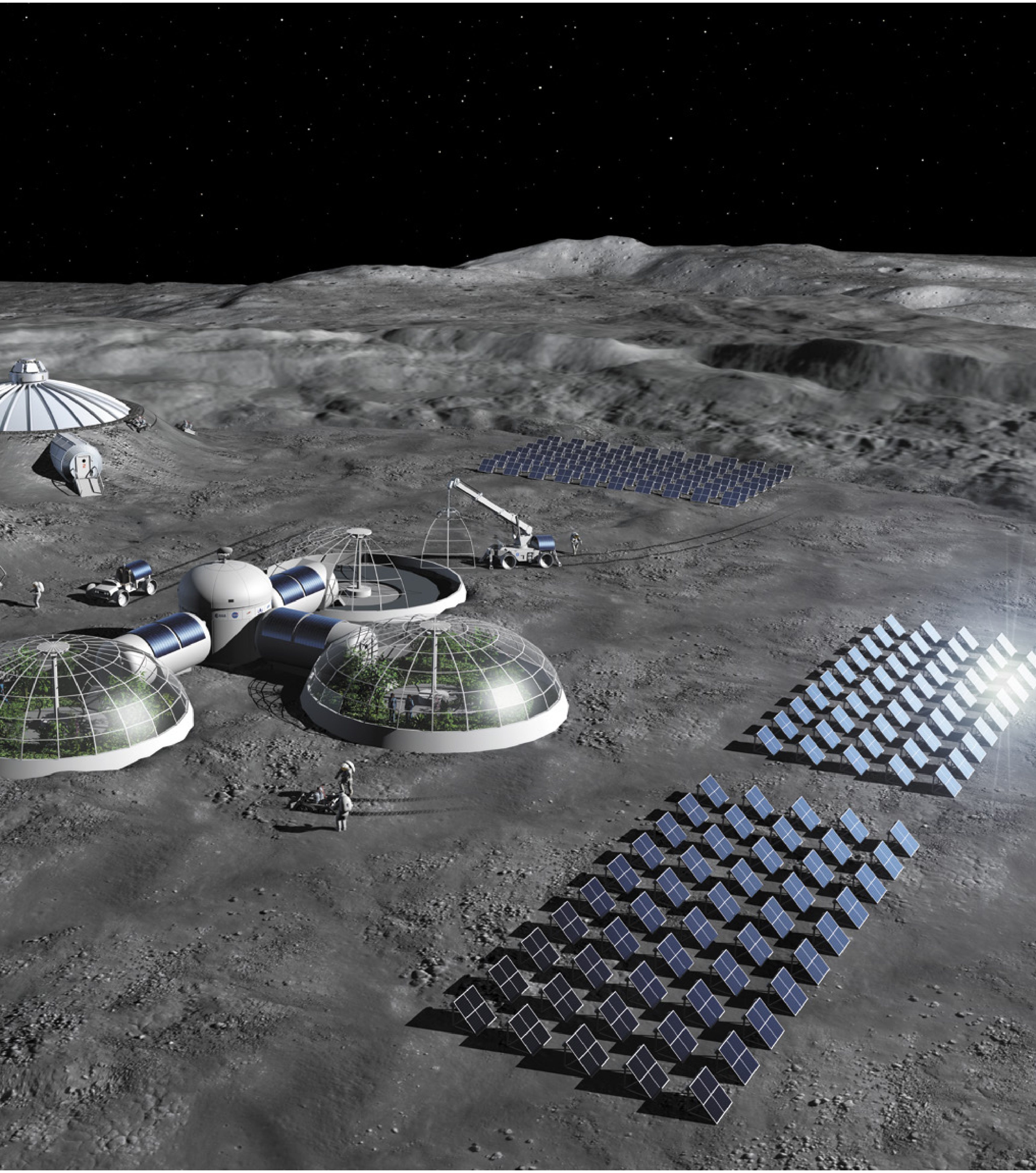
JAN WÖRNER
ESA director general

Without the cold war, Apollo 11 *never would have happened. The urge to beat the Soviets to the moon and prove U.S. technological superiority motivated Congress to devote almost 4.5 percent of the U.S. national budget to NASA at the peak of the space race in 1966. Yet after the first moon landing three years later, the agency never again received more than 2 percent of the budget, and it has gotten around half a percent every year since 2010.*

These days national prestige is not enough of an incentive for most countries to go it alone in space. If we are to travel again to another planetary body, it will have to be together. This idea has perhaps been expressed most vociferously by Johann-Dietrich ("Jan") Wörner, director general of the European Space Agency (ESA). In 2015 Wörner introduced his vision for the "Moon Village," a cooperative campsite of sorts on the lunar surface. Countries, private companies, universities, nonprofits and individuals are welcome to send people, robots, and all manner of scientific, exploratory and commercial ventures to take part. And to back up the Moon Village's international and collaborative bona fides, the project is officially being organized not by ESA but by a Vienna-based nongovernmental organization called the Moon Village Association, which

SCIENTIFIC and commercial activities by multiple nations and companies could coexist in the Moon Village.

MATTHEW STAVER Getty Images (photograph); P. CARRIL European Space Agency (illustration)



is open for groups and individuals to join. SCIENTIFIC AMERICAN *spoke to Wörner about the Moon Village's goals, the debate over the moon versus Mars, and why now is the right time to go. An edited transcript of the conversation follows.*

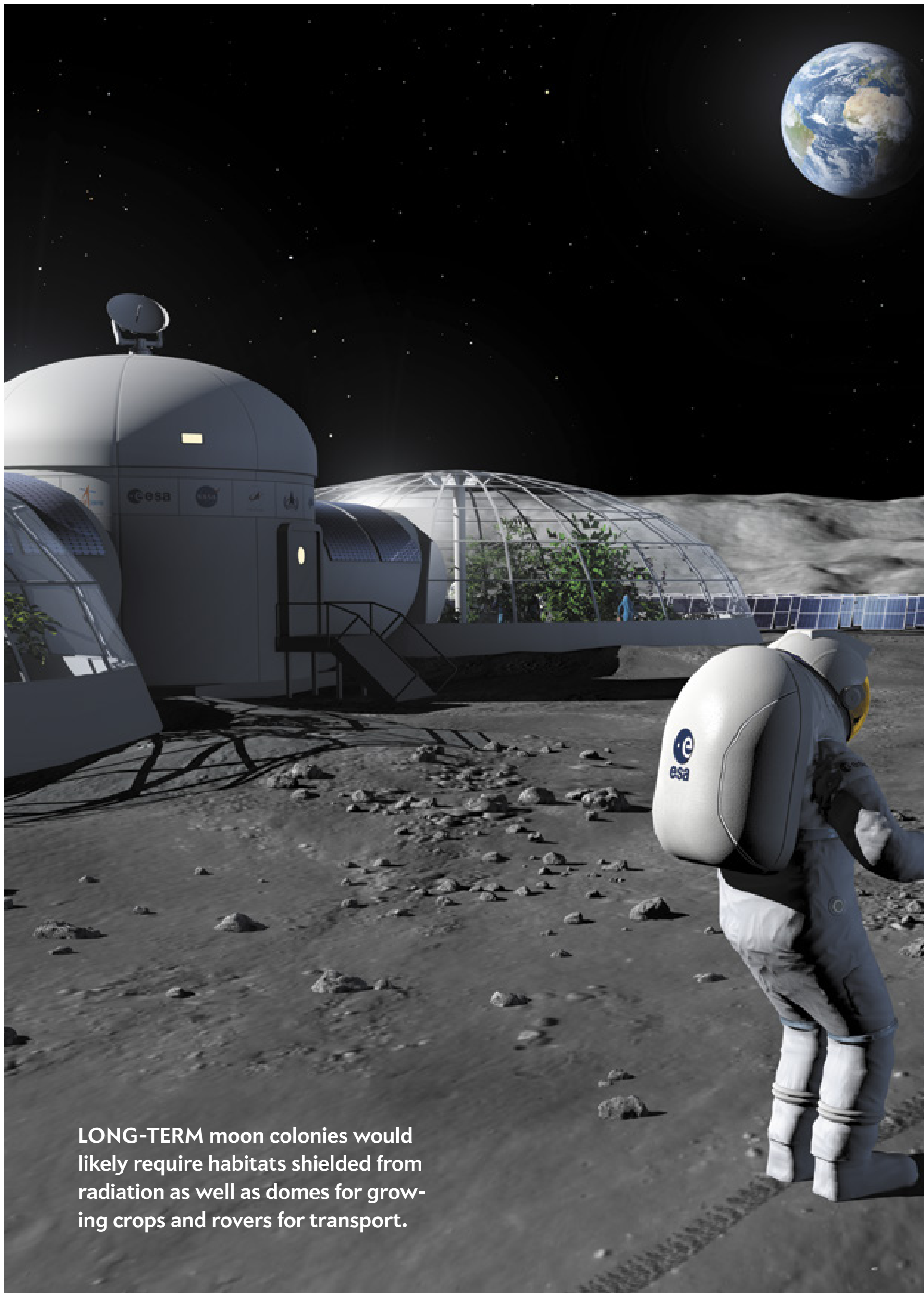
Tell me about your plan for going back to the moon.
We don't want to go back to the moon.

What do you mean?
We want to go forward to the moon. I'm serious. We do not want a space race, with the question of prestige. The moon is the perfect place to really collaborate on a global scale. In the past, space activities were realized by direct procurement of the agencies, as in the Apollo moon missions. We have similar projects right now at ESA. And we have projects where the agency is the broker, the enabler, the facilitator. This is the Moon Village.

The Moon Village is a multipartner open concept. Each and every word in this phrase is important. "Multipartner" means not only one—it can be as many as possible. "Open" means there is no special formality to be a partner of it. And it is a "concept": it is not one project. Different partners should put in what they would like to deliver, whether it's transportation, whether it's mining, whether it's tourism, whether it's science, whether it's technology development for in situ resource utilization—for instance, using the water on the moon for production of fuel. It is totally open for different purposes.

Do you see the Moon Village as part of the legacy of Apollo or a deliberate departure?
Apollo was done in a totally different environment. Then, competition was the driver. Now I believe cooperation is the enabler. But of course, without Apollo, we would maybe not think about it.

Did you watch the *Apollo 11* landing? How did it affect you?
Yes. I was 15 years old. In Germany, it was during the night, and I did not sleep at all. I remember very well: I was looking at the TV; I saw the first steps of Neil Armstrong, Buzz Aldrin. The transmission ended, and I went out of my home, into the fresh air. I was breathing deeply and thinking, "We are doing the future." It was really a big day for me. I would never have thought at that time that I would be part of space activities. Now I am the director general of ESA.



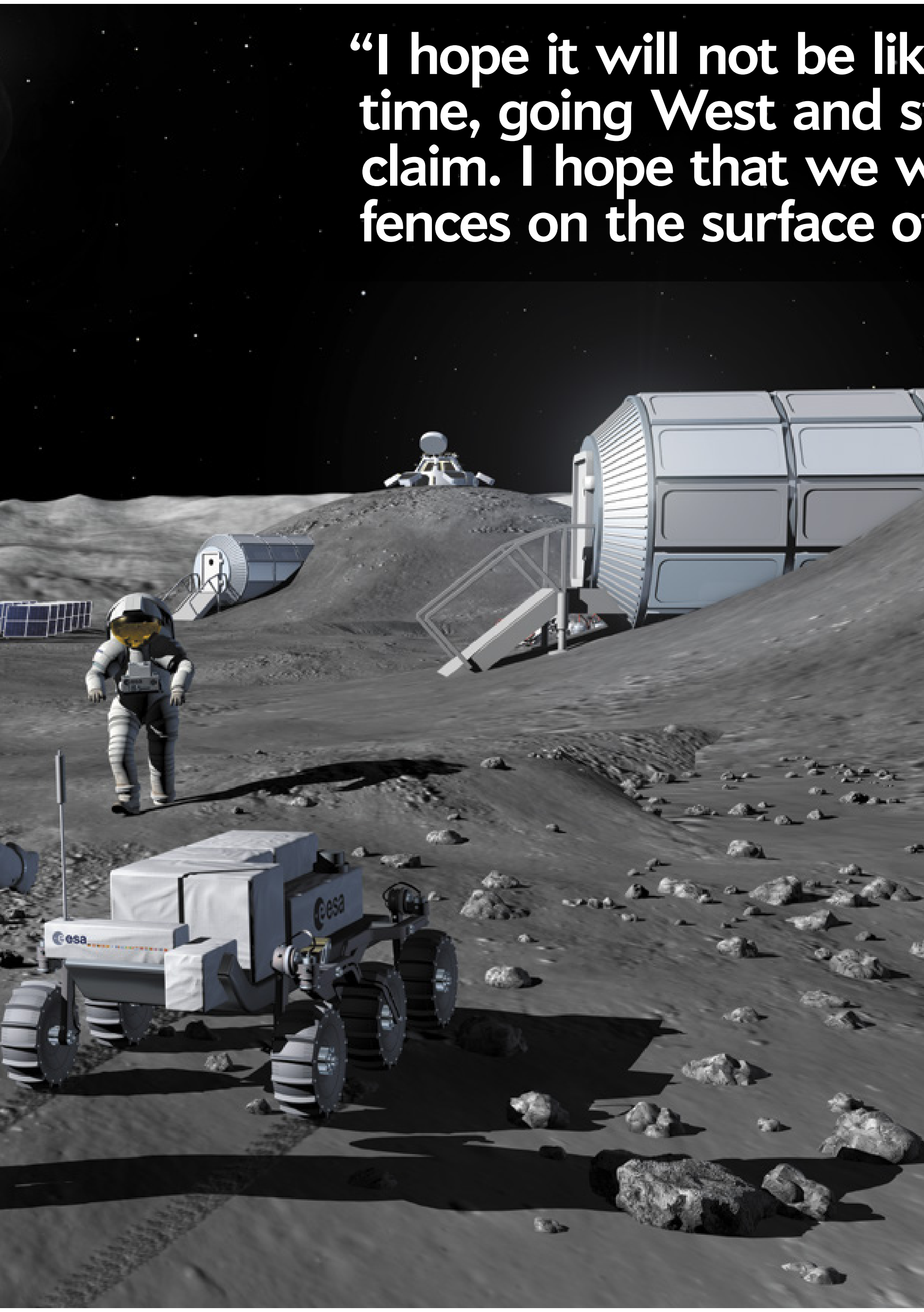
LONG-TERM moon colonies would likely require habitats shielded from radiation as well as domes for growing crops and rovers for transport.

P. CARRIL *European Space Agency*

Why are you targeting the moon and not, say, new destinations, such as Mars?
I'm in favor of also thinking about Mars, but I believe the moon is the right way to go forward. We cannot talk today about human missions to the surface of Mars because of [the dangers of] radiation and other challenges. Can we dare to send humans for a two-year trip in an environment where survival is really difficult, and if they have some disease, we have no way to get them back? We have to develop better technology.

But the moon is a good playground for technology development. For instance, we can use the resources of the surface of the moon to build structures to shelter the astronauts, to build observatories

"I hope it will not be like in the old time, going West and staking our claim. I hope that we will not have fences on the surface of the moon."



or to produce fuels of hydrogen and oxygen. Therefore, the moon is a stepping-stone to go farther: to Mars. But this is far in the future—it will take decades. Even though some are announcing goals of shorter periods, we will see that this is not possible.

It's been 50 years since *Apollo 11.* Why has it taken us so long to send astronauts back?
Forward.

Forward, sorry. But why do you think now is the right time?
I see, worldwide, the readiness to work together. I had discussions with the Chinese, with the Americans, with the Japanese, with the Russians, and all of them are looking to work together in the exploration of the moon, Mars and beyond.

I hope it will not be like in the old time, going West and staking our claim. I hope that we will not have fences on the surface of the moon. In Germany, we have some experience with fences and walls. I hope this can be done in a much better way.

What do you see as the biggest hurdle for the Moon Village to succeed?
There is a kind of paper you can hold in your hand, where I think George Washington is on one side. [*Laughs.*] So, money.

If we were launching the Moon Village today, would you go?
I have an appointment for dinner, but I would skip that if somebody said I could go right now. Yes, I would call my family, and I would do it—I would go immediately. I'm a curious person, and this curiosity would be the driver for me. But I would only go with a return ticket.

MORE TO EXPLORE

Forming a Moon with an Earth-like Composition via a Giant Impact. Robin M. Canup in *Science,* Vol. 338, pages 1052–1055; November 23, 2012.

Tidal Evolution of the Moon from a High-Obliquity, High-Angular-Momentum Earth. Matija Ćuk et al. in *Nature,* Vol. 539, pages 402–406; November 17, 2016.

The Origin of the Moon within a Terrestrial Synestia. Simon J. Lock et al. in *JGR Planets,* Vol. 123, No. 4, pages 910–951; April 2018.

Apollo Next Generation Sample Analysis Program: **https://sservi.nasa.gov/articles/apollo-next-generation-sample-analysis-program**

Moon Village Association: **https://moonvillageassociation.org**

Transcripts from *Apollo 11:* **www.hq.nasa.gov/alsj/a11/a11trans.html**

Outer Space Treaty of 1967: **www.state.gov/t/isn/5181.htm**

FROM OUR ARCHIVES

The Exploration of the Moon. Wilmot Hess, Robert Kovach, Paul W. Gast and Gene Simmons; October 1969.

The Scientific Legacy of Apollo. G. Jeffrey Taylor; July 1994.

scientificamerican.com/magazine/sa

By Andrea Gawrylewski

APOLLO 11
1969 50 years 2019
ANNIVERSARY

LEGO Ideas NASA Apollo Saturn V

Building set ($119.99)

In the early morning hours of July 16, 1969, technicians at the Kennedy Space Center loaded upward of 750,000 gallons of fuel into the 363-foot Saturn V rocket that would successfully propel the *Apollo 11* spacecraft toward the moon. It would be one of 13 Saturn V launches between 1967 and 1973. This vehicle remains the tallest, heaviest and most powerful rocket ever in operation. In honor of the 50th anniversary of Saturn V's famous flight, this month's column focuses on all things *Apollo 11*. As for the rocket, pick up this 3.3-foot-high feat of LEGO engineering, which includes three removable stages, as well as the lunar lander and command module. Even with 1,969 pieces (get it?), it is by no means the largest LEGO set ever created, but it's a handsome and fun tribute to one of NASA's most accomplished workhorses of space travel.

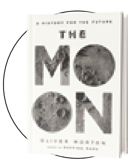
One Giant Leap: The Impossible Mission That Flew Us to the Moon

by Charles Fishman. Simon & Schuster, 2019 ($29.99)

Landing astronauts on the moon was, by some estimates, the greatest achievement of the 20th century and has been painstakingly chronicled. But many of the behind-the-scenes stories of the *Apollo 11* mission remain surprisingly unknown. Journalist Fishman shares details such as the fact that the moon smells like wet ashes or that while Buzz Aldrin took the first moon walk, one of the engineers who developed his spacesuit watched in silent horror, fearing Aldrin would trip, tear the suit and doom the mission. Fishman also gives an account of heated conversations in late 1962 between President John F. Kennedy and NASA chief James E. Webb, revealing that Kennedy was annoyed by the budget and difficulties of the Apollo program. In the end, the lunar mission succeeded against the odds. *—Jim Daley*

The Moon: A History for the Future

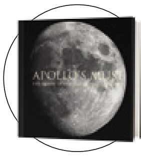
by Oliver Morton. Economist Books, 2019 ($28)



Humankind's fascination with the moon came long before two American astronauts first walked on its surface. "It defines the sky," science writer Morton says in *The Moon*. "It completes the Earth." In tribute, he thoughtfully describes the history of this intimate relation, from earlier generations that depended on the natural satellite as a utility to illuminate the night sky to the triumph of the Apollo missions and the possibility of commercial space travel. Morton also reflects on the influence of science fiction in society before the moon landing—lunar-settlement stories represented the future, he writes, sometimes idyllic, sometimes terrible. Today the moon continues to inspire us: our species harbors new ambitions to return to our planet's closest companion and use it as a stepping-stone for further exploration of the universe. *—Sunya Bhutta*

Apollo's Muse: The Moon in the Age of Photography

Metropolitan Museum of Art, New York City. On exhibit July 3–September 22, 2019 (general admission, $25)



When Italian scientist Galileo Galilei peered at the moon through his homemade telescope, he sketched its surprisingly craggy surface, published his drawings in 1610 and launched a new field of astronomy called selenography. They were certainly not the first pictures of the moon but perhaps a more scientific iteration of the age-old human captivation with Earth's satellite. This summer the Metropolitan Museum of Art will display an enchanting collection of moon images, from daguerreotypes—including two from the 1840s that were previously undiscovered—to the epic portrait of Buzz Aldrin in his mirror-faced space helmet taken by Neil Armstrong on the lunar surface in 1969. And, of course, Galileo's famous originals.

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

"Emotional AI" *Sounds* Appealing

But its consequences could be troubling

By Zeynep Tufekci

Perhaps you're familiar with Data from *Star Trek: The Next Generation,* an android endowed with advanced artificial intelligence but no feelings—he's incapable of feeling joy or sadness. Yet Data aspires to more. He wants to be a person! So his creator embarks on a multiseason quest to develop the "emotion chip" that would fulfill that dream.

As you watch the show, it's hard not to wonder about the end point of this quest. What would Data do first? Comfort a grieving person? Share a fellow crewmate's joy? Laugh at a joke? *Make* a joke? Machine learning has already produced software that can process human emotions, reading micro expressions better than humans can and generally cataloguing what may be going on inside a person just from scanning his or her face.

And right out of the gate, advertisers and marketers have jumped on this technology. For example, Coca-Cola has hired a company called Affectiva, which markets emotion-recognition software, to fine-tune ads. As usual, money is driving this not so noble quest: research shows that ads that trigger strong emotional reactions are better at getting us to spend than ads using rational or informational approaches. Emotional recognition can also be used in principle for pricing and marketing in ways that just couldn't be done before. As you stand before that vending machine, how thirsty do you look? Prices may change accordingly. Hungry? Hot dogs may get more expensive.

This technology will almost certainly be used along with facial-recognition algorithms. As you step into a store, cameras could capture your countenance, identify you and pull up your data. The salesperson might get discreet tips on how to get you to purchase that sweater—Appeal to your ego? Capitalize on your insecurities? Offer accessories and matching pieces?—while coupons customized to lure you start flashing on your phone. Do the databases know you have a job interview tomorrow? Okay, here's a coupon for that blazer or tie. Are you flagged as someone who shops but doesn't buy or has limited finances? You may be ignored or even tailed suspiciously.

One potential, and almost inevitable, use of emotion-recognition software will be to identify people who have "undesirable" behaviors. As usual, the first applications will likely be about security. At a recent Taylor Swift concert, for example, facial recognition was reportedly used to try to spot potential troublemakers. The software is already being deployed in U.S. airports, and it's a matter of time before it may start doing more than identifying known security risks or stalkers. Who's too nervous? Who's acting guilty?

In more authoritarian countries, this software may turn to identifying malcontents. In China, an app pushed by the Communist party has more than 100 million registered users—the most downloaded app in Apple's digital store in the nation. In a country already known for digital surveillance and a "social credit system" that rewards and punishes based on behavior the party favors or frowns on, it's not surprising that so many people have downloaded an app that the *New York Times* describes as "devoted to promoting President Xi Jinping." Soon people in China may not even be able to roll their eyes while they use the app: the phone's camera could gauge their vivacity and happiness as they read Xi's latest quotes, then deduct points for those who appear less than fully enthusiastic.

It's not just China: the European Union is piloting a sort of "virtual agent" at its borders that will use what some have called an "AI lie detector." Similar systems are being deployed by the U.S. government. How long before companies start measuring whether customer service agents are smiling enough? It may seem like a giant leap from selling soda to enforcing emotional compliance, and there can certainly be some positive uses for these technologies. But the people pushing them tend to accentuate the positive and downplay the potential downside. Remember Facebook's feel-good early days?

If Data had ever been able to feel human emotions, he might have been surprised by how important greed and power are in human societies—and "emotional AI," unless properly regulated, could be a key tool for social control. That should give us all unhappy faces. SA

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Illustration by Cornelia Li

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.

What, Us Worry?

Fixing a problem first requires recognizing that it exists

By Steve Mirsky

Perhaps the only funny item in Jared Diamond's new book *Upheaval: Turning Points for Nations in Crisis* is an anecdote about what was known as the Winter War. When the Soviet Union invaded Finland in late 1939, the Finns resisted against the much larger Soviet forces until the two countries compromised on an uneasy peace.

Various countries sent equipment to help Finland defend itself. One such gift was World War I artillery from Italy. "Each artillery piece requires not only a gunner … but also someone called a spotter stationed some distance in front of the gun, in order to spot where the shell lands and thereby to correct the range setting for the next shot," Diamond explains. Of course, these large guns have hefty recoils—and they were not designed well for absorbing that jolt. So the Finns wound up using two spotters: the usual one in front to see where the shell landed, "plus another spotter behind the gun to see where the gun landed!"

Other than that story, the book ranges from unemotionally informational to somewhat grim—but necessarily so. Diamond—a professor of geography at the University of California, Los Angeles, National Medal of Science honoree, recipient of a MacArthur "genius grant" and winner of the Pulitzer Prize for nonfiction—focuses on seven countries he knows well, including us, aka the U.S., as the convenient abbreviation would have it.

We and the world are facing big problems, and Diamond points out that we're never going to solve those problems without acknowledging their existence. In fact, he sets up his arguments by examining how individuals in personal crises do or do not deal with those situations successfully and then drawing analogies, when possible, to countries.

In such a framework, a decision by a smiling Senator James Inhofe of Oklahoma in 2015 to display a snowball on the Senate floor to somehow refute the reality of climate change could be considered a symptom of a national delusional disorder.

Of course, that disorder has really bloomed in the years since. "Not enough American citizens and politicians take our current major problems seriously," Diamond writes, regarding the deterioration of political compromise, the increase in incivility, tainted elections (including by voter suppression) and economic inequality. (Climate change is in the section on global threats.)

The U.S. is also hampered by what I think is a misinterpretation of the idea of American Exceptionalism—a term first coined, ironically, by Joseph Stalin, when he wasn't busy attacking Finland. The notion of exceptionalism dates to Alexis de Tocqueville in the 19th century and originally covered the country's democracy and personal freedoms. But in more recent times it often seems (especially if you tune for a moment to Fox News) like exceptionalism has come to signify a belief that the U.S. is simply special—and shame on you if you question that specialness.

Nevertheless, Diamond notes, "although per-capita income is somewhat higher in the U.S. than in most European countries, life expectancy and measures of personal satisfaction are consistently higher in Western Europe. That suggests that Western European models may have much to teach us."

But we seldom even bother to see if there's anything to learn. "That's because we are convinced that … the U.S. is such a special case that Western European and Canadian solutions could have nothing relevant to suggest to us. That negative attitude deprives us of the option that so many individuals and countries have found useful in resolving crises: learning from models of how others have already resolved similar crises."

Perhaps the only hope of curing that particular flight of fancy can be found in this hypothetical exchange that Diamond quotes: "QUESTION: When will the U.S. take its problems seriously? ANSWER: When powerful rich Americans begin to feel physically unsafe."

Finally, and perhaps of most concern to this audience, Diamond delivers a solar plexus punch: "Skepticism about science is increasingly widespread in the U.S., and that's a very bad portent, because science is basically just the accurate description and understanding of the real world." But as the muckraking writer Upton Sinclair put it in 1934, "It is difficult to get a man to understand something, when his salary depends upon his not understanding it." Especially if that man is a U.S. senator. ■

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Illustration by Matt Collins

50, 100 & 150 YEARS AGO

INNOVATION AND DISCOVERY AS CHRONICLED IN *SCIENTIFIC AMERICAN*

Compiled by Daniel C. Schlenoff

JULY

1969 Neutrino Puzzle

"Most physicists and astronomers believe that the sun's heat is produced by thermonuclear reactions that fuse light elements into heavier ones. To demonstrate the truth of this hypothesis, however, is still not easy, nearly 50 years after it was suggested by Sir Arthur Eddington. Of the particles released by the hypothetical reactions in the solar interior, only one species has the ability to penetrate to the surface (a distance of some 400,000 miles) and escape into space: the neutrino. Within the past year a giant neutrino trap has begun operating in a rock cavity deep below the surface in the Homestake Mine in Lead, S.D. The initial results published have left astronomers and astrophysicists somewhat puzzled because the neutrino flux rate seems low.—John N. Bahcall"

1919 Aviation Glory

"The Tarrant triplane provides one more historic landmark in the growth of aircraft, the future of which rapidly vanishes from the sight of even the most gifted of prophets. The machine has a total plane surface of 5,000 square feet, and weighs with full normal load 45,000 pounds. The machine is particularly remarkable, inasmuch as it is not only the largest airplane in the world, but some of the methods of construction are entirely new. Unfortunately, the first Tarrant airplane, known as the 'Tabor,' was destined to be short-lived, despite the months upon months of painstaking work involved in its construction. In a few minutes' time the entire structure was destroyed upon takeoff at Farnborough, England."

The Seeds of War

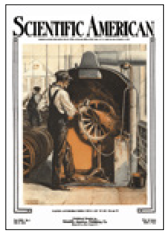
"The Signing by Germany of the Treaty of Peace at Versailles brings to an end the War of Arms begun by the Germans on the fields of Belgium. If the vanquished nations who set their hand and seal to the covenant of peace did so with a hatred, blind, unreasoning and implacable in their hearts, it will be merely a question of time and opportunity before the armed multitudes will be on the march, and red ruin will stride again across the world. It is our firm belief—for there is no evidence to the contrary—that the nations of the Entente, in this the supreme hour of accomplishment, are more concerned with the healing of the world than with the humiliation of the enemy."

Economist John Maynard Keynes predicted at the time, correctly, that the harsh punitive measures in the treaty would cripple the German economy.

A Monkey's Tale

"An interesting article by Prof. E. W. Gudger, in a recent issue of *Natural History,* deals with the time-honored story on which most of us were brought up that South American monkeys are in the habit of crossing alligator-infested streams by linking their tails and legs to form a living bridge. The story was first told, so far as known, by the Jesuit priest Padre Jose Acosta in a work published in 1589. The first person to dispute its veracity was Baron Humboldt. Lately, Messrs. Leo E. Miller and George K. Cherrie, of the American Museum of Natural History, who have done so much traveling and collecting in South America, have suggested a plausible origin for such tales. They think that the story of the 'monkey bridge' has come about through observation of a procession of monkeys crossing a ravine or stream on a pendent liana [vine]."

1969

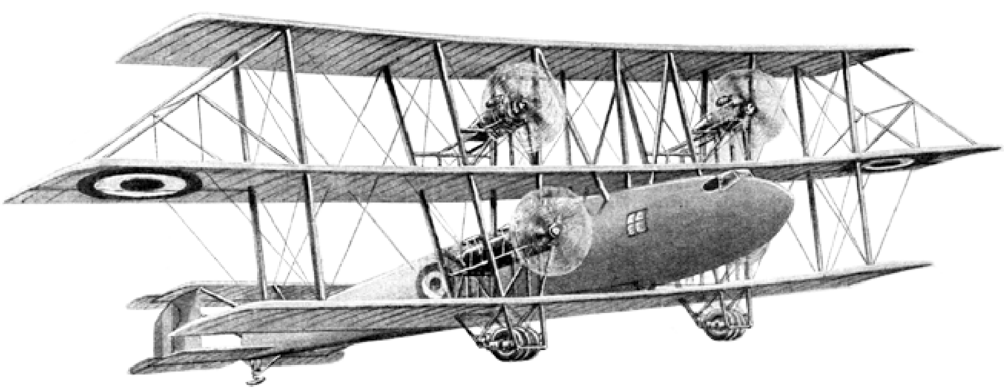


1919

1869

1869 Industrial Hazard

"The *British Medical Journal* says: 'Owing to the impossibility of keeping paint from coming into contact with the skin while they are at work; and to the almost universal practice among them of touching their food with unwashed hands; and to the habit of some of them of wearing corduroy, fustian, and other clothes difficult to cleanse, painters absorb large quantities of the hurtful metal [lead], and suffer gravely in consequence. If he continue to follow his trade, the more serious diseases—paralysis or kidney disease—are almost certain to attack him, and to render him, if not entirely unable to work, so weak and prostrated that in mental as well as in physical power, he will be but as the ghost of his former self. Different substances have been used instead of lead in the manufacture of paint, and with an encouraging amount of success. Zinc has been employed, and we have had favorable reports of it.'"



SCIENTIFIC AMERICAN, VOL. CXXI, NO. 1; JULY 5, 1919

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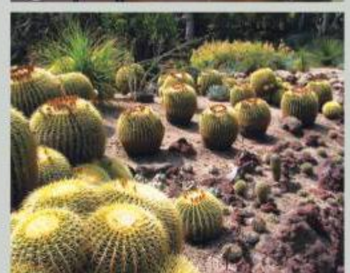

NOTES: Maximum of 40 for our private telescope reservation. Mt. Wilson Observatory is at 5,700 feet of elevation and not ADA compliant.

Millie Hughes-Fulford, Ph.D.

Professor of Medicine University of California Medical Center

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

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Jill Tarter, Ph.D.

Emeritus Chair for SETI Research, SETI Institute

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

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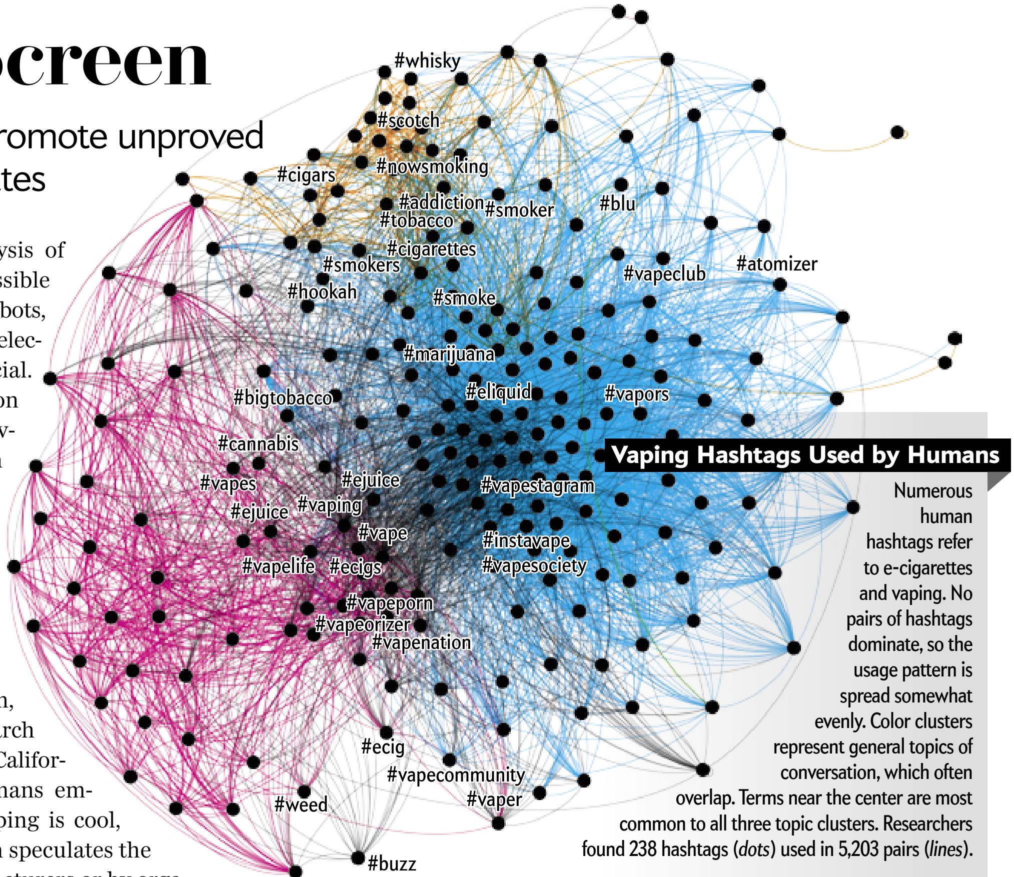
Text by Mark Fischetti | Graphic by Sree Priyanka Uppu

Smoke Screen

Social media bots promote unproved benefits of e-cigarettes

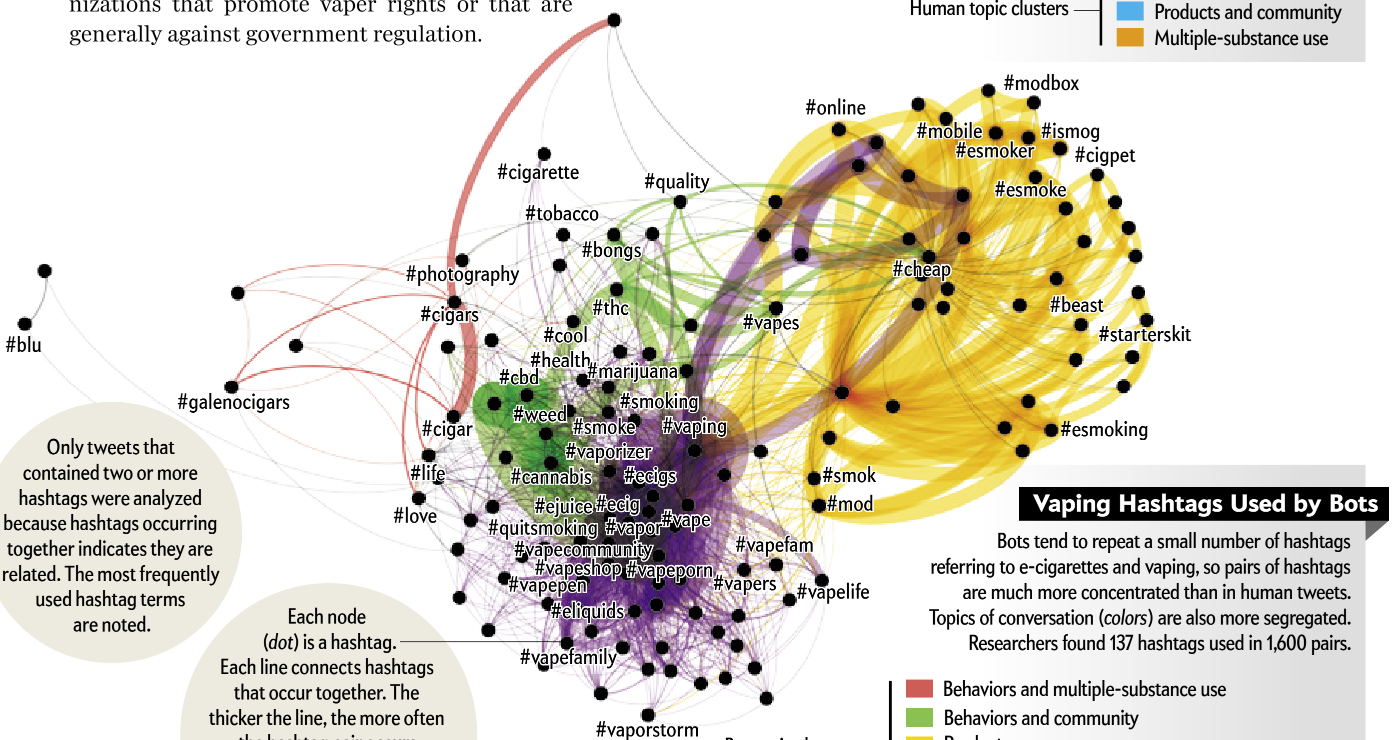
Vaping is hot. A clever analysis of Twitter posts reveals one possible reason: automated accounts, or bots, may be convincing people that electronic cigarettes are beneficial. Researchers analyzed 2.2 million tweets about vaping and discovered that hashtags used in tweets by humans differ from those in tweets by bots. Bots focus on new products and on vaping as an effective way to stop smoking tobacco even though "there is limited scientific evidence for that," says study leader Jon-Patrick Allem, an assistant professor of research at the University of Southern California. Hashtags written by humans emphasize people's lifestyles—vaping is cool, vapers are a community. Allem speculates the bots are propagated by manufacturers or by organizations that promote vaper rights or that are generally against government regulation.



Vaping Hashtags Used by Humans

Numerous human hashtags refer to e-cigarettes and vaping. No pairs of hashtags dominate, so the usage pattern is spread somewhat evenly. Color clusters represent general topics of conversation, which often overlap. Terms near the center are most common to all three topic clusters. Researchers found 238 hashtags (*dots*) used in 5,203 pairs (*lines*).

Human topic clusters
- Behaviors and community
- Products and community
- Multiple-substance use



Only tweets that contained two or more hashtags were analyzed because hashtags occurring together indicates they are related. The most frequently used hashtag terms are noted.

Each node (*dot*) is a hashtag. Each line connects hashtags that occur together. The thicker the line, the more often the hashtag pair occurs. Gray lines do not fall within the primary topic clusters.

Vaping Hashtags Used by Bots

Bots tend to repeat a small number of hashtags referring to e-cigarettes and vaping, so pairs of hashtags are much more concentrated than in human tweets. Topics of conversation (*colors*) are also more segregated. Researchers found 137 hashtags used in 1,600 pairs.

Bot topic clusters
- Behaviors and multiple-substance use
- Behaviors and community
- Products
- Health, smoking cessation and multiple-substance use

SOURCE: "E-CIGARETTE SURVEILLANCE WITH SOCIAL MEDIA DATA: SOCIAL BOTS, EMERGING TOPICS, AND TRENDS," BY JON-PATRICK ALLEM ET AL. IN *JMIR PUBLIC HEALTH AND SURVEILLANCE*, VOL. 3, NO. 4, ARTICLE E98; 2017

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