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Telescopes on the Far Side of the Moon

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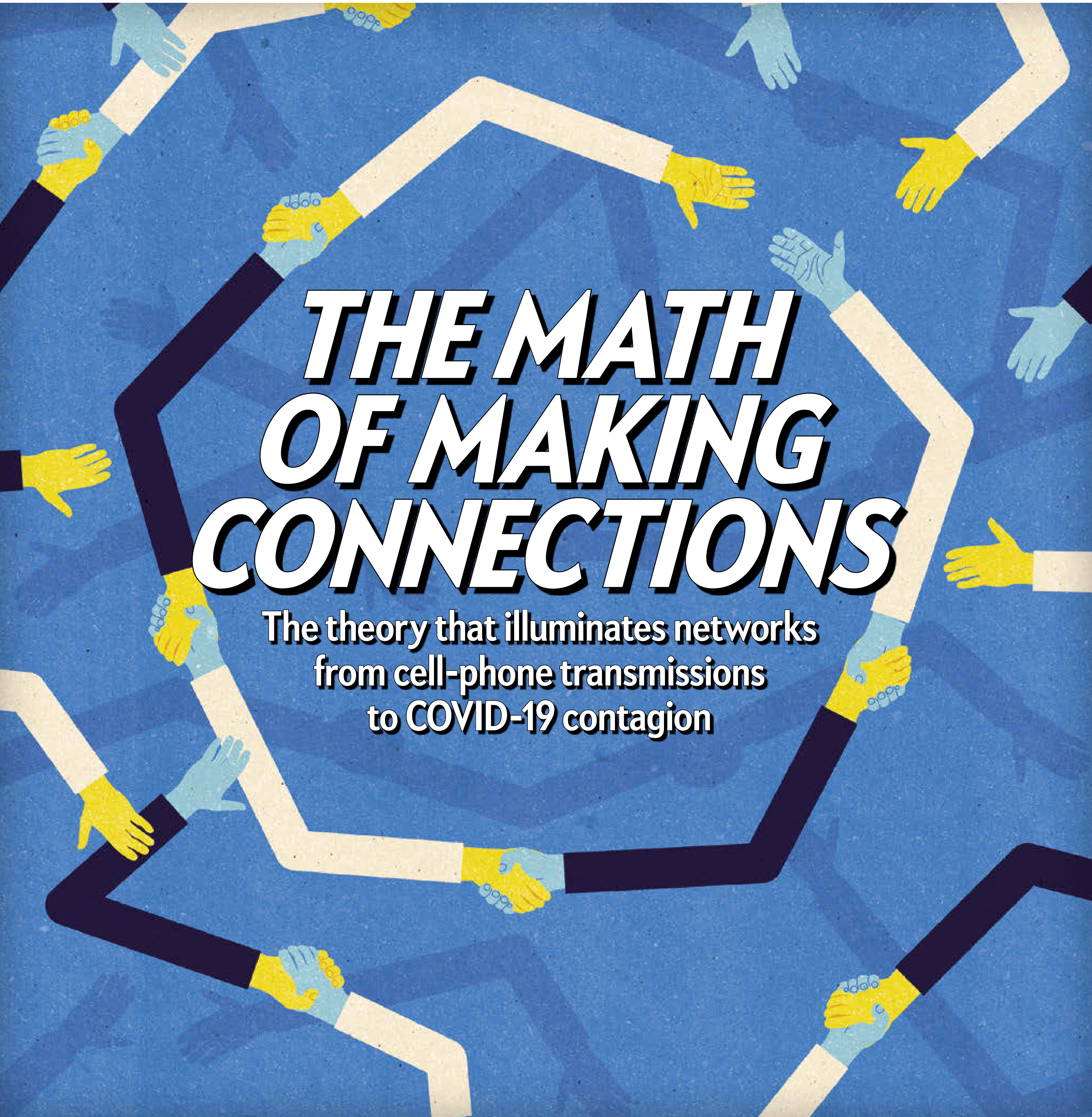
Dark Matter's Last Stand



THE MATH OF MAKING CONNECTIONS

The theory that illuminates networks from cell-phone transmissions to COVID-19 contagion

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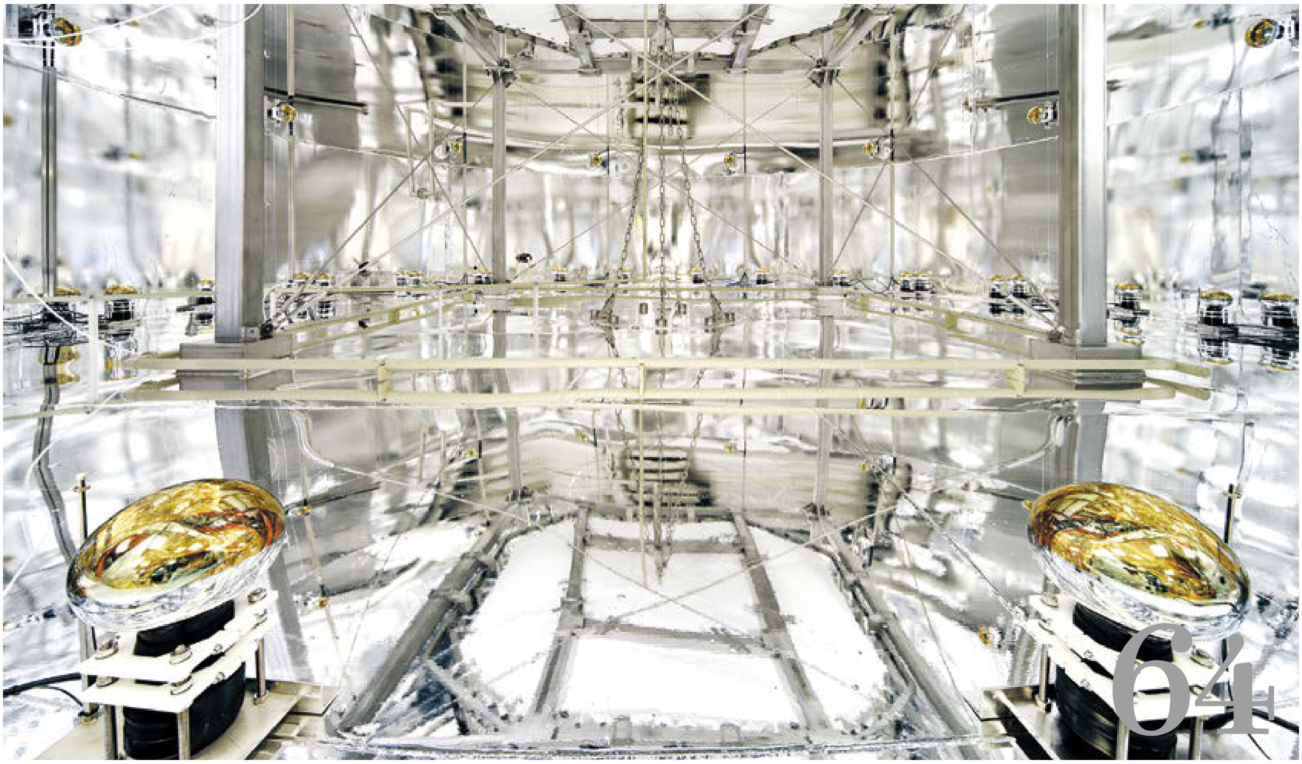
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ENRICO SACCHETTI

ON THE COVER

A remarkable variety of real-world systems involve networks. A versatile branch of mathematics called percolation theory finds that as the density of links within a network increases, it suddenly becomes highly connected: a message hops from phone to phone across a city, or a disease becomes pandemic. **Illustration by Kotryna Zukauskaite.**

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Laura Helmuth is editor in chief of *Scientific American.* Follow her on Twitter @laurahelmuth

Hard Lessons

In the Before Times, science and health journalists would talk about how much we appreciated our readers but just wished that more people took an interest. In the Pandemic Times, we have to add: but not like this! It's been a scary and exhausting year but also the most educational time in living memory. Hundreds of millions of people now understand concepts such as epidemiological modeling, asymptomatic transmission, herd immunity, phase 3 vaccine trials, and more. Our collective vocabulary has expanded with serious and grimly funny terms like "pandemic fine" (in response to "How are you?") or "Blursday" (in response to "What day is it?").

As the pandemic starts to come under control, we at *Scientific American* are grateful for all the scientists around the world who collaborated at lightning speed on studying the coronavirus and creating vaccines, the health-care workers who developed best practices to treat sick patients while their own lives were in danger, all the experts who talked with reporters to get the right information to the public, and especially to everyone—to all of you—who has helped spread knowledge.

Public policy scholar and communication professor Kathleen Hall Jamieson shares evidence-based, practical advice for how best to do just that, beginning on page 44. Anyone can be an effective science communicator and support a culture that endorses science by using her pro tips to help friends reject myths about the coronavirus, vaccines, masks, or (is this really the year 2021?) whether Earth is round or flat.

We have a trio of stories this month about how astronomers and physicists are using new technology to understand some of the biggest mysteries in the universe. The far side of our moon could soon be teeming with radio telescopes, orbiters and rovers, as author Anil Ananthaswamy explains on page 60. Shielded from Earth's radiation, it's an ideal place to look for signs of the universe's dark ages, the first few hundred million years after the big bang.

Adaptive optics technology gives telescopes a crisper view of distant objects by compensating for turbulence in the atmosphere—it's a way to "untwinkle the stars." Astronomers Tony Travouillon and Céline d'Orgeville and optical instrumentation expert Francis Bennet share on page 38 about how the technology is now being used to study space debris and could allow clear and secure quantum-encrypted communication.

If any experiment is likely to detect dark matter particles in the coming years, it's a new version of XENON at the Gran Sasso National Laboratory in Italy. Starting on page 64, see the magnificent instruments being set up now, as senior editor Clara Moskowitz describes them.

Mathematics based on simple connection diagrams underlies some of the most complex networks of modern life, including cell-phone networks, viral memes on social media, or even the spread of disease. In our cover story, mathematician Kelsey Houston-Edwards shows the power of "percolation theory." Turn to page 22.

Natural gas is the biggest source of electricity in the U.S., and consumption has risen about 30 percent in the past 15 years. It's not going away, but a range of achievable technologies can make it much more climate-friendly, as energy resources expert Michael E. Webber explains on page 30.

Our flight of fancy for April takes wing on page 52. Paleontologist Michael B. Habib and illustrator Terryl Whitlatch blend biomechanical rules and research on pterosaurs and other extinct creatures to create plausible body plans for dragons, angels and flying horses. We had a lot of fun with this one and hope you do, too. SA

Illustration by Nick Higgins

December 2020

"Anti Gravity was the highlight of every issue. Thank you, Steve Mirsky, for your wonderful, humorous and insightful writing."

TRUDY DENTON *VIA E-MAIL*

LEGACY OF LAUGHTER

Everyone is hoping that 2021 proves to be a better year than 2020. But some of the most depressing news I've seen was Steve Mirsky's announcement of the end of his Anti Gravity column in "The Real Deal." In my opinion, Anti Gravity was the highlight of every issue. Such a sad thought to contemplate—having to face this new year and not having this column to cheer me up. Thank you, Steve, for your wonderful, humorous and insightful writing.

Trudy Denton *via e-mail*

All *Scientific American* subscribers should be bummed by learning of Steve Mirsky's departure. His wry view of the many, many farces in this world has always been greatly appreciated, especially by us technophiles. Presuming he has not turned into a giant cockroach himself, let's see his righteously cockeyed view of the world again as often as editorially possible. I'm sure his wife and cats can be convinced to agree.

Bradford Kruger *via e-mail*

Steve Mirsky's column has always been the first thing I read each month when *Scientific American* reaches our home. For me, he'll never be an *alte kaker*. I will miss him.

Esther Hecht *Jerusalem, Israel*

I'm sure I speak for many when I say that I have thoroughly enjoyed Steve Mirsky's column for many centimeters of continental drift. Because he is just the kind of person who would enjoy this sort of pun: I've always remembered his name mnemonically as "Steve Mirthsky." I wish him good luck on future endeavors!

Dave Detlefs *via e-mail*

Congratulations to Steve on a quarter of a century of Anti Gravity, a column I've looked forward to and enjoyed reading over the years. The puns aside (all are meant to be bad), his erudition and surprising perspectives have provided both wit and wisdom.

William Lanouette *via e-mail*

MIRSKY REPLIES: My sincere thanks to everyone. But rest assured, I'll be everywhere. Wherever there's a creationist trying to screw up science education, I'll be there. Wherever there's a nincompoop on Twitter mansplaining to the scientist who did the research, I'll be there. And when Yankees fans yell bad things at Red Sox players too far away to hear them, well, I'll be there. I have free time now.

BIASED MEDICAL SCREENING

In "Racism in Medical Tests" [Science Agenda], the editors argue that health-care screening assessments that make race-based scoring adjustments are harmful to people of color. As a retired pathologist and medical laboratory director, I would certainly not argue that systemic racism does not exist in medicine, as it does in every other aspect of racist American society. But I have heard the opposite argument: that the failure to incorporate racial differences into decision algorithms also constitutes racism.

The editors' point that "race" has no biological meaning is well made, and it is a poor substitute for better genetic information. Nevertheless, it is usually all we have, and it is legitimate for clinicians to take this information into account. For instance, knowing that prostate cancer is more common in Black men than in white men, a urologist might have a lower threshold for doing a prostate biopsy based on a borderline elevated prostate-specific antigen (PSA) level in a Black man.

The predictive value of a laboratory test is based on "prior probability," the likelihood that the patient has a disease before testing has been performed. Estimating that probability involves a certain amount of guesswork. Yet when a disease has a wide racial disparity in prevalence, it is legitimate to include it in the estimate. Specific algorithms are being tweaked and adjusted all the time, and one can certainly argue about some of them. But the basic methodology is sound.

Thomas J. Reed *via e-mail*

THE EDITORS REPLY: In medicine, as in the rest of society, ignoring race is not the answer to racism. Indeed, there are cases where a clinician should factor in race when assessing a patient's needs. But it is important to critically interrogate race-based adjustments in medical algorithms because some of them may exacerbate existing inequalities. For example, in the Maternal-Fetal Medicine Units (MFMU) Network's prediction calculator for people who wish to attempt a vaginal birth after previously experiencing a cesarean section (VBAC), Black and Latinx individuals are assigned a lower score than their white counterparts, making it more likely that they will end up with an unwanted C-section.

The race adjustments were based on data showing that nonwhite patients had a lower rate of successful VBACs. But the reason is societal, not biological—racism, not race, is responsible for the higher incidence of poor birth outcomes among people of color. So by using the race adjustment, doctors may be reinforcing the inequalities reflected in the data. As a result, at press time, the MFMU Network is developing a new VBAC calculator that omits race and ethnicity.

STRANGE STARS

"Explosions at the Edge," by Anna Y. Q. Ho, describes a growing number of unusual supernovae that challenge the traditional view of stellar death. Physicists often simplify complex situations to make them computationally feasible. So I wonder whether Ho or any of her colleagues have modeled the consequences of small to large asymmetries in both stars and their environment (for example, the density variations that are visible in planetary nebulae).

I would expect large-scale homogeneity and symmetry but potentially significant extreme values (for example, locally dense or sparse environments). Would those deviations have observable effects and possibly explain some of what Ho and her colleagues are seeing in the unusual stars?

GEOFFREY HART *Fellow, Society for Technical Communication*

HO REPLIES: There is a lot of observational evidence that stellar explosions are asymmetric, but we are only just beginning to account for asymmetry in our modeling and simulations because of the large computational power required. For example, it is very difficult to get a spherical star to explode in a simulation, but including turbulence and asymmetry makes doing so much easier.

HOT LAVA, COLD ISLAND

In "Quick Hits" [Advances], Sarah Lewin Frasier reports that the record for the coldest outdoor temperature in the Northern Hemisphere was recently uncovered in data from December 1991 at a site in Greenland. It is important to note that six months earlier in the Philippines, Mount Pinatubo erupted, ushering in a couple of years of global cooling. Although the volcano is on the other side of the world from Greenland, and temperature changes were inconsistently distributed worldwide, overall data clearly show significantly cooler than normal temperatures in Greenland during the winter of 1991–1992.

FRED PORTER *Carbondale, Colo.*

CLARIFICATION

"Digital Medicine," by P. Murali Doraiswamy [Top 10 Emerging Technologies of 2020], describes a children's health startup called Odin. That company is now known as Luminopia.

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Stop Domestic Terrorism

National leaders must take on racist-driven violence in the U.S.

By the Editors

In 2015 a white supremacist with a handgun walked into a historic African-American church in Charleston, S.C., and murdered nine worshippers. In 2019 a gunman went on a rampage in El Paso, Tex., and has been charged with 23 murders, as well as hate crimes for targeting Mexicans and immigrants. In June 2020 a man whom prosecutors described as a Ku Klux Klan leader drove his vehicle into a crowd of peaceful Black Lives Matter protesters in Virginia, injuring several. That fall the U.S. Department of Homeland Security drafted warnings saying white supremacist extremists will remain "the most persistent and lethal threat" to the country. Then, on January 6, as Congress met to certify the presidential election, a deadly mob stormed the U.S. Capitol with clothing mocking Nazi death camps; flags celebrating the Confederacy and Donald Trump; and insignia of white supremacist groups such as the Proud Boys and militia groups such as the Oath Keepers.

The number of assaults by white supremacists has been climbing in recent years. The Federal Bureau of Investigation has cited new highs in hate crimes: more than 7,000 in 2019, and that is likely an undercount. The Center for Strategic and International Studies notes in a report that "right-wing extremists perpetrated two thirds of the attacks and plots in the United States in 2019 and over 90 percent between January 1 and May 8, 2020." Yet most law-enforcement agencies in the U.S. have remained focused on foreign-based "jihadi" terrorism, say experts in national security. Now is the time for the Biden administration and the U.S. Congress to take on the homegrown horror, with several effective initial steps.

Domestic terrorism, as defined by federal law, consists of criminal acts on U.S. soil that are dangerous to human life and are intended to coerce and intimidate a civilian population. We do not know many details about the groups and individuals who take such actions or about their white supremacist connections. Last December, at a meeting of the Council on Foreign Relations, three former heads of Homeland Security—Frances Townsend, Janet Napolitano and former acting secretary Kevin McAleenan—agreed that security agencies have not made such identification a priority. "There has not been the same focus" on U.S. communities as there was on Muslim extremists after the 9/11 attacks, said Townsend, who ran the agency from 2004 to 2008.

A bill now in Congress, the Domestic Terrorism Prevention Act, would remedy this omission. It authorizes the creation of offices in three agencies—Homeland Security, the Justice Department and the FBI—to monitor, investigate and prosecute cases of domestic terrorism. The bill also requires these offices to give Congress twice-yearly reports on domestic terror groups, with specific focus on white supremacists. This kind of data collection and reporting is a key step against the threats, according to the Center for American Progress. Federal agencies should also trace connections between domestic groups and foreign white power movements.

Congress should also enact an antilynching law. Lynching is an act of terror used by white supremacists, but it has never been a federal crime. Congress considered such a law last year with a bill aimed at conspiracies by two or more people to cause bodily harm in connection with a hate crime. Its passage would have empowered federal law enforcement to investigate and prosecute such plots. Senator Rand Paul of Kentucky stalled a vote on the bill with the meritless contention that it allowed extreme penalties against people who simply slapped their victims. The bill actually permits penalty ranges that vary with offense severity, and it should be reintroduced and passed.

There is also an urgent need to root out extremism in law enforcement and the armed forces. Among the first 150 people arrested and charged with federal crimes after the attack on the Capitol, 21 were current or former members of the U.S. military, according to CNN. Some were affiliated with the Proud Boys. Last year police officers in North Carolina were fired after posting racist videos, and an FBI threat-assessment report dating back to 2006 expressed alarm about supremacist infiltration of law-enforcement ranks. Most officers and service members are not extremists, of course. But little has been done to deal with those who are, according to a 2020 report from the Brennan Center for Justice at New York University. Codes of military and police conduct need to be strengthened and breaches officially reported and pursued.

Building on these steps, we can make it clear that homegrown terror and bigotry are real crimes. With real punishments. SA

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Illustration by Brian Stauffer


Howard Frumkin and **Richard J. Jackson,** both physicians, are former directors of the CDC's National Center for Environmental Health. Frumkin is emeritus professor and former dean of the University of Washington School of Public Health. Jackson is emeritus professor at the U.C.L.A. Fielding School of Public Health.

Needed: Climate Change and Health Institute

Research into a growing danger is unfocused and underfunded

By Howard Frumkin and Richard J. Jackson

The climate catastrophes of 2020—wildfires, hurricanes, oppressive heat—left no doubt that climate change threatens health. And the COVID-19 pandemic left no doubt that preparing for predictable health challenges is essential to preventing needless suffering and dying. The two lessons are linked. We know climate change will increasingly affect health. Research shows, for example, that global temperature changes could lead to more heat-related deaths and deaths from diseases such as dengue fever and cholera that spread via insects and water. We urgently need to prepare. But we face critical knowledge gaps in areas such as diagnosis and prevention.

We recommend a solution: the immediate creation of a new unit at the National Institutes of Health—the National Institute of Climate Change and Health. With a budget of more than $40 billion, the NIH is the world's largest, best-funded health research institution. Yet it devotes a measly $9 million annually to research directly related to climate change and health, according to its own tally.

How could the NIH spend so little on one of our greatest health threats? The long-standing culture of reductionist biomedical thinking—organizing research with an organ-by-organ approach rather than looking at population health—plays a role. (If you've ever been shunted from specialist to specialist, yearning for a doctor who'd care for you as a whole person, you know how well that works.) Political meddling and special-interest lobbying by groups such as disease advocacy organizations also inappropriately shape priorities. The new institute would support research to answer critical questions such as these:

Diagnosis: How can climate change impinge on health? What infectious diseases are coming? Where will they emerge? What nutritional problems? How are allergies affected? Who is most vulnerable?

Treatment and prevention: What are the most effective, as well as cost-effective, ways to protect people?

Co-benefits: As we work to cut carbon emissions, what are the healthiest approaches, and how do we build them in? How do we avoid unintended adverse consequences?

The health-care system: How do we reimagine hospitals, clinics and supply lines so the health sector is climate-ready, delivers high-quality care to all and reaches net zero carbon emissions as soon as possible?

Research on climate change and health needs to draw on many disciplines: such an institute should coordinate closely and co-sponsor research with federal departments such as agriculture, energy and transportation. Climate change requires an all-of-government response.

In addition to supporting research, NIH funding helps train young researchers—a critical role. The Pentagon supports military academies because leaders know that a supply of smart, competent service members is crucial for U.S. defense capability. The same is true for health and medicine, particularly in the face of inexorable threats such as climate change. We need a cutting-edge research workforce for years to come. Today, dangerously, there is no training pipeline on climate change and health comparable to the network of postgraduate programs, funded academic research centers and training grants available to scientists studying, for example, genomics and pharmacology.

It's fair to ask whether an existing NIH institute could do this job. The Biden administration has moved to establish an office of climate and environmental justice at the Department of Health and Human Services, of which NIH is a part, but it will not have responsibility for research funding and training. The NIH has the National Institute of Environmental Health Sciences, but it is focused mostly on chemical toxins and pollutants. Even with a midrange budget (by NIH standards)—say, $1 billion per year, which is less than the funding for 10 of the existing institutes—a climate and health institute would deliver needed insights to protect the public from the ravages of climate change. SA

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Illustration by Tiffany Dang

ADVANCES

Dire wolves encounter gray wolves during the late Pleistocene, as depicted in this illustration.

FROM "DIRE WOLVES WERE THE LAST OF AN ANCIENT NEW WORLD CANID LINEAGE," BY ANGELA R. PERRI ET AL., IN *NATURE;* JANUARY 13, 2021 (HTTPS://DOI.ORG/10.1038/S41586-020-03082-X)

PALEONTOLOGY

Dire—but Not Wolves

The extinct giant canids are a remarkable example of convergent evolution

Dire wolves are iconic beasts. The remains of thousands of these extinct Pleistocene carnivores have been recovered from the La Brea Tar Pits in Los Angeles, and the massive canids even played a prominent role in the television series *Game of Thrones.* But a new study of dire wolf genetics has startled paleontologists: the authors found that these animals were not wolves at all, but rather the last of a canid lineage that evolved in North America.

Ever since they were first described in the 1850s, dire wolves have captured the human imagination. Their remains have been found throughout much of the Americas, from Idaho to Bolivia. The La Brea asphalt seeps famously document how prey animals mired in tar lured many of these Ice Age predators to a sticky death. Dire wolves' tar-preserved remains reveal an imposing hunter up to six feet long, with skull and jaw adaptations to take down enormous, struggling megafauna.

Although these canids had clearly evolved to handle the mastodons, horses, bison and other large herbivores then roaming the Americas, skeletal resemblances between dire wolves and today's smaller gray wolves suggested a close kinship. Paleontologists long assumed that dire wolves made themselves at home in North America before gray wolves fol-

lowed them across the Bering Land Bridge from Eurasia. Now some well-preserved DNA may fundamentally change that story.

The new study, published in *Nature*, began as an effort to understand dire wolves' biological basics. "For me, it started with a decision to road-trip around the U.S. collecting dire wolf samples and see what we could get, since no one had managed to get DNA out of dire wolf samples at that point," says Durham University archaeologist and study co-author Angela R. Perri. At the same time, geneticist and co-author Kieren J. Mitchell of the University of Adelaide in Australia was also trying to extract and study ancient DNA from dire wolf remains—as were other laboratories that eventually collaborated on the project.

The researchers hoped to pinpoint how dire wolves were related to other wolves. For decades, paleontologists have noted how similar dire wolves' and gray wolves' bones are. "My hunch was that dire wolves were possibly a specialized lineage or subspecies of gray wolf," Mitchell says. But the new evidence suggested otherwise. Preliminary genetic analyses indicated that dire and gray wolves were ***not*** close relatives. "I think I can speak for the whole group when I say the results were definitely a surprise," Perri says.

By sequencing five genomes from dire wolf fossils between 50,000 and 13,000 years old, the scientists found that the animals belonged to a much older lineage of dogs. Dire wolves, the data suggest, had evolved in the Americas and had no close kinship with the gray wolves from Eurasia; the last time gray wolves and dire wolves shared a common ancestor was about 5.7 million years ago. The strong resemblance between the two, the researchers say, is a case of convergent evolution. This occurs when different species develop similar adaptations—or even appearances—thanks to a similar way of life. Sometimes such convergence is only rough, such as both birds and bats evolving wings despite their differing anatomy. In the case of dire and gray wolves, a dedication to chasing large herbivores resulted in two different canid lineages independently producing similar wolflike forms.

"These results totally shake up the idea that dire wolves were just bigger cousins of gray wolves," says Yukon government paleontologist Grant Zazula, who was not involved in the new study. In fact, the similarity between the two has led gray wolves to be taken as proxies for dire wolf biology and behavior, from pack dynamics to the sound of the animal's howls. The dire wolf's new identity means that many previous assumptions—including about what it looked like in life—require reinvestigation. "The study of ancient DNA and proteins from fossil bones is rapidly rewriting the Ice Age and more recent history of North America's mammals," Zazula says.

These findings mean dire wolves may

BIOMIMICRY

Faux Flowers

A fungus infects grasslike plants to create bizarre "flower" doppelgängers

The second and third flowers are imposters.

On a collection trip to Guyana in 2006, botanist Kenneth Wurdack was strolling along an airstrip at Kaieteur National Park when he noticed something unusual about the flowers on two species of yellow-eyed grasses. Unlike the species' typical blooms, these were an oranger shade of yellow, tightly clustered and spongy in texture.

Digging through relevant botanical literature, Wurdack learned that, in fact, the orange oddities were not really flowers at all.

Instead they were mimics: the product of a fungus that Wurdack, who works at the Smithsonian National Museum of Natural History, and his colleagues recently examined in *Fungal Genetics and Biology*. This fungus, *Fusarium xyrophilum,* infects a *Xyris* plant and sterilizes it to block the plant's own blooms. Then the invader hijacks an as yet unknown aspect of the plant's operations to make it host pseudoflowers built entirely of fungal tissue—potentially tricking pollinators into dispersing fungal spores rather than pollen from the plant's flowers.

"This is the only example that we know of, anywhere on planet Earth, where the false flower is all fungal," says Kerry O'Donnell, a microbiologist at the U.S.

need a new genus name to indicate they are not actually part of the gray wolves' genus, *Canis.* Perri, Mitchell and their colleagues suggest *Aenocyon,* meaning "terrible wolf," a name coined a century ago. But the researchers do not expect their findings to completely overturn tradition, and *Aenocyon dirus* would likely still be called the dire wolf. "They will just join the club of things like maned wolves that are called wolves but aren't really," Perri says.

The study also adds layers to experts' ruminations on why dire wolves eventually disappeared as the last Ice Age closed. These predators had become specialized in hunting camels, horses, bison and other herbivores in North America over millions of years. As those prey sources disappeared, so did the dire wolves. "In contrast to gray wolves, which are a model for adaptation," Perri says, "dire wolves appear to be much less flexible to deal with changing environments and prey."

Nor did dire wolves leave a genetic legacy beyond their ancient bones' decaying DNA. Canids such as wolves and coyotes can mate and produce hybrids, but dire wolves apparently did not do so with any other canid species that remain alive today. Perri, Mitchell and their colleagues found no DNA evidence of interbreeding between the genetically isolated dire wolves and gray wolves or coyotes.

By 13,000 years ago dire wolves were facing extinction. Evolving in Eurasia's harsh, variable environments may have given gray wolves an edge, Zazula notes, "while the big, bad dire wolves got caught off guard relaxing in southern California at the end of the Ice Age." But the apparent end of the dire wolf's story is really only the beginning. Preserved genes have shown that dire wolves and their ancestors were top dogs in the Americas for more than five million years—and the early chapters of their story are waiting to be rewritten. —*Riley Black*

"This is the only example that we know of, anywhere on planet Earth, where the false flower is all fungal."

—Kerry O'Donnell
U.S. Department of Agriculture

Department of Agriculture and a co-author of the pseudoflower study. A handful of other known fungal imposters go only partway, typically modifying a host's leaves rather than building their own mock flower.

The authors of the new paper wondered if *F. xyrophilum*'s mimicry might run even deeper. For example, they knew that many plants take advantage of the ways that some pollinating insects navigate by smell and perceive ultraviolet light. So the study's lead author Imane Laraba, also a USDA microbiologist, used an ultraviolet filter to photograph *F. xyrophilum* pseudoflowers that Wurdack collected in 2010 and 2012. As speculated, the fungus's tissues reflected UV light, a property of many yellow-hued flowers that could help pollinators locate them. *Xyris* flowers most likely also reflect UV light in the wild, Laraba says. Two pigments isolated from the pseudoflowers—and confirmed in lab-grown *F. xyrophilum*—could be responsible for this UV reflectivity and let the fungus fluoresce at ranges especially visible to bees, the scientists say.

The researchers also documented the lab-cultured *F. xyrophilum* emitting up to 10 aromatic chemical compounds, many of them known to attract insect visitors.

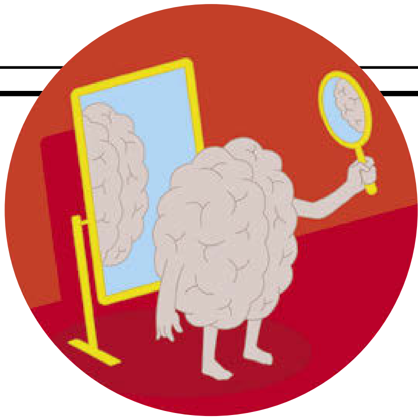
Still, aromas are better understood as a blended profile than as individual compounds. "I think it's a case of mimicry that still needs more documentation," says Jonathan Gershenzon, a biochemist at the Max Planck Institute for Chemical Ecology in Jena, Germany, who was not involved in the new study. "But when you look at the [pseudoflowers'] shape, the color, it's hard not to be incredibly impressed with what nature has done." —*Priyanka Runwal*

KENNETH WURDACK *Smithsonian Institution*

NEUROSCIENCE

Prediction Predicament

Forecasting hurts memory making



Making predictions hinders the brain's ability to remember the present moment, new research suggests. The hippocampus, a brain structure usually associated with remembering events, also uses experiences to make forecasts (neuroscientists call this "statistical learning"). But scientists writing in the *Proceedings of the National Academy of Sciences USA* have now demonstrated that the latter function can disrupt the former.

Researchers showed participants a series of photographs on a screen without telling them that some image categories always followed others: mountains always came immediately after beaches, for example. The subjects were intended to subconsciously learn these associations and begin to expect these pairings. Later, the participants were shown the same photos again, mixed in with new examples, and were asked if they had spotted any of them before. They accurately recalled seeing random images at a much better rate than the "predictive" ones (like the beach pictures).

The scientists repeated this process while scanning participants' brains with functional MRI. Each image category prompted a distinct neural activity pattern, and the patterns for "predictable" categories were seen in the hippocampus when the corresponding predictive category was displayed. Moreover, this effect's strength in fMRI corresponded inversely with participants' memory task scores. "The more evidence for prediction we saw, the worse their memory was for those predictive items," such as a particular beach scene, says study lead author and Yale University cognitive neuroscientist Brynn Sherman. This suggests that predictive images triggered the hippocampus to shift gears toward prediction—and away from encoding a new memory.

The study is among the first to demonstrate how making predictions affects human memory. Scientists previously suspected that the hippocampus had a role in statistical learning but had not known how it interacts with memory formation. "This paper is a really nice demonstration of the trade-off where the hippocampus is doing both these things," says University of Virginia cognitive neuroscientist Nicole Long, who was not involved in the research.

The team says this compromise occurs because remembering and predicting both use some of the same biological pathways. In the paper, the authors compare it with "using one's right foot to operate both the brake and gas pedals in a car … but not both at the same time." This setup could prevent memory redundancies and thus conserve brainpower, Sherman says: a successful prediction would contain the same information as an actual outcome.

The brain circuitry that makes all this possible still requires further research, Long says. For instance, she wonders how much repetition is needed before the hippocampus shifts from recording to predicting and whether it is possible to train the structure to improve both modes in tandem. —*Hannah Seo*

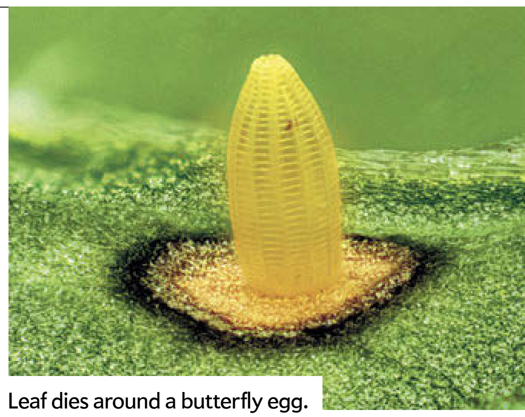
BIOLOGY

Butterfly Arms Race

Plants sacrifice leaf tissue to take out butterflies' eggs

A few plants in the cabbage and mustard family pay a dramatic price to fend off hungry caterpillars: they kill off patches of their own leaves where butterflies have laid eggs. Deprived of a living anchor, the eggs shrivel and die. These plants' egg-slaying abilities have been documented since at least the 1980s, but a new study shows they appear in just a few closely related plants in this family—and they are triggered only by certain butterfly species.

Nina Fatouros of Wageningen University in the Netherlands and her colleagues investigated 31 plant species in the target family. First, they dabbed the plants' leaves with liquid that had been exposed to egg material from a butterfly species known to lay eggs on them. Four closely related plant species reliably killed off the treated leaf patches. Further tests confirmed that the species with the most pronounced response only reacted strongly when the egg material came from one group of butterflies, *Pieris*, which lays eggs on these plants in the wild. This is "clear evidence" that specific butterfly species could have stimulated the evolution of the necrosis defense, Fatouros says. The researchers also tracked eggs laid by wild butterflies to confirm that the defense mechanism desiccates or detaches them. The work was detailed in *New Phytologist*.



Leaf dies around a butterfly egg.

"It's very unlikely that you find this by coincidence," says University of Sheffield molecular plant biologist Jurriaan Ton, who was not involved in the study. He adds that the plants' relatedness, coupled with their exaggerated reaction to these butterflies, suggests a heated evolutionary "arms race" took place between the plants and insects.

"This is the first study to my knowledge where they really looked at the appearance of this trait within a particular plant family," says ecologist Julia Koricheva of Royal Holloway, University of London, who was also not involved in the work.

Future research could explore how recently the trait evolved, Fatouros says. She notes that arms races rarely end—and evidence suggests the butterflies may be fighting back. Some prefer to lay their eggs in tightly grouped clusters, making them less susceptible to the plants' strategy. —*Chris Baraniuk*

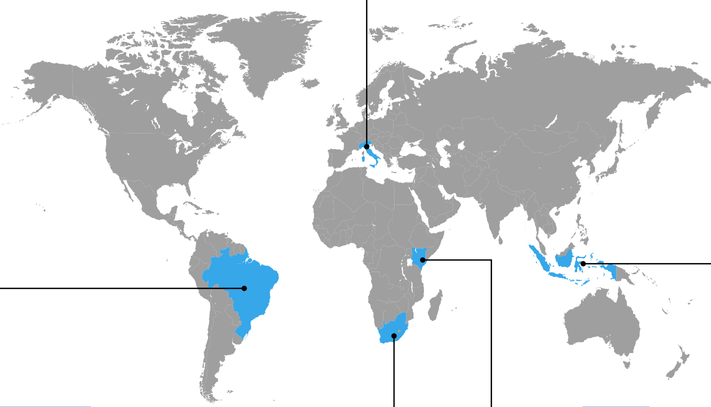
HANS M. SMID

Illustration by Thomas Fuchs

IN THE NEWS

Quick Hits

By Sarah Lewin Frasier



BRAZIL
Scientists recorded groups of more than 100 electric eels working together to circle shoals of small prey fish and herd them to shallow waters in a lake in North Brazil. Once the fish were corralled, up to 10 eels would move in and unleash a synchronized shock.

ITALY
A fossilized track of 10 footprints in the Alps points to a crocodilelike animal that was at least four meters long and lived shortly after the Permian mass extinction. Its survival of the event some 250 million years ago suggests more of the ecosystem endured than previously thought.

ANTARCTICA
A yellow-brown mineral called jarosite—rare on Earth but abundant on Mars—has been identified deep in an Antarctic ice core. This discovery suggests the brittle substance forms from dust accumulating and reacting inside massive ice deposits.

INDONESIA
A painting of pigs in dark-red mineral pigment, found in a cave on the island of Sulawesi, dates back at least 45,000 years and sets the record for the earliest-known figurative art. Additional samples could push the date even earlier.

SOUTH AFRICA
A computer algorithm processing satellite images of Addo Elephant National Park proved as accurate as the human eye at counting the animals against complex backgrounds. Currently conservationists spend hours in low-flying planes to tally the creatures.

KENYA
A materials scientist's new recycling process is turning plastic waste and sand into bricks that are five to seven times stronger than concrete. Her factory can accommodate a variety of plastic types.

For more details, visit www.ScientificAmerican.com/apr2021/advances


Amur tiger

EPIDEMIOLOGY

A Tiger Vaccine

An unconventional strategy could help Amur tigers

In 2003 a young Amur tiger, seeming disoriented, wandered into a Russian village on the Chinese border. Wildlife Conservation Society scientists anesthetized the tiger and determined that she had canine distemper—the first case confirmed in a wild tiger. The feline patient zero died six weeks later.

Since then, canine distemper, an untreatable virus that can infect many types of carnivores, has spread among Amur tigers across the subspecies' range in Russia's far east. An exhaustive new analysis suggests that if the virus runs its course, it could wipe out a key population of these endangered cats. But this risk can be lessened, the researchers found, by vaccinating the tigers.

"We found that distemper does have the capacity to impact wild tiger populations, particularly smaller ones, quite profoundly," says Martin Gilbert, a wildlife veterinarian and epidemiologist at Cornell University and lead author of the study in the *Proceedings of the National Academy of Sciences USA*. Small populations of other susceptible species could be threatened as well, he adds.

To predict distemper's long-term effects, the team simulated disease dynamics in the region's two main tiger populations, which have about 500 and 30 animals, respectively. The researchers found distemper increases extinction risk in the next 50 years by 65 percent for the smaller tiger population—whose range makes it critical for potentially repopulating the animals in northeastern China.

By comparing the disease's genetic sequences in various species, the researchers also found that the tigers primarily get distemper from other wild animals, so vaccinating domestic dogs—often assumed the disease's main reservoir—would not be enough. But vaccinating just two tigers from the smaller population per year during routine monitoring work would reduce the group's extinction risk by 75 percent.

"I think distemper vaccination definitely has a role in assisting small, isolated tiger populations at risk, such as those described in the Russian far east," says Edward Ramsay, a professor emeritus of zoological medicine at the University of Tennessee, who was not involved in the research. "Studies have shown the vaccines are safe, and experience with Asian lions in India demonstrates that even an incomplete vaccination program can help prevent deaths."

But gaining support could be challenging. "There is still considerable uncertainty among wildlife managers around vaccination as a conservation tool," says study co-author Sarah Cleaveland, a University of Glasgow veterinary surgeon and comparative epidemiologist. "We hope that our research will address some of the issues around the scientific uncertainties, but as with vaccine hesitancy in the human health field, there is also misinformation and quite a lot of unwarranted concern about the risks of vaccination in wildlife." —*Rachel Nuwer*

JEANNETTE RUDLOFF *Zonar GmbH and Alamy Stock Photo*

ARCHAEOLOGY

Volcanic Threat

Corrosive salts form on buried Pompeii murals

Smothered under volcanic ash and rocks from the eruption of Mount Vesuvius, the ancient city of Pompeii in modern-day Italy lay buried for more than 1,500 years before it was discovered and excavations began. Most archaeologists expect that the volcanic debris will safely preserve the remaining ruins. But new work suggests these materials, called pyroclasts, can themselves impart damage under certain conditions.

Researchers reported in *Angewandte Chemie International Edition* that when exposed to water, the pyroclasts leach fluoride ions—charged particles that can combine with other ions to form a salty crust on Pompeii's famously vivid murals. As salts dissolve and recrystallize, they can alter pigment colors, create cracks, and more.

When University of the Basque Country chemist Maite Maguregui and her colleagues detected fluoride salts on previously excavated Pompeii murals, they suspected the fault lay with pyroclasts. "For us, fluoride was a marker of the influence of pyroclastic material," Maguregui says. Fluoride ions are rare in the atmosphere, but volcanoes spew them in their ash and debris.

To prove fluoride was coming from Pompeii's pyroclasts, the researchers lab-tested volcanic ash and rock fragments from various depths. When these fragments were exposed to water, the authors observed fluoride ions trickling out. They calculated that the ion concentrations released could form salts like the ones on the murals.

Pompeii's buried paintings are comparatively safe if they stay dry, Maguregui says. But groundwater and rainfall let the ions form damaging salts, even underground. This harm dramatically worsens when the paintings are exposed to the atmosphere, accelerating salt formation.

"I think this will sound a little bit of a warning bell because excavated paintings can deteriorate very rapidly if not treated properly," says Austin Nevin, head of conservation at the Courtauld Institute of Art in London, who was not involved in the research. Archaeologists must assess paintings immediately after excavation for ions such as fluoride, he adds, so they can take the right steps for preservation.

Signals from fluoride ions, along with their corresponding atom fluorine, are too weak to detect with standard portable equipment. So Maguregui's team developed a new technique for field detection: a portable laser instrument breaks down a minuscule amount of limestone on an excavated painting's surface, releasing calcium. The calcium interacts with any nearby fluorine to form calcium fluoride, which then emits a characteristic wavelength of light.

This measurement can provide an early warning, but researchers say they have yet to find the best way of treating paintings to mitigate damage from these salts. Until they do, Nevin says, if fluoride is detected on a newly unearthed mural, it may be best to simply rebury it. —*Lakshmi Supriya*

2020's August Complex Fire devastated California forests.

ECOLOGY

Rebuilding Forests

A new model pinpoints where to plant trees after a devastating wildfire

California's August Complex Fire tore through more than 1,600 square miles of forest last summer, igniting nearly every tree in its path. It was the largest wildfire in the state's recorded history, breaking the record previously set in 2018—which had broken the one set the year before. In the fire's aftermath, land managers confronting the effects of steadily larger and hotter infernos burning enormous swaths of forest must determine where to most efficiently plant new trees.

A predictive mapping model recently described in *Ecological Applications* could inform these decisions, saving time and expense. Called the Postfire Spatial Conifer Restoration Planning Tool, it incorporates data on where conifers are least likely to regenerate naturally and suggests where planting would pack the biggest punch. The tool can "target where seedlings are needed most, where the forest isn't going to come back on its own, where we need to intervene if we want to maintain forests," says lead author Joseph Stewart, an ecologist at the University of California, Davis.

To develop the model, Stewart and his colleagues catalogued data collected from more than 1,200 study plots in 19 areas that burned between 2004 and 2012. They combined these data with information on precipitation, topography, climate, forest composition and burn severity. They also included how many seeds sample conifer trees produced in 216 locations over 18 years, assessing whether the trees release different numbers of seeds after a fire.

Land managers can plug details from a specific area into the model; they would find, for example, that in low- to moderate-elevation forests that happen to experience drought after a fire, conifers are much less likely to regenerate naturally.

The tool's potential benefits are significant, says Kimberley Davis, a conservation scientist at the University of Montana, who was not involved in the study. Land managers face ever larger burn areas, some with limited natural forest regeneration. "Helping managers to quickly understand where natural regeneration is likely or not will inform the prioritization of limited resources for reforestation efforts," she says.

Those managers will still have to make hard decisions, such as which species to plant in areas that may experience warmer and drier conditions resulting from climate change, but the model provides some research-based guidance to help the forests recover. And managers of areas affected by the August Complex Fire have time to develop their plans: seedlings they ordered at the time will arrive in 2022. *—Susan Cosier*

KENT NISHIMURA *Getty Images*

ENVIRONMENT

Water Colors

Satellites reveal large-scale changes in the hues of U.S. rivers

A river's colors hold clues to what flows in its water, from soft-green algae to yellow-brown mud. Human eyes might miss subtle shifts in these shadings, but satellites can detect them—and researchers can use them to track large-scale changes and potentially spot signs of trouble.

A team led by University of Pittsburgh environmental scientist John R. Gardner analyzed 234,727 satellite images, covering 67,000 miles of U.S. rivers over 35 years, for a study published in *Geophysical Research Letters*. The researchers isolated the main light wavelength each river reflected, transforming shifting colors into grids of numbers. "It's a very novel approach," says Carl Legleiter, a U.S. Geological Survey scientist, who was not involved in the study.

Gardner's group found sediment-laden yellow (56 percent) and algal green (38 percent) dominated the country's rivers. A third of them had changed color over the past few decades, with the fastest shifts often near sediment-trapping dams. This effect is clear and striking, says Illinois State University environmental scientist Catherine O'Reilly, who was not involved in the study but currently collaborates with two of the authors.

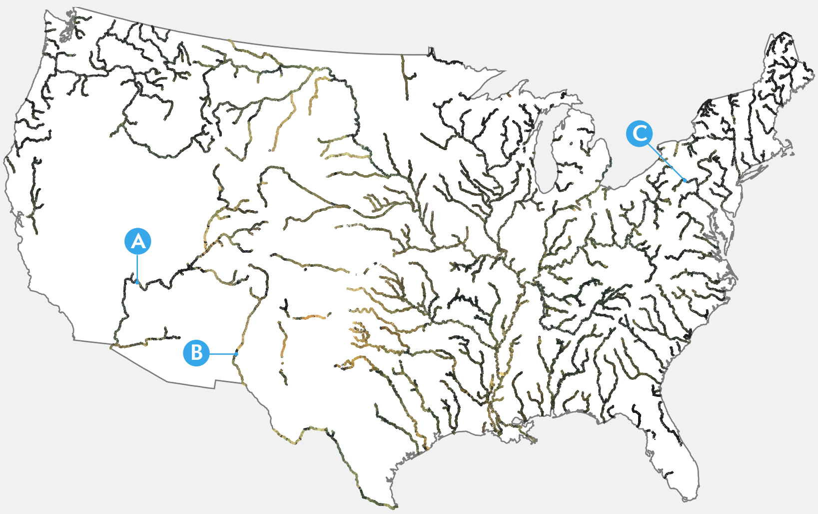
Western U.S. river colors mostly moved toward the blue end of the spectrum over time, suggesting they carried less sand and silt. But many rivers in the Northeast showed a "redshift" that made them appear more yellow, indicating lower water levels or increasing sediment. Gardner says this divergence suggests that regional factors, such as land-use patterns and watershed-management practices, influence long-term river hue shifts. (Some rivers shifted against these trends because of local influences.)

"We also found very distinct seasonal patterns," Gardner says. Many of the nation's rivers turn yellower in spring or summer as peaking rainfall muddies the waters. But the timing also depends on geography and on human activity such as agriculture.

Using satellites to gauge changes in river composition could warn scientists when environments begin to fall out of balance, the researchers say. Legleiter is particularly interested in watching for harmful algal blooms. "A lot of times with environmental change, we don't see it until too late," O'Reilly adds. "But with satellites, we could start to see changes early on." *—Nikk Ogasa*

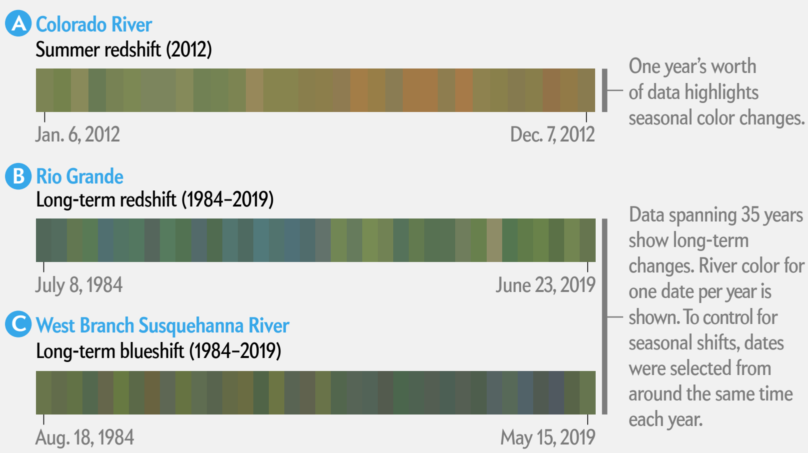
RIVER COLORS ACROSS THE U.S.

Colors of rivers can range from warm yellows and browns to cool greens and blues. The map shows the most common, or modal, colors of U.S. rivers as they would appear to the human eye from space.



COLOR SHIFTS OVER TIME

River colors were captured on select dates over the study period. Each band represents the river color captured at each location on a particular date.* These three locations are examples of hotspots of change—river segments that showed particularly dramatic color shifts, often caused by local factors such as dams or urban surroundings.



Colors have been brightened to show differences in hue more clearly.

SOURCE: "THE COLOR OF RIVERS," BY JOHN R. GARDNER ET AL., IN *GEOPHYSICAL RESEARCH LETTERS*, VOL. 48; DECEMBER 6, 2020

Graphic by John R. Gardner (map) and Amanda Montañez (color time lines)

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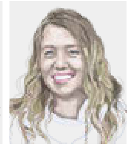
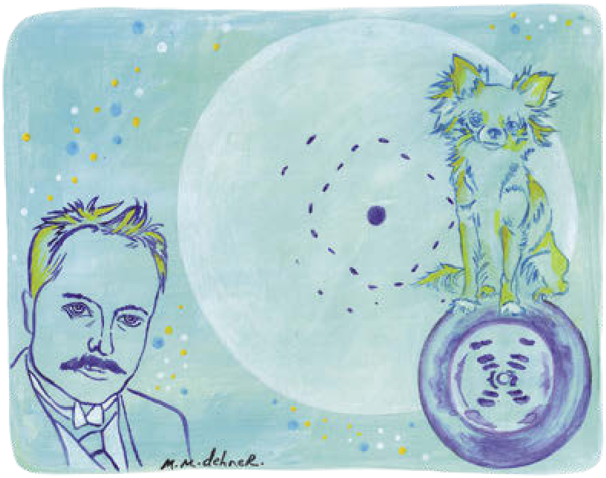
William B. Ashworth, Jr., is a consultant for the history of science at Linda Hall Library in Kansas City, Mo. He writes a daily Scientist of the Day post for that library, in which clerihews such as these first appeared. **Melissa Dehner** is a graphic designer at Linda Hall Library and a freelance illustrator.

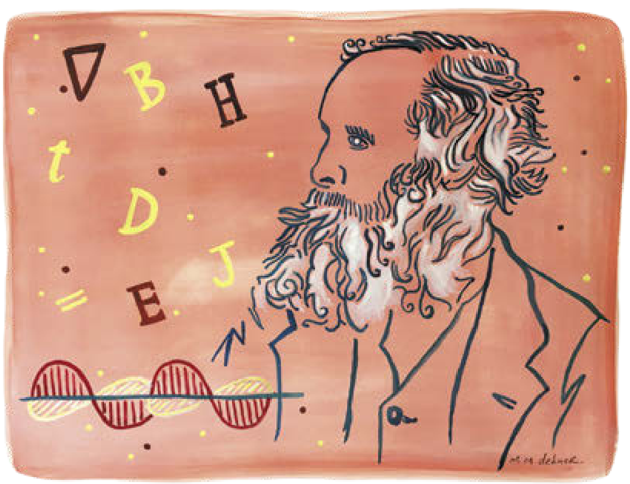


Picture a Clerihew

SOPHIE GERMAIN
HAD CAUSE TO COMPLAIN
WHEN THE MEN IN POWER
LEFT HER NAME OFF THE TOWER

MAX VON LAUE
LOVED HIS CHIHUAHUA
WE LEARN FROM HIS AUTOBIOGRAPHY
HE INVENTED X-RAY CRYSTALLOGRAPHY



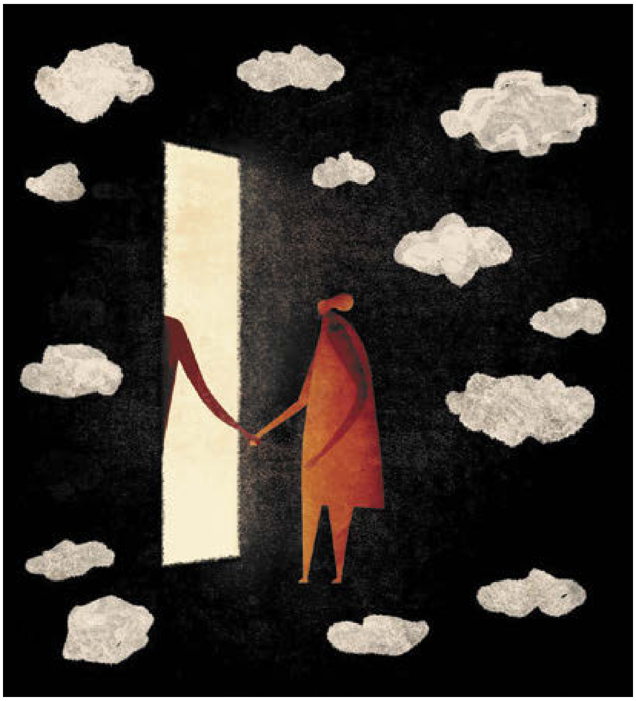


JAMES CLERK MAXWELL
COULD NOT PLAY THE SAX WELL
BUT HE WON RAVES
FOR HIS ELECTROMAGNETIC WAVES

NOTE: A clerihew is a four-line poetic format invented in 1905 by Edmund Clerihew Bentley, who wrote humorous rhymes about all manner of persons, making frivolous fun of their names. Because Bentley rarely chose scientists as subjects, the author and illustrator seek to fill that gap.

Illustrations and hand lettering by Melissa Dehner

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



Hope for Meth Addiction

After many failures, research is finally pointing to effective treatments

By Claudia Wallis

A decade ago I traveled on assignment to a Rocky Mountain rehab facility where the rich and famous go to dry out and confront their drug habits. It offered every imaginable therapy to its well-heeled clientele and claimed strong results. But I will never forget what the director of operations told me about the clinic's biggest failure: "Our results with meth addicts are dismal," he admitted.

Poor results remain all too typical for what is more formally known as methamphetamine use disorder. About one million people in the U.S. are addicted to meth, a powerful stimulant that—smoked, snorted, injected or swallowed—ruins lives and contributed to more than 12,000 overdose deaths in 2018. Fatal overdoses appear to have spiked by nearly 35 percent during the COVID pandemic. Unlike people battling alcoholism or opioid misuse, meth users have no approved medications to help them shake their habit. And most behavioral therapies fail.

But this tragic picture at last may be changing. A recent study found that a regimen of two medications helped some users stay off the drug. In addition, a psychosocial intervention called contingency management (CM) has been shown to be especially effective and, while not widely available, is now the first-line therapy for people seeking treatment for meth or cocaine addiction within the U.S. Department of Veterans Affairs health system.

All addictions are tough to beat, but methamphetamine poses a particular challenge. A key way that researchers measure the addictive grip of a substance is to look at how much dopamine (a neurotransmitter associated with pleasure) floods into the brain's major reward center during use, based on animal studies. "Methamphetamine is the drug that produces the largest release," says Nora Volkow, director of the National Institute on Drug Abuse. "An animal will go crazy pressing a lever in order to get the drug," she adds. Another metric involves real-world human experience: When you try a new substance, what is the likelihood of becoming addicted? "In this respect, methamphetamine ranks along with heroin among the top addictive drugs," Volkow says.

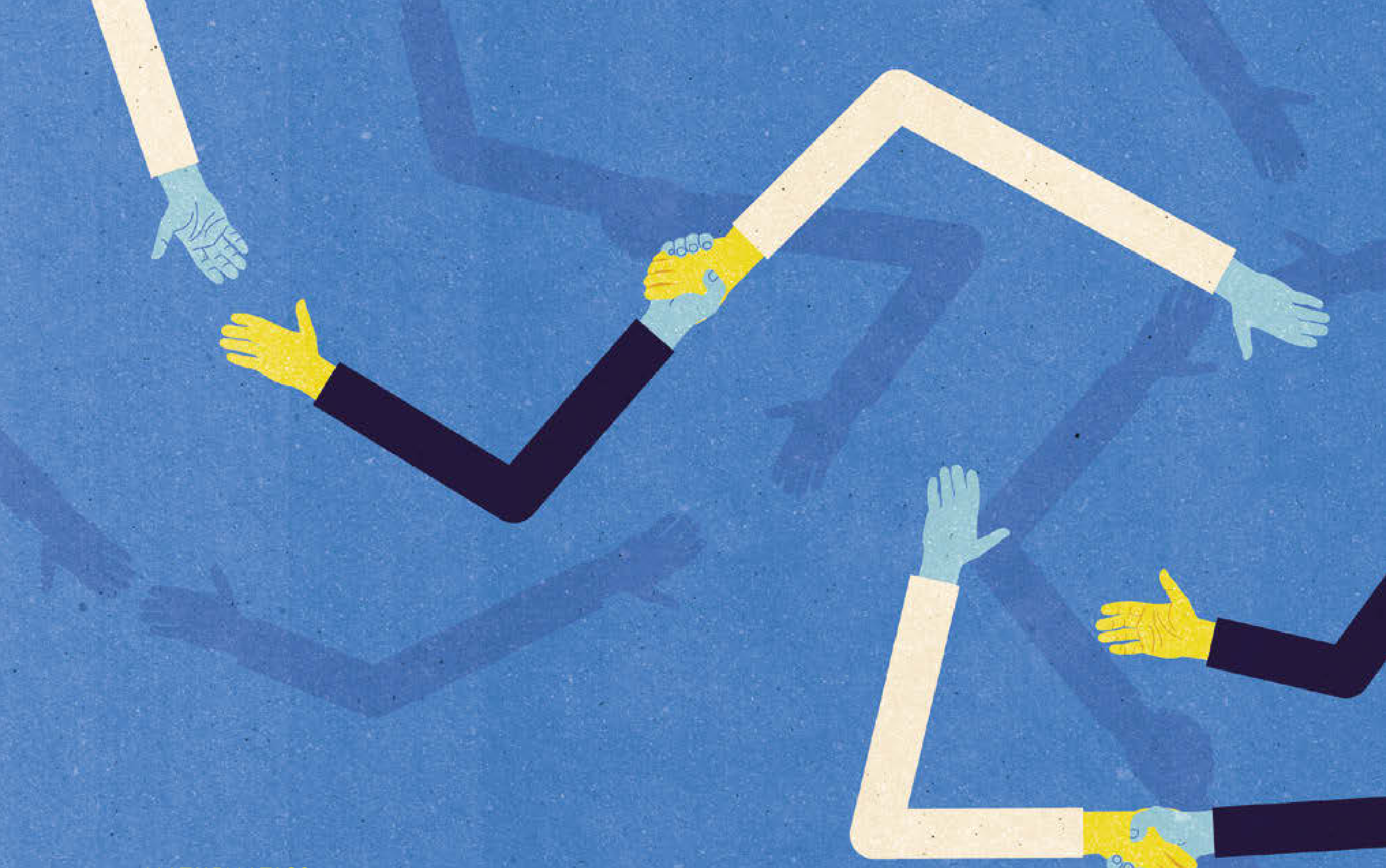
The medication study used two substances that target withdrawal. Bupropion, an antidepressant also prescribed for smoking cessation, raises dopamine levels in the brain and thus may buffer the misery of steep drops that occur when people stop using meth. Naltrexone, the second medication, is an opioid blocker that "has an effect on the reward circuit, potentially relieving cravings," explains the study's lead author, Madhukar H. Trivedi, a psychiatrist at the University of Texas Southwestern Medical Center. In a trial with 403 heavy users of meth, a regimen of the two medications helped 13.6 percent stay off the drug, testing meth-free at least three quarters of the time over a six-week period. Only 2.5 percent of those given placebos achieved that level of abstinence.

Contingency management works on behavior by reinforcing abstinence with prizes. At VA clinics, addicted veterans submit a urine sample twice a week. If the sample is meth-free, they get to pull a slip of paper from a fishbowl. Half the slips show various dollar amounts that can be spent at VA shops, and the rest feature words of encouragement. Two clean samples in a row earn two draws from the fishbowl, three in a row earn three draws, and so on, up to a maximum of eight. But drug-positive urine means no prize. The key "is the immediacy of the reinforcement," says Dominick DePhilippis, a clinical psychologist at the Corporal Michael J. Crescenz VA Medical Center in Philadelphia. That is important, he notes, because the rush of meth is also immediately reinforcing, whether it is the "euphoric feeling that substance use brings or the escape from fatigue or unpleasant mood states" of withdrawal.

A 2018 study with 2,060 VA patients, led by DePhilippis, found that over a 12-week period, participants, on average, showed up for 56 percent of their 24 sessions and that 91 percent of their urine samples were free of the targeted drug. According to a 2018 analysis of 50 trials involving nearly 7,000 patients with meth or cocaine habits, one person benefits from CM for every five treated.

DePhilippis's team is gathering data on CM's long-term efficacy for drug users. If results are good, perhaps more health insurers will overcome concerns about using financial rewards in treatment and cover the therapy. Volkow hopes that meth users will ultimately have a variety of treatments, including some that combine medication with behavioral therapy. That, she says, is how diseases from depression to diabetes are treated. But "we stigmatize addiction," Volkow says, "and insurance is willing to pay much less than for another condition. There's a double standard." SA

Illustration by Fatinha Ramos



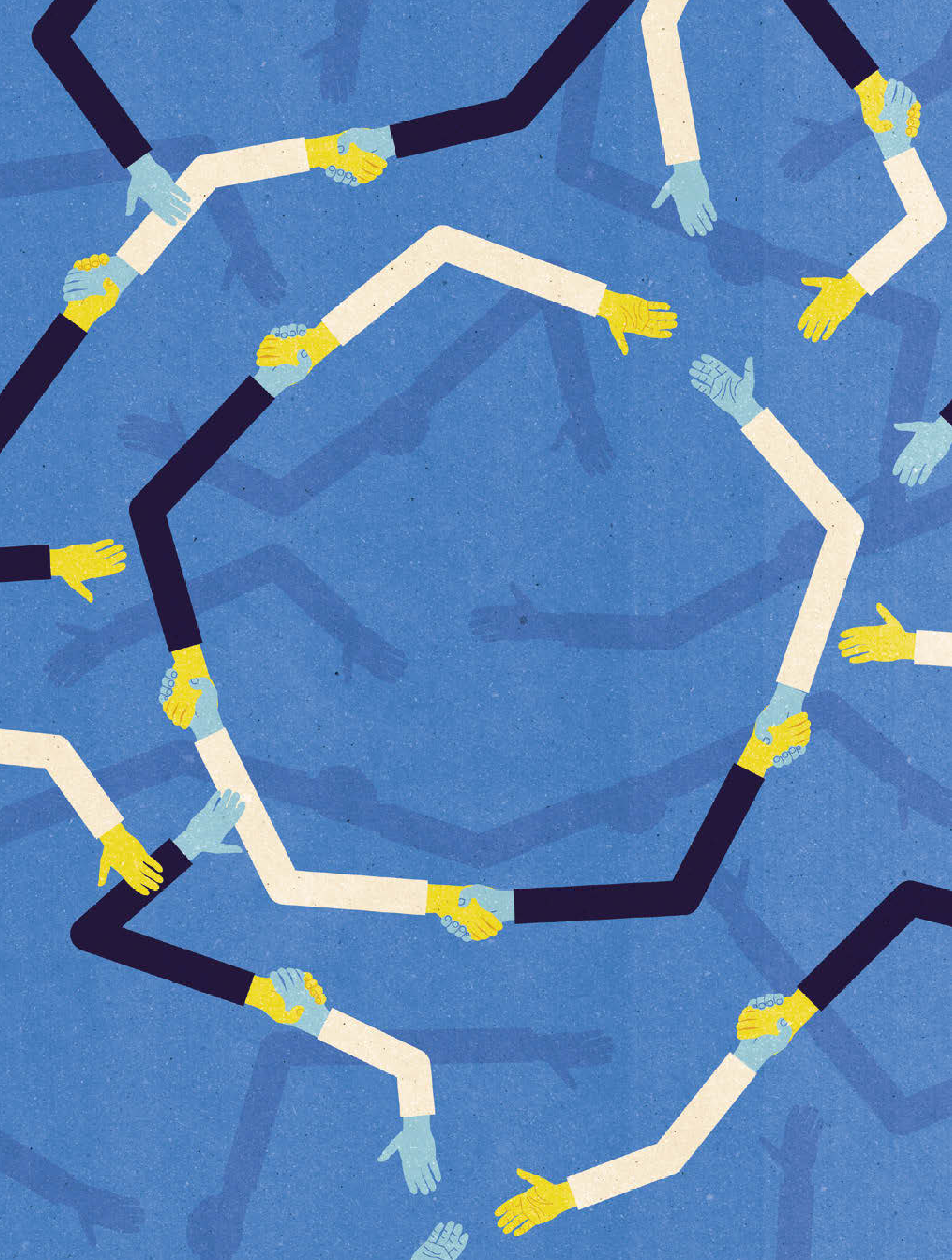
MATHEMATICS

The Math of Making Connections

Percolation theory illuminates the behavior of many kinds of networks, from cell-phone connections to disease transmission

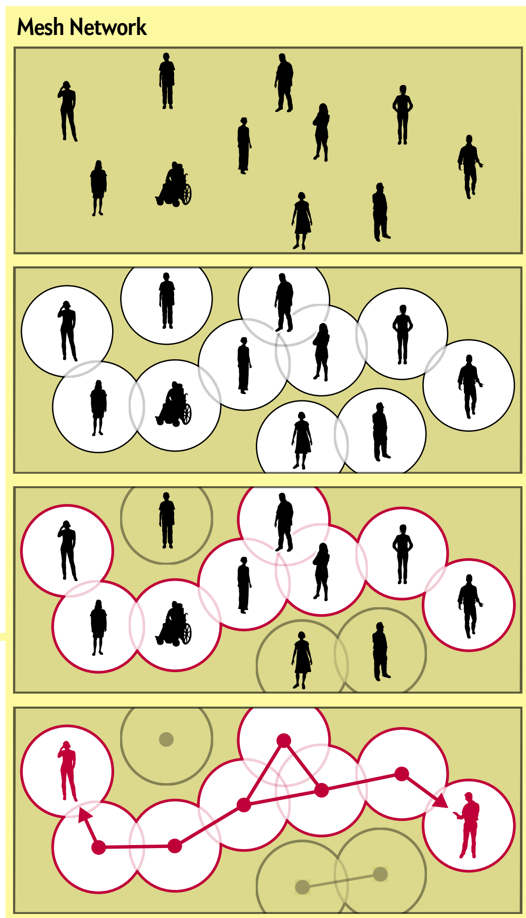
By Kelsey Houston-Edwards

Illustration by Kotryna Zukauskaite



Kelsey Houston-Edwards is a mathematician and journalist. She formerly wrote and hosted the online show *PBS Infinite Series.*

WHEN YOU HIT “SEND” ON A text message, it is easy to imagine that the note will travel directly from your phone to your friend’s. In fact, it typically goes on a long journey through a cellular network or the Internet, both of which rely on centralized infrastructure that can be damaged by natural disasters or shut down by repressive governments. For fear of state surveillance or interference, tech-savvy protesters in Hong Kong avoided the Internet by using software such as FireChat and Bridgefy to send messages directly between nearby phones.



WEE PEOPLE FONT, PROPUBLICA AND ALBERTO CAIRO *(figure drawings)*

These apps let a missive hop silently from one phone to the next, eventually connecting the sender to the receiver—the only users capable of viewing the message. The collections of linked phones, known as mesh networks or mobile ad hoc networks, enable a flexible and decentralized mode of communication. But for any two phones to communicate, they need to be linked via a chain of other phones. How many people scattered throughout Hong Kong need to be connected via the same mesh network before we can be confident that crosstown communication is possible?

A branch of mathematics called percolation theory offers a surprising answer: just a few people can make all the difference. As users join a new network, isolated pockets of connected phones slowly

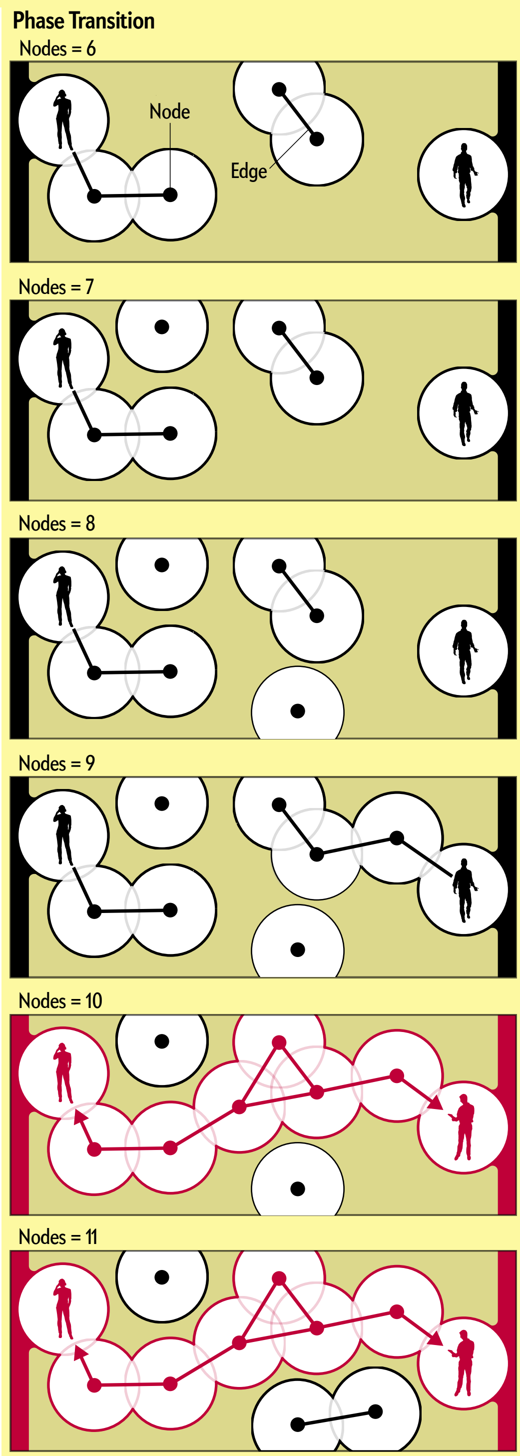
Illustrations by Jen Christiansen

emerge. But full east-to-west or north-to-south communication appears all of a sudden as the density of users passes a critical and sharp threshold. Scientists describe such a rapid change in a network's connectivity as a phase transition—the same concept used to explain abrupt changes in the state of a material such as the melting of ice or the boiling of water.

Percolation theory examines the consequences of randomly creating or removing links in such networks, which mathematicians conceive of as a collection of nodes (represented by points) linked by "edges" (lines). Each node represents an object such as a phone or a person, and the edges represent a specific relation between two of them. The fundamental insight of percolation theory, which dates back to the 1950s, is that as the number of links in a network gradually increases, a global cluster of connected nodes will suddenly emerge.

The question that scientists struggle to answer is: When? What is the equivalent, for any given network, of the zero degrees Celsius at which ice melts or the 100 degrees C at which water boils? At what point does a meme go viral, a product dominate a market, an earthquake begin, a network of cell phones achieve full connectivity or a disease become a pandemic? Percolation theory provides insight into all these transitions.

Mathematicians typically study idealized networks—symmetric in geometry and infinite in extent—because they are the ones amenable to theoretical calculations. Infinite networks are generally the only ones with truly sharp phase transitions. Real-world networks are limited in extent, are often messy and require challenging calculations—but they, too, have transitions, albeit more rounded ones. As the world becomes increasingly connected through complex layers of links that transport people, provide them with energy by means of electrical grids or connect them via social media—and sometimes spread disease among them—percolation theory becomes ever more pertinent.



SNAPPING INTO PLACE

IN 1957 BRITISH MATHEMATICIANS Simon Ralph Broadbent and John Michael Hammersley first framed percolation theory as a purely mathematical problem. They abstracted the study of percolation in chemistry, which describes a fluid filtering through a material, such as oil seeping through porous rock or water filtering through ground coffee. The percolation network of a rock layer consists of little holes in its structure, represented as nodes, along with the channels or cracks that allow fluid to flow between them, represented as edges. Unsurprisingly, oil flows farther through rock that is more fractured. Using percolation theory, Broadbent and Hammersley predicted that in an idealized rock, the oil will switch from flowing through only small regions to suddenly permeating almost the entire rock when the density of cracks passes a certain threshold.

Geologists use a version of percolation theory to study the sizes of clusters in fractured rock, which is relevant to the extraction of oil by fracking and to the occurrence of earthquakes. To model earthquakes, seismologists create percolation networks that match the scale and density of observed cracks, and then they account for stresses by adjusting the

probability of cracks connecting up. As stresses and links increase, clusters expand until, suddenly and unpredictably, a quake breaks out. Modified versions of the percolation process allow cracks to heal and refracture to simulate aftershocks or long-term change.

Percolation theory also illuminates physical and chemical processes on a much smaller scale, such as polymerization, the process by which small, simple molecules called monomers bind together to form larger clusters called polymers. In the percolation-theory framework, each monomer acts as a node, and two neighbors may spontaneously form a bond, or edge. If the likelihood of their joining increases, the system will eventually hit the percolation threshold, and one giant, connected polymer will emerge. This process is what causes powdered gelatin dissolved in water to set and form Jell-O.

The networks in fractured rock or linked polymers are extremely intricate. It would be nearly impossible to describe their structure precisely, but Broadbent and Hammersley showed that they can be approximated by repeating patterns that are amenable to analysis. The simplest example is a square lattice, which looks like an endless sheet of graph paper: the nodes are arranged in a grid and are connected by four edges to their neighbors.

To see how a fluid might travel through this lattice, imagine that each tiny edge on the graph paper is a pipe that is either open or closed. We can determine the state of each pipe by tossing a coin labeled "open" on one side and "closed" on the other. The resulting landscape of open and closed pipes will be a random network, and it will have some "open" clusters in which all the nodes are connected by a series of open pipes. If you poured water into any node in such a cluster, it would flow through the open pipes to reach all the other nodes in that cluster.

Percolation theory is concerned with the connectivity of the network, which corresponds to how large the open clusters are. But "large" is an ambiguous concept that does not easily lend itself to the formalities of mathematics. So mathematicians often substitute large numbers with infinity. The central question then becomes: Is there an infinite cluster? "For us, it's much easier to answer this yes-or-no question than to answer how many big clusters do we see of this or this size," says Benedikt Jahnel, a mathematician at the Weierstrass Institute for Applied Analysis and Stochastics in Berlin.

In fact, the likelihood of an infinite network having an infinite cluster is always either 0 or 100 percent. That is because the process of percolation is subject to a general principle in probability theory called the zero-one law, discovered by Russian mathematician Andrey Kolmogorov in the 1930s. Suppose you flip a coin an infinite number of times. The zero-one law pertains to any questions about the outcome for which the answer does not depend on any finite number of flips. (For example, the answer to the question, "Did you land on heads infinitely many times?" will not change if you alter a finite number of coin flips, but the answer to the question, "Did you land on heads on the third toss?" can be changed by altering just one coin flip.)

The zero-one law tells us that finite changes cannot disturb phenomena that are infinite in nature. So the probability of finding an infinite cluster in an infinite network cannot change slightly, such as from 0.81 to 0.82; it must take one of the extreme positions—zero or one. To put it another way, an infinite network will either have no infinite cluster (a probability of zero for finding an infinite cluster) or have an infinite cluster (a probability of one).

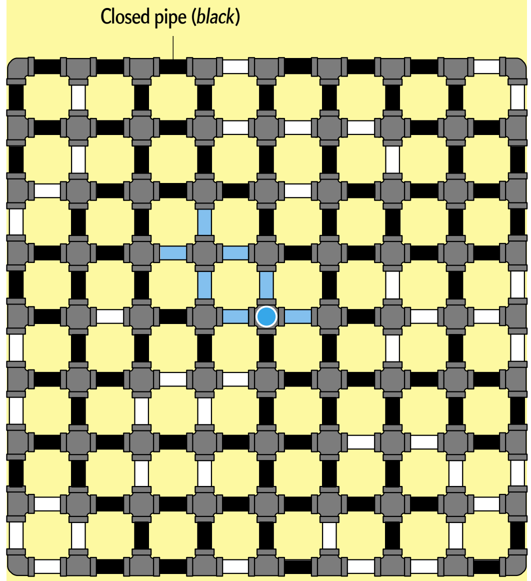
Thus, switching a finite number of open pipes to closed pipes, or vice versa, does not have any effect on whether an infinite open cluster exists. The probability of finding an infinite cluster is either zero or one. Which is it?

FINDING THE THRESHOLD

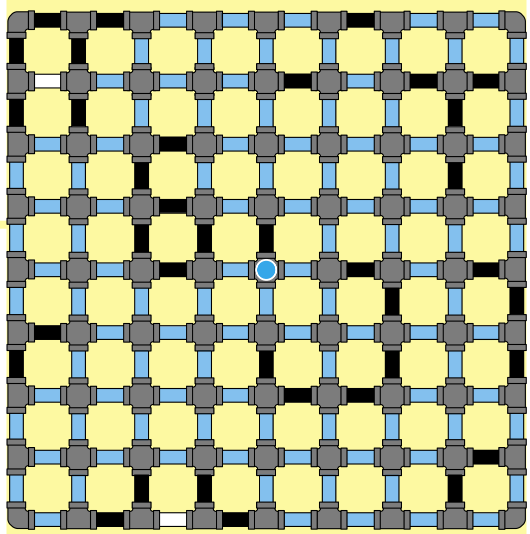
THE ANSWER DEPENDS on the bias of your coin. Imagine you have a dial that controls the bias. When the dial is turned all the way to the left, the coin will always land on "closed." Once all the pipes are closed, water poured into a node

Square Lattice

If probability is set at ⅓, each edge (*pipe*) has a 1 in 3 chance of being open. In this 9 × 9 example, when water (*blue*) is poured into the center node, it gets stuck after traveling to 6 other nodes.

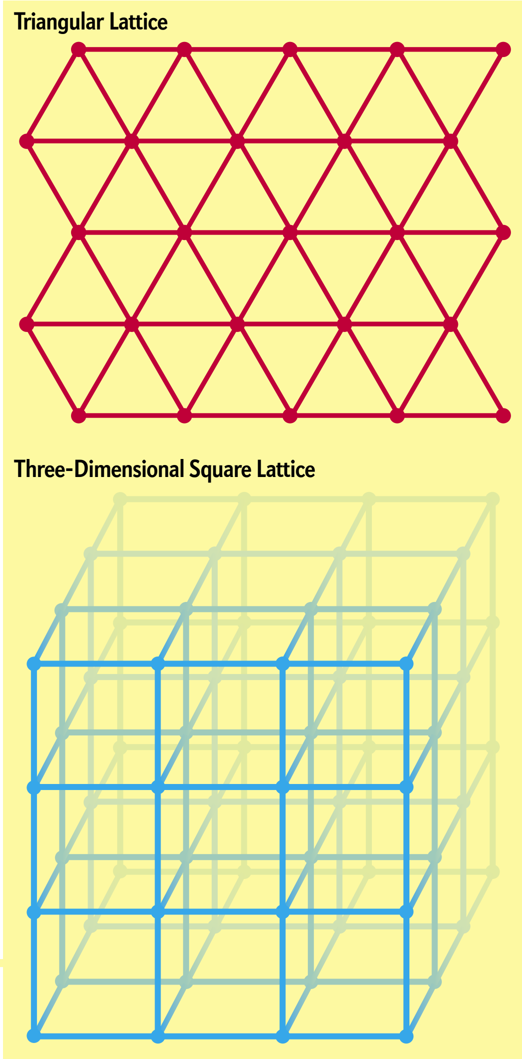


If probability is set at ¾, each edge (*pipe*) has a 3 in 4 chance of being open. In this 9 × 9 example, when water is poured into the center node, it travels all the way to the outside border.



will not flow anywhere, and the probability of finding an infinite cluster will be zero. As you turn the dial clockwise, the probability that the coin will land on "open" increases, and with additional flips there will be more and more open pipes. When the dial is turned all the way to the right, the coin will always land on "open," and eventually the water poured into one node will flow everywhere else. The probability of finding an infinite cluster is then one.

If you slowly turn the dial clockwise, the likelihood of pipes being open gradually increases, and it might seem like the chance of finding an infinite cluster should also increase gradually from zero to one. In fact, the change happens instantly because of the zero-one law: it states that the likelihood cannot be somewhere between zero and one. For the square lattice, the probability snaps from zero to one when the dial is exactly in the middle—when the coin has no bias. This critical position of the dial is known as the percolation threshold. No matter what the shape of the network—whether, for example, it is a triangular lattice or a three-dimensional version of the square lattice—the essential question of percolation theory remains the same: Where is the threshold? How biased does the coin need to be before enough links are open to guarantee an infinite open cluster?



The answer depends on the exact shape of the (infinite) network and is far from easy to find. Even proving that the threshold for a square lattice—the simplest system—is one half was a daunting challenge, finally solved by mathematician Harry Kesten in 1980. And despite decades of effort, the exact percolation thresholds are known only for a few exceedingly simple networks. "There's a whole bunch of work done on just finding what the threshold is," says Robert M. Ziff, a statistical physicist at the University of Michigan. "It's mind-boggling how many different systems people have looked at." Ziff put together a Wikipedia page documenting the percolation thresholds for hundreds of different networks. The bias for the triangular lattice is roughly 0.347, a number determined analytically, but the vast majority of the numbers on that page (including the threshold bias of a three-dimensional square lattice) are approximations derived through computer simulations.

MESH NETWORKS

LATTICES ARE GOOD MODELS for percolation in physical systems such as fractured rock, where the holes are in fixed locations and the cracks between them form randomly. But other real-world networks are far more complicated. In the FireChat and Bridgefy mesh networks mentioned earlier, for example, the locations of the nodes—the phones carried by the Hong Kong protesters—changed constantly. The edges in such a network, or connections, form when two phones are near enough to each other—within the tens-of-meters range of the Bluetooth-based apps used to share messages. Such networks are described by a different model, called continuum percolation, because the nodes of the mesh network can be anywhere in a continuous space.

Like any mathematical model, the abstract version of this network is based on simplified assumptions. The smartphones are randomly scattered, without any mimicking of the natural clusters and patterns in a map of people's meanderings, and two smartphones are linked based only on their distance from each other, without any consideration of walls or other interference. The model nonetheless highlights the central role that percolation theory plays in real mesh networks.

There are two ways to increase the connectivity of this continuum percolation network: enable direct connection at a longer range or add more smartphones, increasing the density of users. These modifications can be thought of as dials like those described for the pipe network; turning either one clockwise will increase connectivity. And in these models, "there's a switch where you really go from local to global connectivity," Jahnel says.

For designers of mesh-networking apps, finding the percolation threshold is a practical engineering problem. Changing the device's power, which controls the range, is one way to turn a dial. The central question, says Ram Ramanathan, chief scientist for the mesh-networking company goTenna, is, "What do you want the transmit power to be to have a connected network?" The answer would be fairly simple if power and connectivity had a linear relation—if each small increase in power led to a proportional small increase in connectivity. But the existence of a percolation threshold means there is a risk that the network will suddenly lose connectivity as peo-

ple move around. The optimal power is one that ensures the network is always connected but does not waste energy.

The other dial is the density of phones. Mesh networks with a fixed range need a critical density of users and are most likely to provide widespread connectivity at crowded events such as a music festival, a soccer game or a large protest. Jorge Rios, Bridgefy's CEO and co-founder, says that the company saw large spikes of new users in Kashmir, Nigeria, Hong Kong and Iran during periods of civil unrest, when people turned to mesh networks to maintain communications in case the government shut down the Internet or large crowds jammed cellular connections. Some neighborhoods, such as Red Hook in Brooklyn, N.Y., are using mesh networks to expand Internet access by fixing permanent nodes to the tops of buildings. Much of the necessary hardware and routing technology is still evolving, but it is easy to imagine bold, futuristic applications—autonomous vehicles could communicate directly, for example, sharing information about traffic patterns or road hazards without relying on any extra infrastructure.

DISEASE CONTACT NETWORKS

THE NETWORKS USED TO MODEL the flow of oil through rocks or direct communication between phones mimic the real spatial structure of these systems: two nodes are connected by an edge if the objects they represent are close to each other in physical space. But for networks that track the spread of disease from person to person, the links are determined by the ways in which that specific germ is transmitted among them. Such networks are particularly tangled: one infected person spending an hour in a nightclub in a big city may pass a virus to a person who carries it across the country or even across continents in the following days.

The simplest epidemiological models lump everyone into three buckets—susceptible, infected and recovered—and neglect this complex structure of connections. In such models, infected people pass the disease to random others in the susceptible bucket under the assumption that everyone in that group—students in a dorm or residents in a city—is equally likely to get it. The rate at which susceptible people get infected depends on the basic reproductive number, the average number of new infections caused by a single infected person, abbreviated as R_0. If R_0 is greater than one, then the virus is spreading, and if it is less than one, then the outbreak is dying out.

In practice, however, how people interact with one another influences the overall spread of the disease. For example, a 2003 outbreak of severe acute respiratory syndrome, or SARS, initially had R_0 values between 2.2 and 3.6, but case counts were "much lower than expected during this period, as suggested by a simple calculation," wrote Lauren Ancel Meyers, now director of the University of Texas COVID-19 Modeling Consortium, in a 2006 article. The discrepancy, she argued, followed from the assumption that "all susceptible individuals are equally likely to become infected," which ignores the complex shape of people's contact networks. In particular, the estimated R_0 values for SARS were based on its rapid spread within apartment buildings and hospitals, which have "anomalously high rates of close contacts among individuals" compared with the general population. But because people infected with SARS became very sick rather quickly, they ended up in hospitals before they could infect many people outside of them.

The edges in a disease network express specific relations. In one showing the potential spread of HIV, for example, two people are connected by an edge if they have exchanged bodily fluids. A network showing the potential spread of COVID-19 has a very different structure of edges, representing close contact without respiratory protection. Lockdowns or restrictions such as closing businesses and limiting travel alter this edge structure and, along with masks and physical distancing, prevent the virus from leaping from one person, or node, to another. One challenge for epidemiologists is to find ways to sufficiently disconnect the network.

Real-world disease contact networks such as those that show the spread of COVID-19 are extremely complicated and difficult to describe precisely. Even if the exact structure of the network were known, it would be challenging to analyze mathematically. Computer simulations and massive data analysis are used to predict future case numbers, evaluate the impact of one meter versus two meters of social distancing, and quantify the significance of schools and restaurants in the spread of the coronavirus. Alessandro Vespignani, a complex-network theorist at Northeastern University, refers to this research as his "wartime" work—tactical and occasionally messy but producing the immediate, numerical results that policy makers and health-care workers need. Vespignani and his colleagues create "a kind of synthetic society where all these individuals are packaged into a computer" to run simulations, he says.

In contrast, Vespignani refers to his "peacetime" research as the period when "you develop the model, you calibrate different ways of modeling things, you develop specific approaches, you look up how you can improve on your results." To obtain a theoretical understanding of how the basic shape and structural features of a network impact the spread of a disease, scientists turn to percolation theory.

The tools offered by the traditional pen-and-paper mathematics of percolation work only in the simplest cases, where the network is artificially ordered and symmetrical. Even so, "the mathematics

is crucial to guide your understanding," Vespignani says. Network epidemiologists strip the network down to its essentials, in particular, its so-called degree distribution. A degree is the number of other nodes that a specific node is connected to. In the square lattice, for example, all nodes have degree four. In a disease network, however, the degree varies dramatically: some individuals have many contacts and may potentially spread the disease to many people, whereas others are fairly isolated.

The degree distribution describes how likely a node is to have each degree. In disease contact networks, this translates to how likely someone is to infect (or potentially be infected by) a certain number of other people. To understand how this aspect affects the percolation threshold, mathematical epidemiologists such as Meyers generate thousands of sample networks that are essentially random except for one feature: they all have the same degree distribution. This approach is a way of isolating the degree distribution to perceive its role in the network's structure. If the properties of the generated networks match up with the real-world networks, then the degree distribution or any other features that are "baked into the math" are likely to be relevant to the spread of the disease, Meyers says. If the match is perfect, "then your mathematical results would look just like your simulations."

Research shows that the percolation threshold for a network drops if the network has a broader degree distribution, meaning a wider range in the degrees of the nodes. So a disease will spread more easily in a network with some highly connected people and some isolated individuals than in a network where everyone has roughly the same number of contacts. Joel Miller, a mathematical epidemiologist at La Trobe University in Melbourne, Australia, explains the observation heuristically: "If I have 10 times as many contacts as you, I'm 10 times as likely to get infected, and I'm 10 times as likely to spread as you, so that's 100 times more important for disease spread."

NETWORKS OF THE FUTURE

PERCOLATION THEORY is used to model other "contagion" phenomena, such as when a meme on a social media network slowly gains traction before suddenly going viral. It can be applied to economic models to show how a particular product can quickly come to dominate a market as people share recommendations among their social contacts. Voter models, where people influence their community, also show threshold effects.

In contrast to the infinite, neatly ordered networks that mathematicians have traditionally studied, networks derived from real examples are finite in extent and messy. Finite networks do not instantly jump from being connected within small pockets to being connected almost everywhere the way infinite networks do, but they do usually make the switch very quickly. To understand these processes, network theorists go back and forth between the mathematics and the computer simulations. The simpler networks guide them in building detailed computer models of actual networks, lessons from which in turn influence how they modify the pen-and-paper models to gain insight into the real world.

Many important network models of the spread of COVID-19 integrate information from other networks. School systems, train routes and hospital-employee schedules all form networks—and each of them influences the course of the pandemic. "We live in this system of interdependent networks, and we can't just think about one without understanding the consequences that the others bring," says Raissa D'Souza, a complex-network theorist at the University of California, Davis. Each network is its own complex system with its own emergent behavior. Increasingly, we are coupling these networks to create an even more complex system. But there is no clear theoretical framework to study such networks of networks. Understanding how their properties are affected by the properties of the constituent networks is a challenge for the future.

Simplified networks provide insight for building detailed computer simulations of actual networks, lessons from which in turn influence how scientists modify the pen-and-paper models.

"We are not living in a bubble or a fully mixed world. We live in a world with contacts, we follow Twitter accounts, and these are places where percolation and other models enter," Vespignani says. Gaining a better understanding of those theoretical mathematical models now "can make the difference in the future." Percolation networks are easily adaptable, yielding new playgrounds for mathematicians and practical applications for scientists, but these diverse models are unified by one surprising feature: they all have a sharp pivot point where just a few new connections tie the network together. As the world becomes ever more connected, the necessity of understanding these crucial transitions becomes ever more urgent. ■

FROM OUR ARCHIVES

Numbers Game. Kelsey Houston-Edwards; September 2019.

scientificamerican.com/magazine/sa

ENERGY

WHAT TO DO ABOUT NATURAL GAS

The massive gas infrastructure could pose a barrier to decarbonizing our energy system, but it doesn't have to. Here's how

By Michael E. Webber

Illustration by David Plunkert

Michael E. Webber is a professor of energy resources at the University of Texas at Austin and head of the Webber Energy Group there. He is also chief science and technology officer at ENGIE, a global energy and infrastructure firm in Paris that operates the world's largest independent electricity company as well as large natural gas networks.

IN THE MID-2010S IT BECAME COMMON TO SAY THAT NATURAL GAS WOULD BE A BRIDGE FUEL TO a zero-carbon future, in which solar, wind and other renewable technologies provide all of our energy without any carbon dioxide emissions to worsen climate change. But if natural gas is really a bridge, then it's not part of the long-term plan. And if we actually build the bridge, we're likely to stay on it.

Natural gas consumption in the U.S. has risen by a third in the past 15 years. Gas accounts for 32 percent of total energy consumption and is now the biggest source of electricity nationwide, largely displacing coal-fired power plants. Natural gas—primarily methane—burns much cleaner than coal does, and it provides ready backup to variable wind and solar farms. That sounds promising, except burning natural gas still creates CO_2. Methane in wells and pipelines can leak into the atmosphere, amplifying global warming. And once the last coal plant closes, natural gas plants become the dirtiest electricity sources.

To reduce CO_2 emissions, society has to decarbonize its energy systems as quickly as possible. Building more wind and solar farms is relatively inexpensive and fast, and it accelerates the shutdown of coal plants. But exploiting the best locations—the windswept plains and sunbaked deserts—requires a greatly expanded transmission grid to bring the electrons to major cities and manufacturing complexes. Those wires and poles introduce risks from windstorms, floods and fires—all rising because of climate change—and township after township routinely fights expansion plans: "Not in my backyard."

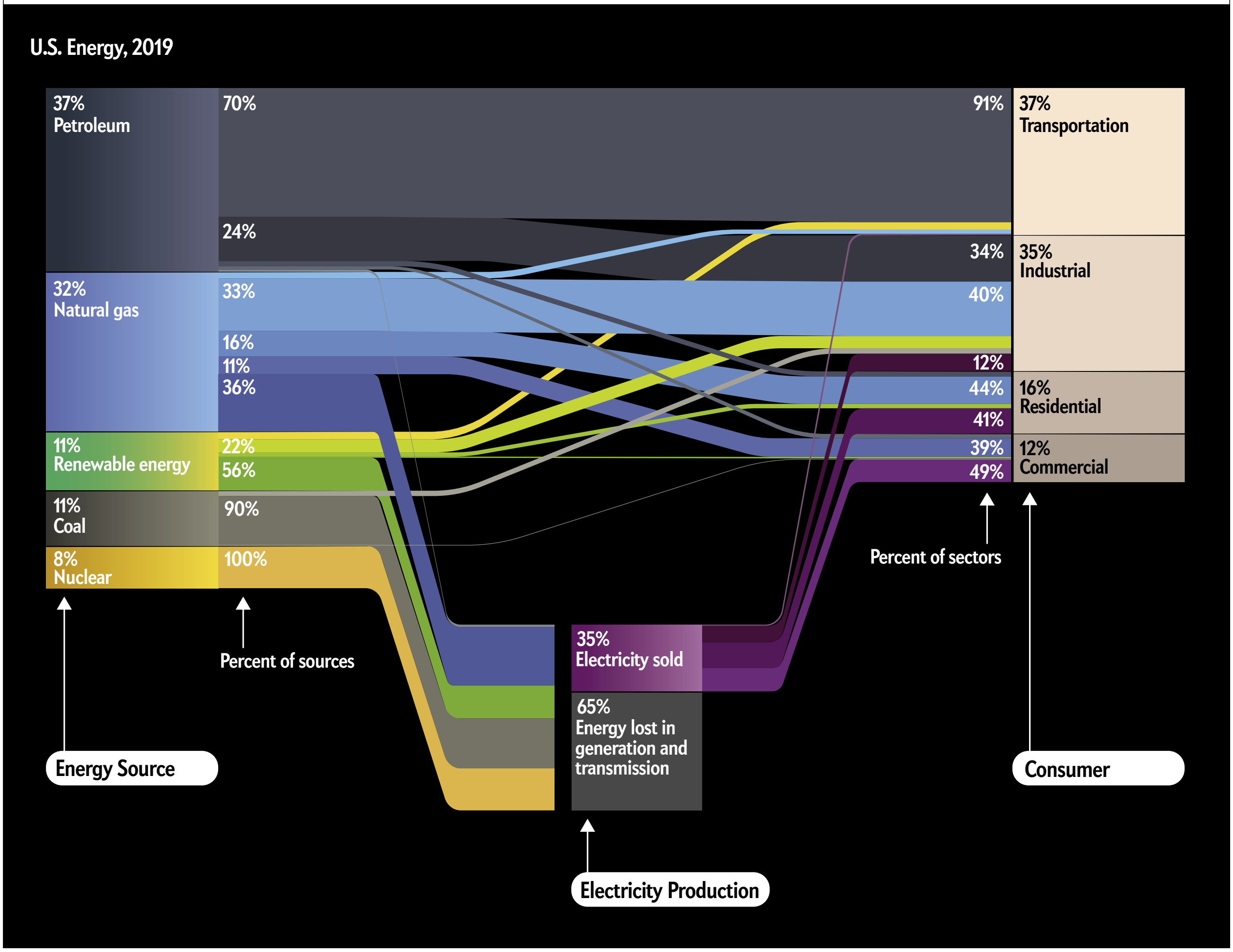
The natural gas infrastructure, almost all belowground, is far less prone to interruption. The U.S. has about three million miles of natural gas pipelines running underneath nearly every major city in the contiguous 48 states. After adding all the compressors, tanks and storage caverns, the infrastructure is worth several trillion dollars. The power plants themselves add hundreds of billions of dollars more. The nearly 70 million households served by natural gas have furnaces, water heaters and cooktops worth at least another $100 billion. Multiply all that sunk investment by about five for the entire world. Gas is also more intertwined than any other energy source with other sectors of society—transportation, buildings (for heating and cooking) and industry (for heat and as a feedstock for chemicals)—making it harder to replace.

Swapping out that infrastructure before its natural lifetime ends would also entail financial losses for the current owners, who will push back. The replacement technology could cost taxpayers, ratepayers and homeowners, who will push back, too. And more electricity does not readily solve the need for liquid fuels burned in trucks, ships and planes or for intense heat in industrial foundries, distilleries and refineries that make volumes of metals, cement, glass, jet fuel and chemicals. The energy density of liquid fuels is difficult to match.

If we can clean emissions out of the natural gas system, it could be part of a carbon-neutral future instead of a bridge. The technology exists to extract the car-

Dependence: The U.S. Consumes Large Quantities of Natural Gas

Natural gas accounts for 32 percent of U.S. energy consumption—second only to petroleum—and 31 percent of electricity generation, more than any other source. It is also deeply integrated into the economy's manufacturing, commercial and residential sectors, used for industrial heat and chemical feedstocks, space and water heating, and cooking, as well as electricity. Burning natural gas emits carbon dioxide, and gas wells and pipelines can leak methane that warms the atmosphere, so decarbonizing the system and stopping leaks are crucial to limiting climate change.



SOURCE: "U.S. ENERGY CONSUMPTION BY SOURCE AND SECTOR, 2019," BY U.S. ENERGY INFORMATION ADMINISTRATION (*data*)

bon or to transform the gas so that carbon coming out and carbon going in balance to zero or near zero.

The first step in a comprehensive plan for decarbonizing the nation's energy infrastructure would be improving energy efficiency and conservation to reduce consumption. The second would be to electrify as many cars, space heaters, water heaters and cooktops as is practical, using renewable sources. At the same time, tighten up the leaky gas infrastructure. And replace as much natural gas as possible with low-carbon alternatives such as biogas, hydrogen and synthesized methane or use a process called pyrolysis at the end of the natural gas pipes to get the carbon out.

Clean energy supporters rightly worry that any investment in gas infrastructure creates a lock-in effect. Each new power plant, pipeline or gas storage unit has an expected lifetime of 25 to 80 years, so each element could either become a trap for more emissions or a stranded asset. But we can solve the lock-in problem with drop-in alternatives to natural gas: low-carbon gases that can flow through existing pipes, tanks and power plants, taking advantage of those trillions of dollars of assets.

ZERO-CARBON GAS

THE DROP-IN SUBSTITUTE most ready for natural gas is biomethane—methane gas produced from biological sources. Microbes inside large drums called anaerobic digesters chew up organic matter such as crop waste, manure, sewage, and food waste and other garbage in landfills, producing methane. Biodigesters, already a mature technology, transform waste streams

Graphics by Datalands and Jen Christiansen

at landfills and the waste lagoons adjacent to concentrated animal feeding operations from environmental liabilities into valuable commodities, generating revenues for municipalities and farmers.

Biomethane is working in Austin, Tex. Waste Management, which operates one of the city's landfills, collects biomethane from 128 wells on its site and burns it to generate enough electricity for 4,000 to 6,000 homes. And one of the city's wastewater-treatment plants has eight biodigesters, each with two million gallons of capacity; microbes convert sewage into biogas that fuels on-site electricity generators. The process creates a solid by-product called Dillo Dirt, which feels and smells like a clumpy compost. A city contractor sells it by the bag in area stores to enrich soil.

About a quarter of the more than 2,000 U.S. landfills now harvest their gas or process their waste into biogas using biodigesters. That only offsets less than 1 percent of the country's total natural gas use, however. Biogas can serve as a direct substitute for natural gas, but the relative volume, globally, is low. If a farm, landfill or sewage plant cannot readily use the gas to make electricity or is not next to a gas grid, the biomethane might need to be liquefied and trucked to another location, reducing the carbon payoff. Still, biomethane is a commercially ready technology that can begin to decarbonize part of the gas system.

HYDROGEN INSTEAD OF METHANE

NATURAL GAS can be replaced altogether, with hydrogen. Turbines can burn hydrogen to generate electricity for the grid, and internal-combustion engines can burn it in heavy-duty vehicles. Hydrogen in fuel cells can produce electricity for cars, homes or offices. And hydrogen is a ready building block for many basic chemicals. Burning it, or reacting it in fuel cells, does not produce CO_2. Leaked hydrogen has a warming effect that is just a fraction of that of methane.

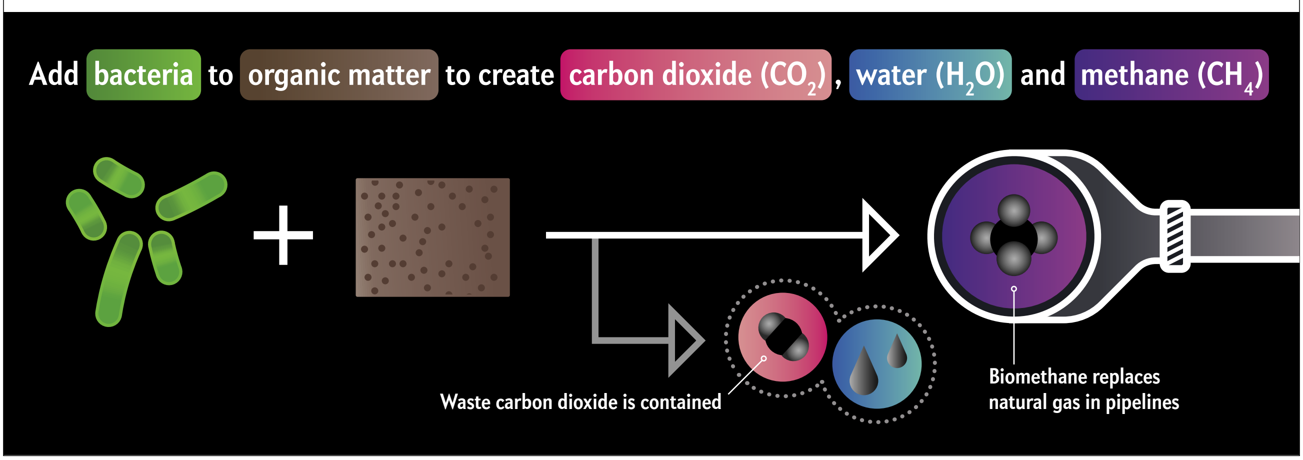
Natural hydrogen seeps out of the ground from basins in many cratons in the earth—large blocks of ancient rock that form the central parts of continents. Scientists have stumbled across these seeps for more than a century. Oil and gas companies, however, have considered hydrogen a nuisance when they find it alongside underground reservoirs because it can catch fire and can degrade metal piping. But today corporate and university researchers are drilling hydrogen test wells and launching multiyear programs to search for hydrogen underground. Anticipation feels similar to what arose during the very early days of fracking shale: a huge resource is out there, if engineers can figure out how to harness it cheaply and safely.

We can also manufacture hydrogen. Right now most hydrogen for industry is produced from steam re-forming of methane—adding heat and hot water to methane to create hydrogen and CO_2. Electrolysis—using electricity to split water into hydrogen and oxygen—can also create hydrogen gas. Both processes require significant amounts of energy, however.

Moving and storing gaseous hydrogen is also a challenge. Because of hydrogen's low density, it takes a lot of energy to move it through a pipe compared with denser gases such as methane or liquids such as petroleum. After several hundred kilometers the inefficiency makes moving hydrogen more expensive than the value of the energy it carries. And hydrogen can embrittle steel pipelines unless that is mitigated

Strategies for Decarbonizing the Gas System: 1 Replace Gas with Biomethane

To reduce CO_2 emissions from burning natural gas, which is primarily methane, the gas in a pipeline can be replaced with biomethane. Microbes inside large drums break down organic matter—crop waste, manure, sewage or food waste—to produce methane, water vapor, and some CO_2, the last of which is captured for industry or underground storage. If the matter had decomposed naturally, it would have released CO_2 and methane into the atmosphere.



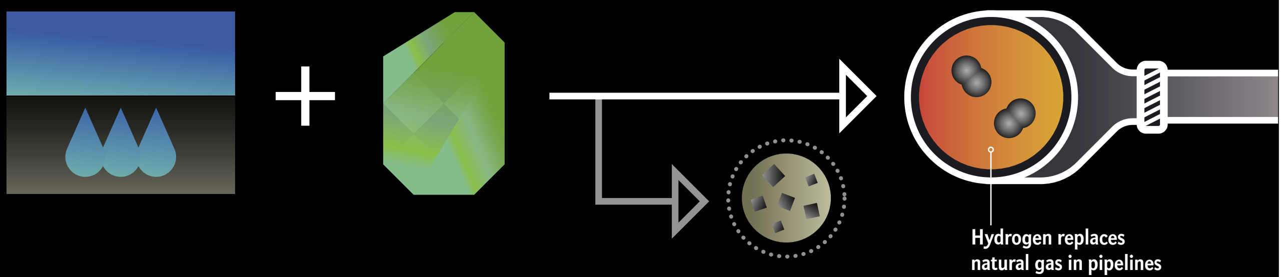
2 Replace Gas with Hydrogen

Natural gas in a pipeline can be partially or fully replaced with hydrogen, which can be burned in power plants and heavy-duty vehicles, fed into fuel cells for cars, homes and buildings, or used as an industrial feedstock. Burning hydrogen emits no carbon. Special pipeline alloys would be needed to transport gas with greater than 20 percent hydrogen. Several sources of hydrogen are described below.

NATURAL RESERVOIRS

When water underground contacts iron-bearing rock, it turns the rock into silicates and hydrogen. Or pumps can send water down to convert the rock.

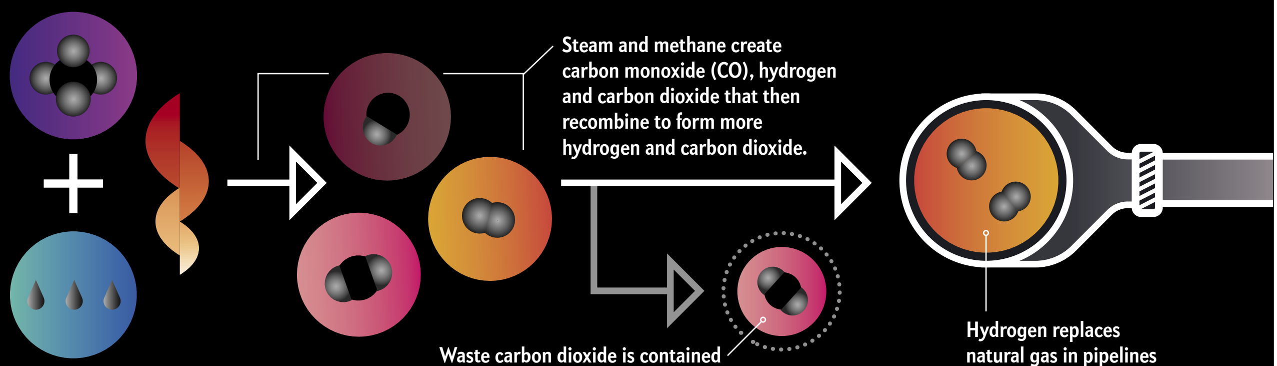
Water (H_2O) naturally reacts with rock containing iron to create silicates and hydrogen (H_2)



STEAM RE-FORMING OF METHANE, WITH CARBON CAPTURE

Heat and water added to methane from a well creates hydrogen and CO_2, which would be captured rather than emitted. Industry already uses this process widely to make hydrogen for refineries and foundries. Clean energy would be required to generate the heat.

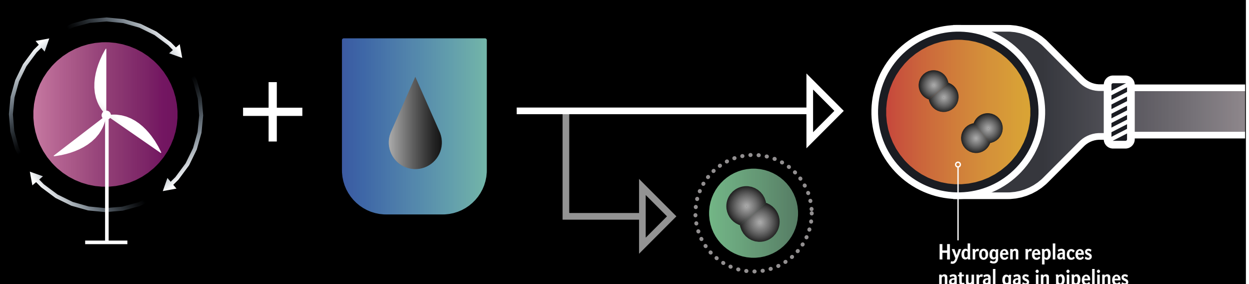
Add heat to methane (CH_4) and steam (H_2O) to create carbon dioxide (CO_2) and hydrogen (H_2)



ELECTROLYSIS

Renewable electricity splits water to create hydrogen. More energy is needed than for steam re-forming of methane, but the only by-product is oxygen, which is released into the air.

Add electricity to water (H_2O) to create oxygen (O_2) and hydrogen (H_2)



by altering operating conditions or incorporating expensive alloys.

One way to integrate hydrogen is to mix it with methane in an existing natural gas pipeline. This blending decarbonizes some of the system by displacing a portion of the natural gas with hydrogen. Experiments in the U.K. and France show that a mixture of 80 percent methane and 20 percent hydrogen can be efficiently moved in a natural gas pipeline. As part of a study from mid-2018 to March 2020, Dunkirk, France, used an 80–20 blend to fuel 100 homes and a hospital boiler without any new equipment along the pipeline or in the buildings.

Fittings inside furnaces and stoves, such as burner tips, might need to be altered or replaced for blends with more than 20 percent hydrogen because, like pure hydrogen, blended gas burns at different temperatures and rates. Another consideration is that because of hydrogen's low energy density, a 20 percent blend by volume provides 14 percent less energy per cubic foot than natural gas.

One way around certain cost and safety challenges is to pipe hydrogen as part of another chemical form we know how to handle, such as ammonia, which has one nitrogen atom and three hydrogen atoms. Molecules that include hydrogen atoms are known as hydrogen carriers. Hydrogen is converted, where it is found or produced, into the carrier, which is dropped into existing pipelines, and is either used in that form or converted again into hydrogen at the destination.

Common carriers such as ammonia, formic acid and methanol are liquid at near-ambient conditions, making them easier to transport than gaseous hydrogen. Although ammonia is caustic, it is already moved worldwide as a fertilizer ingredient, and it can be burned without producing any CO_2. Methane could be the most efficient option because it carries four hydrogen atoms for every carbon atom and is already compatible with existing pipes, compressors, tanks, turbines and appliances.

Demonstration projects are growing quickly in number. Finnish industrial builder Wärtsilä is constructing a new ship for 2023 named Viking Energy that will run on ammonia with fuel cells, avoiding greenhouse gas emissions and other pollutants that plague the maritime sector. Air France and the Charles De Gaulle airport in Paris are very interested in hydrogen as a way to decarbonize aviation. Hydrogen carriers are still in the early stages of research, however, so it is difficult to say how successful they could be.

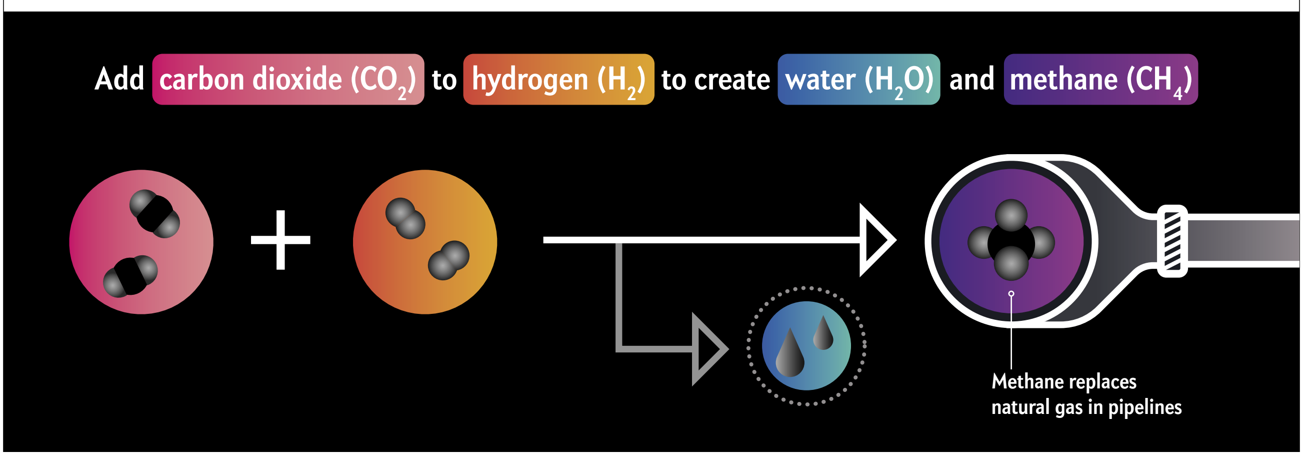
Power plants that burn hydrogen are on drawing boards, too. In Delta, Utah, the Intermountain Power Plant—one of the largest U.S. coal-fired plants—sends electricity hundreds of miles to Los Angeles. To meet the city's long-term requirement for renewable and low-carbon energy, in 2025 plant owners will replace the coal boilers with turbines that can burn hydrogen. They will start with a blend of 30 percent hydrogen in natural gas and will shift to 100 percent hydrogen later. The hydrogen will be generated right there using electrolysis powered by wind and solar and will be stored in more than 100 existing, underground salt caverns, each about the size of the Empire State Building.

END OF THE PIPE

INSTEAD OF DECARBONIZING natural gas before it goes into the pipeline, we could remove the carbon at the end of the pipe, where customers consume the gas.

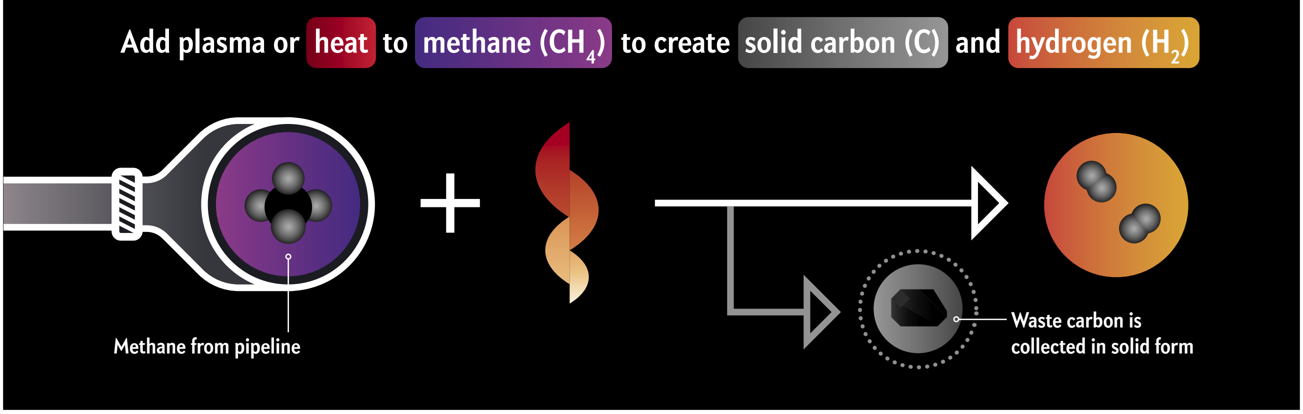
3 Transport Hydrogen in Other Chemical Forms

Hydrogen "carriers" are gases or liquids that contain hydrogen molecules, such as formic acid (CH_2O_2), methanol (CH_3OH) or methane (CH_4). Instead of extracting natural gas and burning it, thereby creating CO_2, machines powered by renewable electricity pull CO_2 from the air or from smokestacks, then combine it with hydrogen to form the carrier, which is shipped in existing pipelines. Burning it releases CO_2 again, but because the fuel was made with CO_2 from the atmosphere, net emissions are low.



4 Extract Carbon at Consumer Locations

Carbon can be pulled from natural gas at the consumer end of the pipeline instead of the supplier's end. In a process called pyrolysis, an appliance splits the incoming methane into hydrogen gas for heaters, stoves or industrial machines, leaving solid carbon dust that the appliance collects. Consumers or haulers cart away the dust, which could be sold as raw material for products such as batteries or fertilizer. Plasma—an electrically charged gas (like a lit neon sign)—or heat splits the methane.



Methane, for example, can be split at the user's location into hydrogen and solid carbon, which looks like a fine, black dust. The process, called methane pyrolysis, is efficient and eliminates CO_2 emissions. Every kilogram of hydrogen produced from pyrolyzed methane generates three kilograms of solid carbon instead of nine kilograms of CO_2 gas that would be emitted if the methane was burned.

The pile of carbon dust that accumulates inside a collector in a furnace or stove would be carted away each month or so. We already pay garbage haulers and municipal wastewater-processing plants to clean up our solid and liquid wastes; we should pay to clean up the waste from our gas use, too. The carbon piles actually have value, though, because they can be sold as a basic ingredient for making graphite, rubber, coatings, batteries and chemicals, as well as a soil amendment for agriculture.

Although engineers have studied methane pyrolysis for decades, they have deployed it only in small demonstration projects. Some equipment at the end of the pipe has to be changed to separate the carbon, but no expensive hydrogen pipelines would have to be built, simplifying matters greatly. Pyrolysis of conventional natural gas can bring the entire system to nearly zero carbon. Adding methane from biodigesters or made from CO_2 in the atmosphere using renewable electricity could make the system carbon-negative.

Imagining any of these decarbonized futures might conjure up visions of large new industrial complexes or millions of small equipment changes for consumers. But so do other proposals to curb emissions. Electrifying every heater, stove and vehicle would require widespread technology replacement. Plans to directly pull CO_2 from the air would require millions of big machines to capture the gas and sequester it—sprawling enterprises that would also demand lots of new land and new electricity.

Decarbonized gas would let us take advantage of trillions of dollars of existing pipelines, equipment and appliances, saving huge sums of money and years of time in creating a zero-carbon energy system. We would, of course, have to fix the leaky infrastructure. Leaks can be minimized by replacing pneumatic equipment with electric devices at well sites, improving the automation of pipe and tank inspections with sensors on drones and robots, and writing regulations that no longer turn a blind eye to leaking, as well as deliberately venting or burning unwanted gas. This work would create jobs for workers in the oil and gas industries and would clean up the energy infrastructure, which in turn could lessen pollution in communities near energy facilities.

Reining in climate change requires many solutions. Declaring who cannot be part of those, such as natural gas companies, only raises resistance to progress. Because decarbonized gas can complement renewable electricity and because it might be a faster, cheaper and more effective path for parts of society that are difficult to electrify, we should not discard gas as an option. We have a massive gas infrastructure, and we have to figure out what to do with it. Scrapping it would be slow, expensive and incredibly difficult, but we could instead put it to work to help create a low-carbon future. SA

FROM OUR ARCHIVES

Burning Natural Gas. The Editors; June 23, 1888.

scientificamerican.com/magazine/sa

LASER LIGHT **creates an artificial star to calibrate the adaptive optics system on the European Southern Observatory's Very Large Telescope in Chile.**

ASTRONOMY

Seeing Clearly

A tool built for astronomy finds new life combating space debris and enabling quantum encryption

By Tony Travouillon, Céline d'Orgeville and Francis Bennet

FOR ASTRONOMERS, it's a magical moment: you're staring at a monitor, and a blurry image of a cosmological object sharpens up, revealing new details. We call this "closing the loop," a reference to the adaptive optics loop, a tool that enables telescopes to correct for haziness caused by turbulence in the atmosphere. Adaptive optics essentially untwinkles the stars, canceling out the air between us and space to turn a fuzzy image crisp.

One night last year our team at the Australian National University was closing the loop on a new imaging system made to resolve the details of space debris. Sitting in the control room of our observatory on Mount Stromlo, overlooking the capital city of Canberra, we selected a weather satellite for this first test. It was an easy target: its large body and solar panels are unmistakable, offering a good way to test the performance of our system.

For some of us, this was the first time we had used a telescope to observe something that was not a star, galaxy or other cosmic phenomenon. This satellite represents one of the thousands of human-made objects that circle our planet, a swarm of spacecraft—some active, most not—that pose a growing risk of overcrowding near-Earth orbits. Our test was part of an effort to build systems to tackle the problem of space debris and preserve these orbital passages for future use. It is one of several new ways that we are using adaptive optics, which has traditionally been used for astronomical observations, to accomplish different goals. After more than three decades of perfecting this technology, astronomers

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Y. BELETSKY (LCO) AND ESO

have realized that they can apply their expertise to any application that requires sending or receiving photons of light between space and the ground.

THE FIGHT AGAINST THE ATMOSPHERE

THE LAYER OF GAS between Earth and the rest of the cosmos keeps us alive, but it also constantly changes the path of any photon of light that travels through it. The culprit is atmospheric turbulence caused by the mixing of air of different temperatures. Light bends, or refracts, when it travels through different mediums, which is why a straw in a glass of water looks like it leans at a different angle under the water than above it—when the light bouncing off the straw moves from water into air, it changes course. The same thing happens when light travels through air of different temperatures. When light passes from warm air to cool air, it slows down and its path changes.

This effect is why stars twinkle and why astronomers have such a hard time taking precise images of the sky. We quantify the impact of atmospheric turbulence with "the seeing," a parameter that describes the angular size of the blurred spot of a star as seen through a ground-based telescope. The more turbulent the atmosphere, the worse the seeing. At a good site, on a high mountain with low turbulence, the seeing is typically between 0.5 and one arcsecond, meaning that any telescope will be limited to this range of resolution. The problem is that modern telescopes are capable of resolution significantly better than that. From a purely optical point of view, the resolution of a telescope is dictated by the "diffraction limit," which is proportional to the wavelength of the light that is collected and inversely proportional to the diameter of the telescope collecting that light. The wavelengths we observe depend only on the chemical composition of our celestial targets, so those cannot be changed. The only way to build telescopes that can resolve smaller and smaller objects is therefore to increase their diameter. A telescope with a two-meter diameter mirror can, for example, resolve objects that are 0.05 arcsecond in optical wavelengths (the equivalent of resolving a large coin 100 kilometers away). But even a very good site with low seeing will degrade this resolution by a factor of 10.

Adaptive optics essentially untwinkles the stars, canceling out the air between us and space to turn a fuzzy image crisp.

It is thus easy to see the attraction of putting telescopes in space, beyond the reach of the atmosphere. But there are still very good reasons to build telescopes on the ground. Space telescopes cannot be too large, because rockets can carry only so much weight. It is also difficult to send humans into space to service and upgrade them. The largest space telescope currently under construction is the James Webb Space Telescope, and its primary mirror is 6.5 meters wide. On the ground, the largest telescope mirrors are more than 10 meters wide; now being built, the Extremely Large Telescope will have a primary mirror that extends 39 meters. Ground-based telescopes can also be upgraded throughout their lifetimes, always receiving the latest generation of instrumentation. But to use these telescopes to the fullest, we must actively remove the effects of the atmosphere.

The first adaptive optics concepts were proposed in the early 1950s and first used in the 1970s by the U.S. military, notably for satellite imaging from the ground. Astronomers had to wait until the 1990s to apply the technology in their observatories. Adaptive optics relies on three key components. The first is a wavefront sensor, a fast digital camera equipped with a set of optics to map out the distorted shape of the light waves heading toward the telescope. This sensor measures the distortion caused by the atmosphere in real time. Because measurements must keep up with fast changes in the atmosphere, it needs to make a new map several hundred to several thousand times per second. To get enough photons in such short exposures, the wavefront sensor requires a bright source of light above the atmosphere. The stars themselves are rarely bright enough for this purpose. But astronomers are a resourceful bunch—they simply create their own artificial stars by shining a laser upward.

This reference light source—the laser guide star—is the second key component of the adaptive optics system. Our atmosphere has a layer of sodium atoms that is a few kilometers thick and located at an altitude of 90 kilometers, well above the turbulence causing the distortions. Scientists can excite these sodium atoms using a specially tuned laser. The sodium atoms in the upper atmosphere absorb bright orange laser light (the same color emitted by the sodium street lamps in many cities) and then reemit it, producing a glowing artificial star. With the laser attached to the side of the telescope and tracking its movements, this artificial star is always visible to the wavefront sensor.

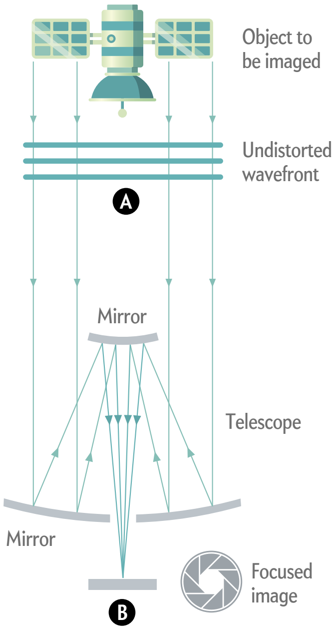
Now that we can continuously track the shape of the wavefront, we need to correct for its aberrations. This is the job of the third major component of the system: the deformable mirror. The mirror is made of a thin reflective membrane, under which sits a matrix of actuators, mechanisms that push and pull the membrane to shape the reflected light. Every time the wavefront sensor makes a measurement, it sends this information to the mirror, which deforms in a way that compensates for the distortions in the incoming light, effectively removing the aberrations caused by the atmosphere. The atmosphere changes so fast that these corrections must be made every millisecond or so. That is a major mechanical and computational challenge. The deformable mirror hardware must be capable of making thousands of motions every second, and it must be paired with a computer and wavefront sensor that can keep up with this speed. There are up to a few thousand actuators, each moving the deformable mirror surface by a few microns. Keeping up with this constant updating process in a self-correcting fashion is what we mean by "closing the loop."

Although the technique is difficult and complex, by now astronomers have largely mastered adaptive optics, and all major optical observatories are fitted with these systems. There are even specialized versions used for different types of observations. "Classical"

How Adaptive Optics Works

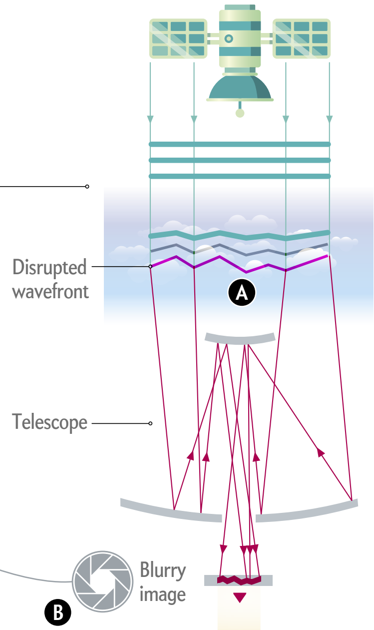
Earth's atmosphere causes unwanted distortion to images observed by ground telescopes. To compensate for these atmospheric effects, astronomers use adaptive optics systems with deformable mirrors that cancel out aberrations to produce sharper images.

A system without distortion



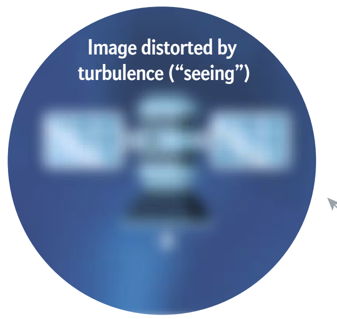
Incoming light from natural sources or human-made objects such as satellites shows a flat wavefront **A**. Absent any external sources of distortion, the light can be focused by a telescope's mirrors into a point, resulting in a sharp image **B**.

The effect of atmospheric disturbance



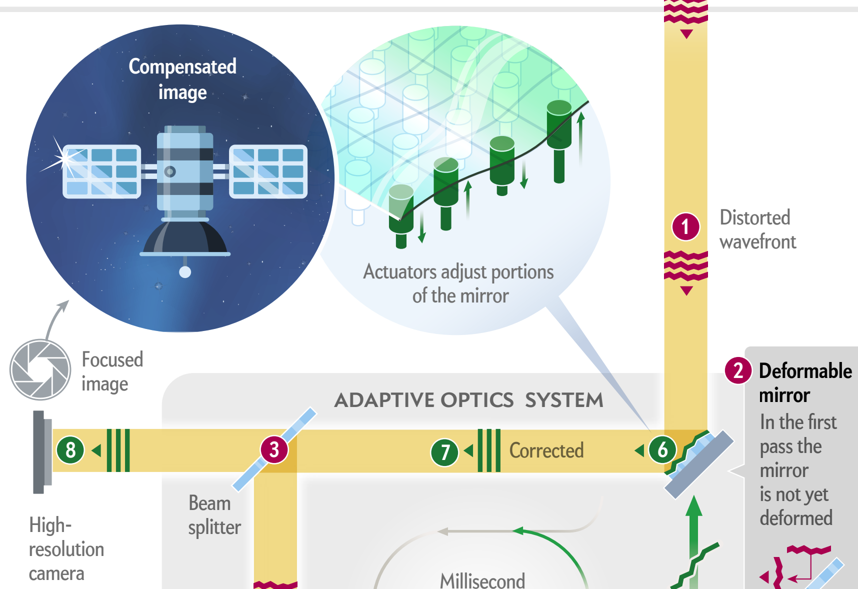
Distortion

But turbulence in the atmosphere, caused by mixing of air of different densities, slows down parts of the wavefront by different amounts **A**. The light components arrive to the focal point out of phase, producing a blurry image **B**.



How Adaptive Optics Fixes It

When the light beam enters an adaptive optics system **1**, it hits a deformable mirror. At first, the still unadjusted mirror reflects the distorted wavefront **2**. The light moves to a beam splitter **3**, and one part hits a sensor that analyzes the wavefront distortion **4**. Similar to the way noise-canceling works, the system generates an "inverse" wavefront that compensates for the distortion **5**, and hundreds of individual actuators warp the deformable mirror with a corresponding compensation shape **6**. The mirror will then be able to cancel out the incoming wavefront distortion and reflect a corrected, flat wavefront **7**. The splitter directs part of it to a high-resolution camera to capture the focused image scientists need **8**, and the other part moves on to the next correction loop.



Closing the Loop

The atmosphere changes very fast, requiring corrections in the system every millisecond or so. Adaptive optics establishes a self-correcting feedback loop, with the wavefront sensor measuring any new distortions and sending real-time compensation instructions to the deformable mirror.

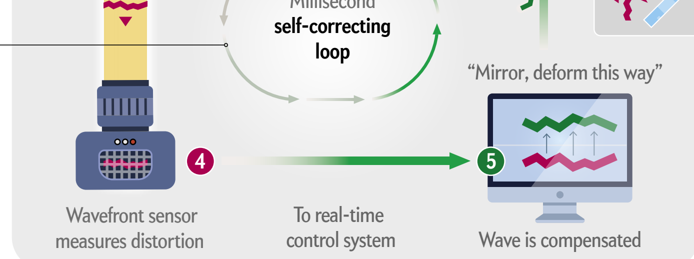
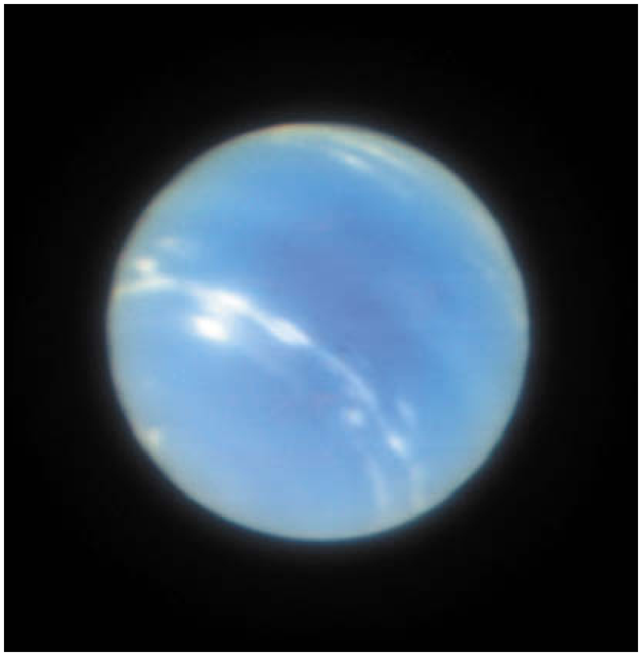


Illustration by 5W Infographics



IN FOCUS: Two images of the planet Neptune taken by the Very Large Telescope—one before the adaptive optics system is switched on and one after—show the difference the technology makes.

adaptive optics uses only one guide star and one deformable mirror, which enable atmospheric turbulence correction over a rather limited patch of sky. More complex systems such as Multi Conjugate Adaptive Optics use multiple guide stars and multiple deformable mirrors to probe and correct for a larger volume of atmospheric turbulence above the telescope. This approach opens up windows of atmospheric-free astronomical observations that are 10 to 20 times larger than what classical adaptive optics can achieve—but at a significantly higher price. In other situations—for example, when astronomers want to study an individual target, such as an exoplanet—the important factor is not field size but near-perfect image resolution. In this situation, an Extreme Adaptive Optics system uses faster and higher-resolution wavefront sensors and mirrors, usually coupled with a filter to block the light of the host star and enable imaging of the dim exoplanets orbiting it. We have now reached an age where it is not a stretch to expect any telescope to come with its own adaptive optics system, and we are beginning to expand the use of this technology beyond astronomy.

THE PROBLEM OF SPACE JUNK

IRONICALLY ONE OF THESE NEW APPLICATIONS helped to inspire the early development of adaptive optics: the observation of objects in close orbit around our planet. This research area, commonly called space situational awareness, includes the observation and study of human-made objects (satellites) as well as natural objects (meteoroids). A legitimate fear is that the ever increasing number of spacecraft being launched will also increase the number of collisions between them, resulting in even more debris. The worst-case scenario is that a cascading effect will ensue, rendering certain orbits completely unusable. This catastrophic, yet rather likely, possibility is called the Kessler syndrome, after Donald J. Kessler, the NASA scientist who predicted it as early as 1978.

About 34,000 human-made objects larger than 10 centimeters are now orbiting Earth; only about 10 percent are active satellites. Space junk is accumulating at the altitudes most heavily used for human activities in space, mainly in low-Earth orbit (some 300 to 2,000 kilometers above the ground) and geostationary orbit (around 36,000 kilometers). Although we can track the larger objects with radar, optical telescopes and laser-tracking stations, there are several hundreds of thousands of pieces of debris in the one- to 10-centimeter range, as well as 100 million more pieces of debris that are smaller than a centimeter, whose positions are basically unknown.

The collision scenes in the 2013 movie *Gravity* gruesomely illustrate what would happen if a large piece of junk were to collide with, for instance, the International Space Station. NASA reports that over the past 20 years the station has had to perform about one evasive maneuver a year to avoid space debris that is flying too close, and the trend is increasing, with three maneuvers made in 2020. Space junk has the power to significantly disturb our current way of life, which, often unbeknownst to us, largely relies on space technologies. Satellites are necessary for cell phones, television and the Internet, of course, but also global positioning, banking, Earth observations for weather predictions, emergency responses to natural disasters, transport and many other activities that are critical to our daily lives.

A number of projects are aiming to clean up space, but these efforts are technologically difficult, politically complex and expensive. Meanwhile some scientists, including our team at the Australian National University, are working to develop mitigation strategies from the ground. Working from Earth is easier and more affordable and can rely on technologies that we already do well, such as adaptive optics.

Various subtle differences exist between the way we use adaptive optics for astronomy and the way we apply it to space situational awareness. The speed of satellites depends on their dis-

P. WEILBACHER (AIP) AND ESO

tance from Earth. At the altitude of 400 kilometers above the ground, the International Space Station, for instance, is flying at the incredible pace of eight kilometers per second and completes a full orbit every hour and a half. This is much faster than the apparent motion of the sun and stars, which take a day to circle overhead due to Earth's rotation. Because of this speed, when telescopes track satellites, the atmospheric turbulence appears to change much more rapidly, and adaptive optics systems have to make corrections 10 to 20 times faster than if they were tracking astronomical objects. We must also point the guide star laser beam slightly ahead of the satellite to probe the atmosphere where the satellite will be a few milliseconds later.

Adaptive optics can be used to track and take images of satellites and debris in low-Earth orbit and to improve the tracking of objects in low, medium and geostationary orbits. One of the ways we track space objects is light detection and ranging, a technique more commonly known as LIDAR. We project a tracking laser (not to be confused with the guide star laser) into the sky to bounce off a satellite, and we measure the time it takes to come back to us to determine the spacecraft's precise distance to Earth. In this case, the adaptive optics system preconditions the laser beam by intentionally distorting its light before it travels through the turbulent atmosphere. We calculate our distortions to counteract the effects of turbulence so that the laser beam is undisturbed after it exits the atmosphere.

In addition to tracking space debris, we hope to be able to use this technique to push objects off course if they are heading for a collision. The small amount of pressure exerted when a photon of laser light reflects from the surface of debris could modify the orbit of an object with a large area-to-mass ratio. To be effective, we need adaptive optics to focus the laser beam precisely where we want it to go. This strategy would not reduce the amount of debris in orbit, but it could help prevent debris-on-debris collisions and possibly delay the onset of the catastrophic Kessler scenario. Eventually such systems could be employed around the globe to help manage the space environment.

QUANTUM TRANSMISSIONS

SPACE SAFETY IS NOT THE ONLY APPLICATION that can benefit from adaptive optics. Encrypted communications are essential to many of the technological advances we have seen in recent decades. Tap-and-go payment systems from mobile phones and wristwatches, online banking and e-commerce all rely on high-speed secure communications technology. The encryption we use for these communications is based on hard-to-solve mathematical problems, and it works only because current computers cannot solve these problems fast enough to break the encryption. Quantum computers, which may soon have the ability to solve these problems faster than their classical counterparts, threaten traditional encryption. Cryptographers are constantly inventing new techniques to secure data, but no one has been able to achieve a completely secure encryption protocol. Quantum cryptography aims to change that.

Quantum encryption relies on the nature of light and the laws of quantum physics. The backbone of any quantum-encryption system is a quantum "key." Quantum sources can provide an endless supply of truly random numbers to create keys that are unbreakable, replacing classically derived keys that are made in a predictable and therefore decipherable way. These keys can be generated at a very high rate, and we need to use them only once, thereby providing a provably unbreakable cypher.

To send a quantum-encrypted communication over long distances without a fiber-optic connection, we must transmit laser light from an optical telescope on the ground to a receiving telescope on a satellite and back again. The problem with sending these signals is the same one we face when we use a laser to push a piece of space debris: the atmosphere changes the path of the transmission. But we can use the same adaptive optics technologies to send and receive these quantum signals, vastly increasing the amount of data we can transfer. This strategy may allow optical communication to compete with large radio-frequency satellite communication dishes, with the advantage of being quantum-compatible. There are other hurdles to implementing quantum communications—for instance, the need to store and route quantum information without disturbing the quantum state. But researchers are actively working on these challenges, and we hope to eventually create a global quantum-secure network. Adaptive optics is a critical part of working toward this dream.

THE ATMOSPHERIC HIGHWAY

SUDDENLY A TECHNOLOGY ONCE RESERVED for studying the heavens may help us meet some of the great goals of the future—protecting the safety of space and communicating securely. These new applications will in turn push adaptive optics forward, to the benefit of astronomy as well.

Traditionally adaptive optics was only viable for large observatories where the cost was justified by big performance gains. But space monitoring and communication strongly benefit from adaptive optics even on modest apertures. We find ourselves in a situation where all these communities can help one another. Undersubscribed telescopes could find a new life once equipped with adaptive optics, and space debris monitors are hungry for more telescope access to cover as many latitudes and longitudes as possible. For future observatories, astronomers are considering adding technical requirements to their telescopes and instruments to make them compatible with other space research applications such as space situational awareness and communication. Not only does it strengthen their science case, it gives them access to new sources of funding, including private enterprises.

We are entering a multidisciplinary age where the sky is a common resource. While we are sharpening images of the sky, we are blurring the lines between all the activities that use a telescope as their primary tool. Scientists and engineers building adaptive optics systems are now broadening their collaborative circles and putting themselves in the middle of this new dynamic.

Adaptive optics is also being used more without telescopes. An important and now rather mainstream use of adaptive optics is in medical imagery and ophthalmology, to correct for the aberrations introduced by imaging through living tissues and the eye. Other uses include optimum laser focusing for industrial laser tools and even antimissile military lasers. There has never been a more exciting time to explore the potential of adaptive optics in space and on Earth. SA

FROM OUR ARCHIVES

Adaptive Optics. John W. Hardy; June 1994.

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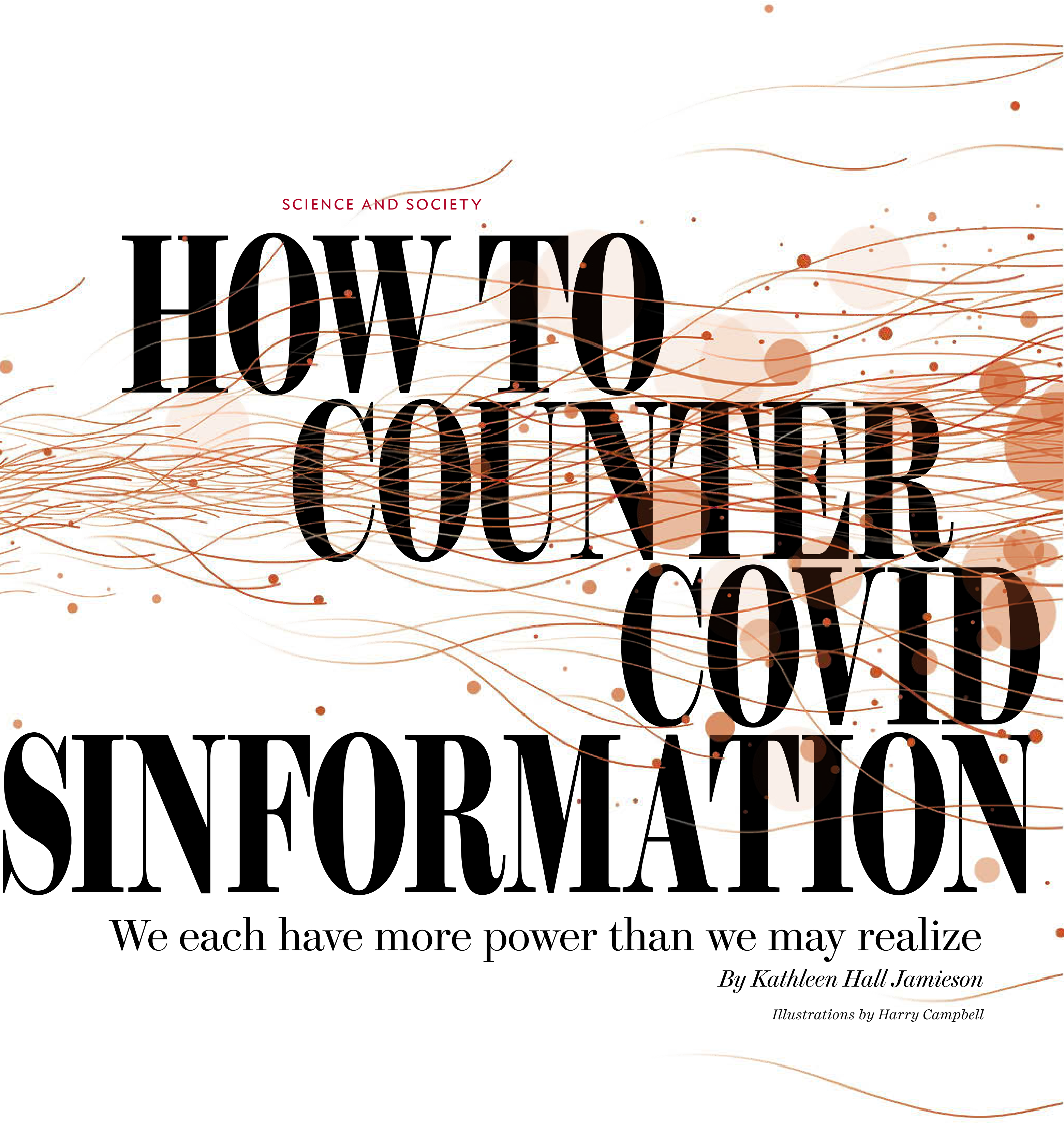

SCIENCE AND SOCIETY

HOW TO COUNTER COVID SINFORMATION

We each have more power than we may realize

By Kathleen Hall Jamieson

Illustrations by Harry Campbell

I have spent much of my career studying ways to blunt the effects of disinformation and help the public make sense of the complexities of politics and science. When my colleagues and I probed the relation between the consumption of misinformation and the embrace, or dismissal, of protective behaviors that will ultimately stop the coronavirus's spread, the results were clear: Those who believe false ideas and conspiracy theories about COVID-19 and vaccines are less likely to engage in mask wearing, social distancing, hand washing and vaccination.

In the midst of a raging pandemic, the importance of science communication is indisputable. Mention "science communication," though, and what comes to mind in this context are public service announcements touting the 3 Ws (Wear a mask, Watch your distance, Wash your hands) or the FAQ pages of the Centers for Disease Control and Prevention. Ask someone what "science communicator" evokes, and responses might include a family physician and experts such as Anthony S. Fauci, director of the National Institute of Allergy and Infectious Diseases, and CNN's Sanjay Gupta, who appear so regularly on our screens that we think of them as friends. But Fauci isn't on your family Zoom call when a cousin mistakenly asserts that the CDC has found that wearing a mask makes you more likely to get COVID-19. Nor is Gupta at the ready when your friend's daughter wonders whether the COVID vaccine contains microchips designed to track us.

It matters how we respond in these moments. As Cailin O'Connor and James Owen Weatherall wrote in this magazine in 2019, the "social transmission of knowledge is at the heart of culture and science." In a large-scale online social network experiment conducted in 2018, Doug Guilbeault and Damon Centola, both then at the University of Pennsylvania's Annenberg School for Communication, confirmed that power. When smokers and nonsmokers collaboratively evaluated antismoking messages, the smokers were more likely to acknowledge the harms of tobacco use than the smokers who evaluated the messages on their own. Similarly Sally Chan and Dolores Albarracin of the University of Illinois at Urbana-Champaign and I found that the level of Twitter chatter from November 2018 through February 2019 about "vaccine fraud" in the counties of our roughly 3,000 panelists were associated with negative attitudes and lower rates of flu vaccination among them later in the year. But those worrisome effects did not occur among people who reported discussing vaccines with family and friends.

Indeed, a sibling or a friend online or next door is in some ways better able to underscore the importance of behaviors such as masking and physical distancing than public health agencies or experts such as Fauci. It's not only that we trust information from knowledgeable people who are close to us but that those in our lives can find opportune moments to explain why preventive behaviors are important to them and why they trust the science that says those actions reduce the spread of the virus. A neighbor or a friend can respond with messages tailored to a person's interests and concerns. In addition to correcting misconceptions in real time, a confidant can create an environment inhospitable to misinformation in the first place. Finally, and critically, deception and debunking usually occur in different venues: those who are exposed to misconceptions rarely encounter the fact-checks.

Equipped with a few tools, we can each become part of a larger misinformation-fighting system—as I like to call it, a science defense system. To see the power of such a role, consider the limitations of the first line of defense against online deception: the willingness of platforms to block it. Even when this happens, there is a lag between the appearance of harmful content, its detection and its removal. Take the 26-minute viral

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video "Plandemic" that appeared online last May. Despite efforts by the major platforms to remove it, within weeks that video managed to reach millions with dangerously false claims (example: certain flu vaccines contain the coronavirus, and wearing a mask activates it). Like a game of Whac-A-Mole, when one platform bans a piece of content, the purveyors of deception simply repost it on another one or share it in invitation-only corners of a platform or in private groups. Last March even as Facebook was clamping down on misinformation and conspiracy theories about COVID, a Politico report on thousands of posts found that the supposedly interdicted content was still on the platform, surviving and spreading harm.

Fact-checking organizations such as PolitiFact and FactCheck.org (which I co-founded in 2003) provide a second barrier in the science defense system. Facebook surfaces the work of many of these groups when a user searches for content that has been flagged for containing misinformation. In a 2015 study, Leticia Bode and Emily K. Vraga, both then at the University of Wisconsin–Madison, found that this kind of corrective juxtapositioning can reduce users' misperceptions. Later, in a 2018 study, Bode and Vraga found that corrections offered by someone's contacts on a simulated social media platform also reduced misperceptions. That conclusion led them to recommend that when it comes to emerging health issues, knowledgeable people online should employ material from appropriate health sources to "refute false or misleading health information clearly, simply, and with evidence." A team of medical doctors at CriticaScience is pioneering this form of online engagement. With support from the Robert Wood Johnson Foundation, my FactCheck.org colleagues and I are seeking to develop new ways to arm the public against COVID-related deception.

When misinformation circumvents blocking, fact-checking and response by online interlocutors—as it too often does—the last line of defense is real-world relationships: family, friends and office buddies. Enlisting in a science defense system requires a commitment to make health-promoting practices the norm in one's community, a willingness to bookmark and turn to public health and fact-checking sites for knowledge about COVID and vaccination, a few premises about the nature and limits of scientific claims, a set of realistic goals, and a strategy for depoliticizing the science if the situation requires it.

Every layer in the model—blocking on platforms, fact-checking, online engagement and creation of a science-friendly community—has limitations. Each additional layer of defense, however, slows the advance of deceptions that, to appropriate a truism, will otherwise get halfway around the world before the truth gets its boots on. And in the case of COVID-19, there are at least two areas where the benefits are so great that they are worthy of concentrated attention: masking and vaccination.

1

Find—and Bookmark—the Facts That Matter

We trust experts to provide us with information that we can't gather for ourselves. If you trust that the FDA's list of the ingredients in the Pfizer/BioNTech COVID-19 vaccine is accurate (a list you can find in the FDA's scope of authorization letter on the agency's site), then that trust and knowledge buffer you from the allegation that the shot injects nano-tracking devices into your arm.

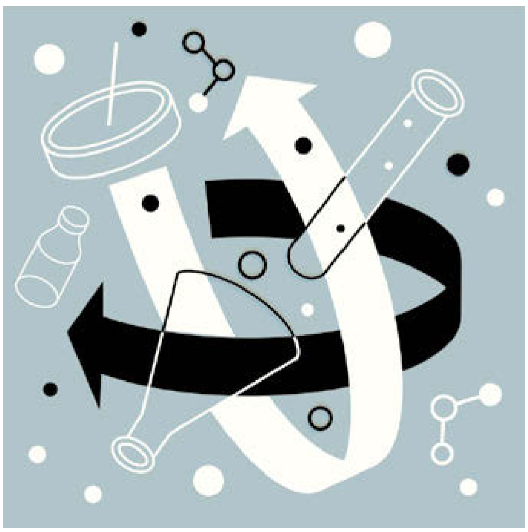
A key question, of course, is: How trustworthy do most U.S. adults consider those who certify health science? The answer, from a *New York Times*/Siena College poll conducted last June, contains both bad and good news. Ninety percent of Democrats trust medical experts, but only 75 percent of Republicans do, which means that appeals to experts such as Fauci and entities such as the FDA will have trouble gaining traction with one out of four GOP loyalists. Yet even in these polarized times, a majority of Americans—84 percent of the U.S. population—say they trust medical scientists, and 77 percent say the same about the CDC.

To get started on stocking a science defense tool kit, then, bookmark the CDC's page addressing frequently asked questions about COVID-19. Do the same for reliable fact-checking groups such as the Associated Press, Reuters, *USA Today,* the *Washington Post,* PolitiFact, and FactCheck.org. To assess their usefulness, try this scenario: Imagine a friend says that a CDC study found that masks are ineffective and wonders whether Donald Trump got it right when he told a town hall audience that a study found that "85 percent of the people that wear masks catch" the virus. The first thing the search reveals is that all the major fact-checkers independently arrived at the same answer to your question. From the Associated Press: "Posts misrepresent CDC study examining

mask use"; from *USA Today:* "Fact check: CDC report doesn't show mask-wearers are more likely to contract COVID-19"; from Reuters: "Fact check: Misrepresented CDC study about community exposure to the new coronavirus." Want to see whether the fact-checkers got the study right? The Reuters and FactCheck.org articles each contain a link to the original CDC study.

The fact-checkers all agree that in the study in question, those who got COVID-19 and those who didn't were equally likely to report mask wearing. Those who were infected, however, were more likely to have eaten in a restaurant or to say that they had been within six feet of a person infected with COVID-19. Because our meta-analysis of studies focused on debunking misinformation showed that detailed explanations can be effective, these kinds of specifics should increase the persuasive power of a correction. In other words, a corrective should point out that the maskers in that study who became infected were more likely to have engaged in behavior that increased their risk. You can't put food in your mouth while wearing a mask, and in the presence of an infected person, masks provide some but not complete protection.

Deception and debunking usually occur in different venues; those exposed to misconceptions rarely encounter the fact-checks.



2

Remember That Science Is Messy and Provisional

Science is an ongoing search for knowledge that yields caveated insights. Yet scientists and reporters sometimes cause confusion by implying that a scientific finding is beyond dispute or by delivering it in a story line that invites that inference. Our analyses, conducted under a grant from the Rita Allen Foundation, revealed that a typical news account casts a new scientific finding as a linear quest by researchers who surmount challenges as they engage in a journey that culminates in "discovery" and, with it, reliable knowledge. Students of literature will recognize this story structure as a classic quest narrative that generally resolves itself with no loose ends.

In news accounts of scientific discovery, the quest story line is pervasive. Our review of more than 600 articles about science published in major news outlets from 2013 to 2018 found that most of the write-ups ignored the false starts, trial and error, and serendipity that characterize the scientific process. Most also failed to note that unanswered questions remained. But as *New York Times* science writer Carl Zimmer notes, a scientific article is "never a revelation of absolute truth. At best it's a status report."

With the iterative, provisional nature of science in mind, the *Washington Post*'s FAQ on masks and COVID-19 declares, "Please keep in mind that as the [novel] coronavirus continues to be studied and understood, masking advice may change, and we will update this FAQ accordingly." Ignoring that insight, some, including Trump, have misinterpreted or misrepresented a statement about masks that Fauci made early last March. "Fauci said, 'Don't wear a mask,' right?" Trump told NBC's Savannah Guthrie at a town hall last October. "Then he changed his mind."

A related selectively edited viral video clip showing Fauci saying people "should not be walking around with masks" has been viewed millions of times on Facebook, YouTube and Twitter. Attacks based on that out-of-context quotation fail to recognize that scientific knowledge is always subject to updating as new evidence emerges. Between early March and the April 3 CDC recommendation that everyone wear masks when in contact with people outside their bubble, scientists learned that those experiencing no symptoms could transmit the coronavirus. Not until October was that agency confident that airborne spread was occurring. Complicating the messaging was the fact that early in the pandemic, hospitals experiencing a surge in COVID patients had too few masks to protect their doctors and nurses. Until mask production could be ramped up, there was a need to reserve the N95 respirators and surgical masks for health-care workers and first responders. Fauci made that point as well.

In context, what he told Jon LaPook of *60 Minutes* on March 8, 2020, was:

"The masks are important for someone who's

ALEX WONG Getty Images

infected to prevent them from infecting someone else.... Right now in the United States, people should not be walking around with masks.... [W]hen you think masks, you should think of health-care providers needing them and people who are ill.... I'm not against it [mask wearing]. If you want to do it, that's fine."

LaPook: "But it can lead to a [mask shortage]?"

Fauci: "Exactly, that's the point. It could lead to a shortage of masks for the people who really need it."

SKEPTICS of mask wearing have misled people by using out-of-context quotations by Anthony Fauci.

So when someone in your social circle says that the director of the National Institute of Allergy and Infectious Diseases should not be trusted because he once said, "people should not be walking around with masks," remind them that, as FactCheck.org has pointed out, when he made that recommendation he was referring to people who weren't infected, and at the time scientists had not yet confirmed that asymptomatic transmission was happening or that the virus was airborne.

Another reason to bookmark the CDC site is that it provides accurate content, context and caveats. When it comes to facial coverings, the CDC says: "Masks are a simple barrier to help prevent your respiratory droplets from reaching others. Studies show that masks reduce the spray of droplets when worn over the nose and mouth." Note the words "help" and "reduce." If a person knows that when scientists say "masks work" they are saying that masks "help prevent" and "reduce" viral spread, they will be less likely to mistakenly conclude that a mask wearer getting infected means that masks do nothing.

Caveats also matter when it comes to vaccination. Rather than categorically declaring that the Pfizer COVID-19 vaccine is safe, the CDC instead reports that the "data [about the FDA-authorized Pfizer-BioNTech COVID-19 vaccine] demonstrate that the known and potential benefits of this vaccine outweigh the known and potential harms of becoming infected with the coronavirus disease 2019 (COVID19)." A small risk: a few of the multitudes being vaccinated have experienced what the CDC characterizes as a severe allergic reaction—that is, one that is treated with epinephrine or an EpiPen onsite or that requires hospitalization. A major benefit: taking two doses of the Pfizer or Moderna vaccine dramatically reduces the chances that the name of the vaccinated person will be added to the list of half a million Americans whose lives have been cut short by COVID-19.

3

Set Norms by Modeling Good Behavior

For decades before COVID-19 upended our lives, public health officials, school nurses, family physicians and our parents reminded us that to minimize contagion during cold and flu season, we should frequently wash our hands and stay away from others when coughing or sniffling. Because social norms powerfully shape what we do and because we saw evidence in our lives that these practices reduced transmission of colds and the seasonal flu, we and our families and friends practiced and preached them. As a result of that combination of knowledge and norms, our survey early last March found that even before ubiquitous health messages urged us to do so, almost nine in 10 in the U.S. (87 percent) had responded to word of a new respiratory virus by increasing hand hygiene and keeping a distance from those with respiratory symptoms.

The lesson: By reinforcing and modeling a behavior

such as mask wearing, science champions can make it a norm in their social circles. We should also remind ourselves that overwhelming numbers do believe in masking up. A poll that the Kaiser Family Foundation conducted last December found that about three in four U.S. adults report doing so every time they leave home.

4

Depoliticize the Science

As psychological reactance theory predicts, injunctions are more likely to elicit counterargument than acceptance; as the proverb tells us, you catch more flies with honey than with vinegar. An effective science defender will listen to a person's reasons for not masking or vaccinating and share counterevidence without questioning their competence, good will or intelligence.

"The Battle Between The Masked And The Masked-Nots Unveils Political Rifts," an NPR headline noted last May. Because mask avoidance has for some become a sign of commitment to conservative politics, the artful science advocate will marshal instances in which those of like ideological bent have championed the behavior, as former senate majority leader Mitch McConnell of Kentucky did in 2020 and as former New Jersey governor Chris Christie did in an op-ed in the *Wall Street Journal,* explaining how getting infected with COVID-19 led him to conclude, as the headline said, "I Should Have Worn a Mask." Conversion narratives like Christie's or, on the vaccination front, like that of physician Eugenia South ("I'm a Black doctor who didn't trust the Covid vaccine. Here's what changed my mind") can be powerful. My co-authors and I saw that power in action in our study of how people reacted to environmental activist Mark Lynas's explanation of why he once opposed but now favors genetically modified crops. The people exposed to his conversion account were significantly more likely to change their attitudes about genetically modified crops than those who were presented only with his arguments about their benefits.

If it's about taking care of the community, even doubters might decide to take preventive measures.

5

Consider before You "Like"

When we click a "like" button on social media, we signal that the content is both acceptable and accepted. By sharing, we invest it with our credibility. Not only do the thumbs-up icon and the retweet symbol serve as signals of community approval, but they also invite our friends to join us in reinforcing the sentiments of our in-group. This process of signaling agreement is agnostic about whether it is used to spread science or viral deception (VD).

In a fashion analogous to that of the original VD, venereal disease, viral deception is contagious and socially transmitted. So, as the editors of *Scientific American* recommended in September 2019, "Before you click 'like,' hit 'pause.' " If the message is VD, quarantine it. If the science comes from a reliable source and is consistent with what you see on the Web sites of the CDC or the National Institutes of Health, give it a boost by clicking "send," "like" and "share."

6

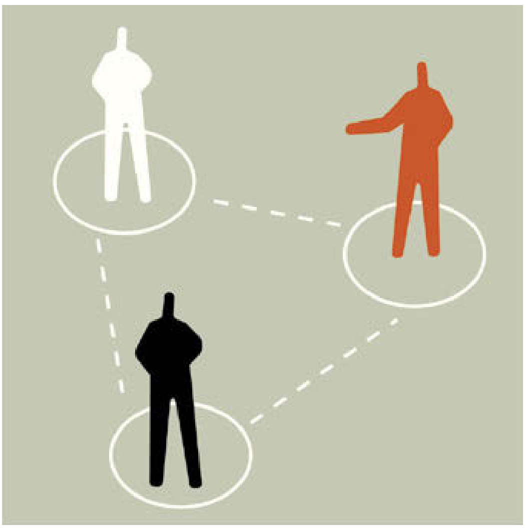
Set Realistic Goals

One of the things that my colleague Joe Cappella and I found in our decade-long study of talk radio was that faithful listeners adopted the arguments and idioms of the hosts who served as their daytime companions. In addition to schooling the members of his audience in ways to support conservatism, the late talk show host Rush Limbaugh reduced their susceptibility to arguments incompatible with that philosophy. His success suggests that a talk show host whose audience is hesitant about protective behaviors or immunization could increase the disposition and capacities of at least some people by using the principles of the science defense system. So, too, could a family member.

Yet no amount of evidence or level of persuasive appeal will sway some people on some topics. For them,

information will inevitably be contorted to conform to the demands of group identity. Rather than trying to convince people whose minds are closed, time is better spent focusing on persuading those who are reluctant but not opposed to engaging in preventive behaviors.

That said, people who are undecided about a health behavior may be more receptive to new information than scholars once thought. A study published last year in *Nature* upended the assumption that those who are undecided about vaccination are disengaged. On the contrary, these people searched Facebook for information. The problem is they were more likely to reach antivaccination than provaccination pages.



7

Make It about Protecting Your Neighbors

People engaged in defending science in their communities can convey its messages in concrete, local contexts with clear, immediate impact—protecting neighborhood kids, teachers, relatives in assisted living facilities, friends who work at the local hospital or the town pharmacy. If it's a matter of taking care of the community, even doubters might decide to take preventive measures.

A case in point is Gary Abernathy of Hillsboro, Ohio, who, in a July 2020 *Washington Post* piece entitled "I'm Not So Sure on Masks. But Here's Why I Wear One," reported that he cared "about the peace of mind of my neighbors who hold different attitudes." At the same time, he reported that he knew that "the Centers for Disease Control and Prevention reported that 'fear and anxiety about a new disease ... can be overwhelming and cause strong emotions in adults and children.' " Additionally, he acknowledged the CDC argument that "directives meant to protect people, like social distancing, 'can make people feel isolated and lonely and can increase stress and anxiety.' " That combination of knowledge, understanding and empathy led him to adopt a community norm despite his doubts about the need. "[T]hat's why," he explained, "whether required or not, and no matter how distant I am from a COVID-19 hot spot, I've been donning a mask when I walk into a busy store where most people are wearing one." Abernathy's decisions to mask up last summer and to articulate a rationale for other doubters to do the same qualify him as part of his community's science defense system. And as Dolores Albarracin and Robert Wyer showed in a 2001 study, doubts aside, engaging in a helpful behavior is likely to increase one's belief in its value.

8

Aim for Community Immunity

Wrapping a science defense shield around the concentric circles in which we live—our homes; our neighborhoods; the places where we come in contact with others from our community, such as the grocery store, our child's school, the dentist's office—is particularly important for encouraging immunization against COVID-19. It is immunity within our community—not at the national or state level—that protects us and our families.

When scientists talk about an immunity threshold—that percentage of the population that needs immunity to prevent spread—they are talking about the level required to protect a community. If a high percentage of people statewide are vaccinated against measles, but that number is low in a specific community within that state, then people living in that place are vulnerable. This was the case in the Somali-American community in Minnesota in 2017, where at the time of a measles outbreak, in one county just 36 percent of Minnesota-born Somali children had been vaccinated against the disease. Instead of thinking of herd immunity, we should dedicate ourselves to achieving immunity within our communities from COVID-19, from measles, from flu—and from viral deception.

By relying on trustworthy sources of scientific information, working from an understanding of how science works, modeling behaviors that prevent the spread of both the coronavirus and viral deception, being realistic about the powers and limits of persuasion, and, where possible, depoliticizing the science, we can play our part in our community's science defense system. Doing so will increase the chances that others in our circles will adopt COVID-fighting behaviors and urge those in their social spheres to do the same.

FROM OUR ARCHIVES

Reestablishing Reality. Jen Schwartz; February 2021.

scientificamerican.com/magazine/sa

Michael B. Habib is a paleontologist and biomechanist at the Natural History Museum of Los Angeles County. He studies the anatomy and motion of pterosaurs, birds and feathered dinosaurs.

Terryl Whitlatch is an illustrator who specializes in animal anatomy, paleontological reconstruction and the design of imaginary creatures. She has designed characters in the *Star Wars* movies, among many other films.

BIOMECHANICS

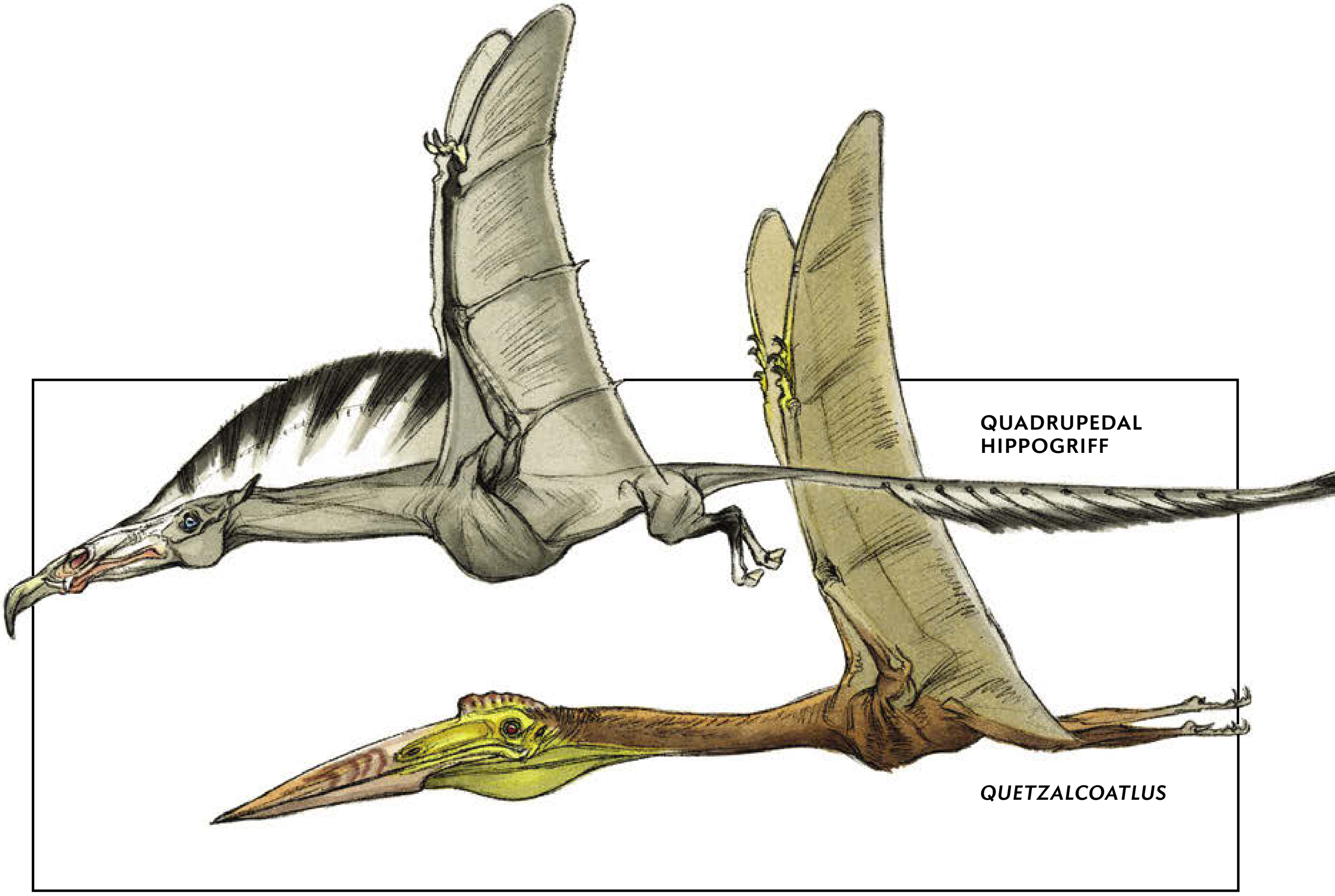
Flights of Fancy

A paleontologist and an illustrator make mythical creatures follow biomechanical rules

By Michael B. Habib and Terryl Whitlatch

Fantastic creatures appear in myths and legends from cultures around the world. These beings take many forms. Some of them run, slither, swim or burrow. Many of them fly. As a paleontologist who studies fossil birds and pterosaurs (Habib) and an illustrator who designs creatures for books and films (Whitlatch), we are especially interested in the biomechanics of flight and how to portray flying beasts believably. We recently teamed up to produce a book on this topic called *Flying Monsters: Illustrating Flying Vertebrates* (to be published in 2021 by Design Studio Press), which covers both real and imaginary animals. In the pages that follow, we riff on three fanciful creatures depicted in the book and explain the science that lifts them up while grounding them in reality.

Illustrations by Terryl Whitlatch



REMAKING A CLASSIC: Flying Horses

Flying horses abound in myths and stories. The most famous is probably Pegasus, the winged horse of Greek legend that sprang from the blood of the snake-haired monster Medusa when the hero Perseus beheaded her. Somewhat lesser known is the hippogriff, a part-equine, part-avian predator capable of galloping on the ground like a horse and then launching into the air to fly like an eagle.

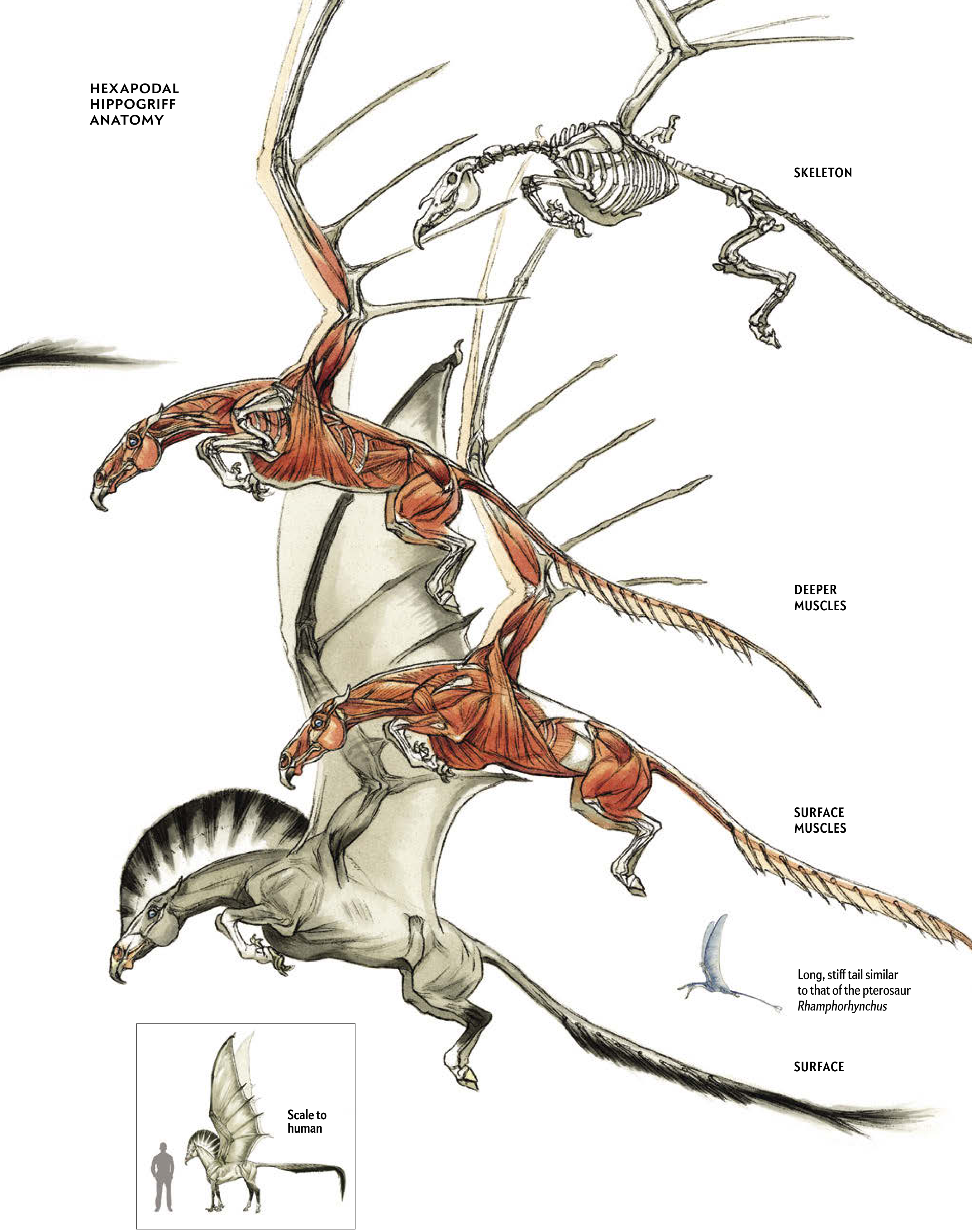
We reimagined the classic hippogriff as a blend of horse and pterosaur. This mix would enable the animal to take flight at horse size. Several factors appear to have been instrumental in allowing giant pterosaurs such as *Quetzalcoatlus, Cryodrakon* and *Hatzegopteryx* to attain their great sizes while maintaining the ability to fly: their bones were light for their strength, their wings were formed by a membrane of muscle and skin rather than by comparatively heavy feathers, and they probably used both their folded wings and their hind limbs to push off from the ground and launch themselves into the air—a much more powerful leap than one executed by the hind limbs alone. Like these pterosaurs, our hippogriff (really a hippoptero) can use its wings as leaping limbs to execute takeoff.

This launch style works for both a quadrupedal winged horse in which the forelimbs double as wings and a hexapodal one in which the wings are a third pair of limbs. In the latter case, the wings push against the ground in a more extended position in tandem with the four running limbs. The two configurations have different considerations: building a flight-capable hexapod requires stacking the shoulder blades, whereas the quadruped requires a complete rebuild of the shoulder because real horses cannot lift their forelimbs out to the sides, much less over their back.

Placing the wings in contact with the ground for takeoff to make the wing muscles do double duty is the most realistic way to get a horse-size fantasy creature into the air. With muscle physiology and bone strength typical of vertebrate animals and with a vaguely pterosaurlike quadrupedal build, 800 pounds is probably about the maximum such a creature could weigh while still being able to fly. If the flying horse had lots of air spaces in its bones, as the giant pterosaurs did (and as many birds do today), then it could weigh less than 800 pounds and still bear a full-size horse exterior. Alternatively, adding bigger muscles or longer limbs for leaping than giant pterosaurs possessed could raise the size limit. With the right anatomy, even a 1,200-pound winged horse could fly.

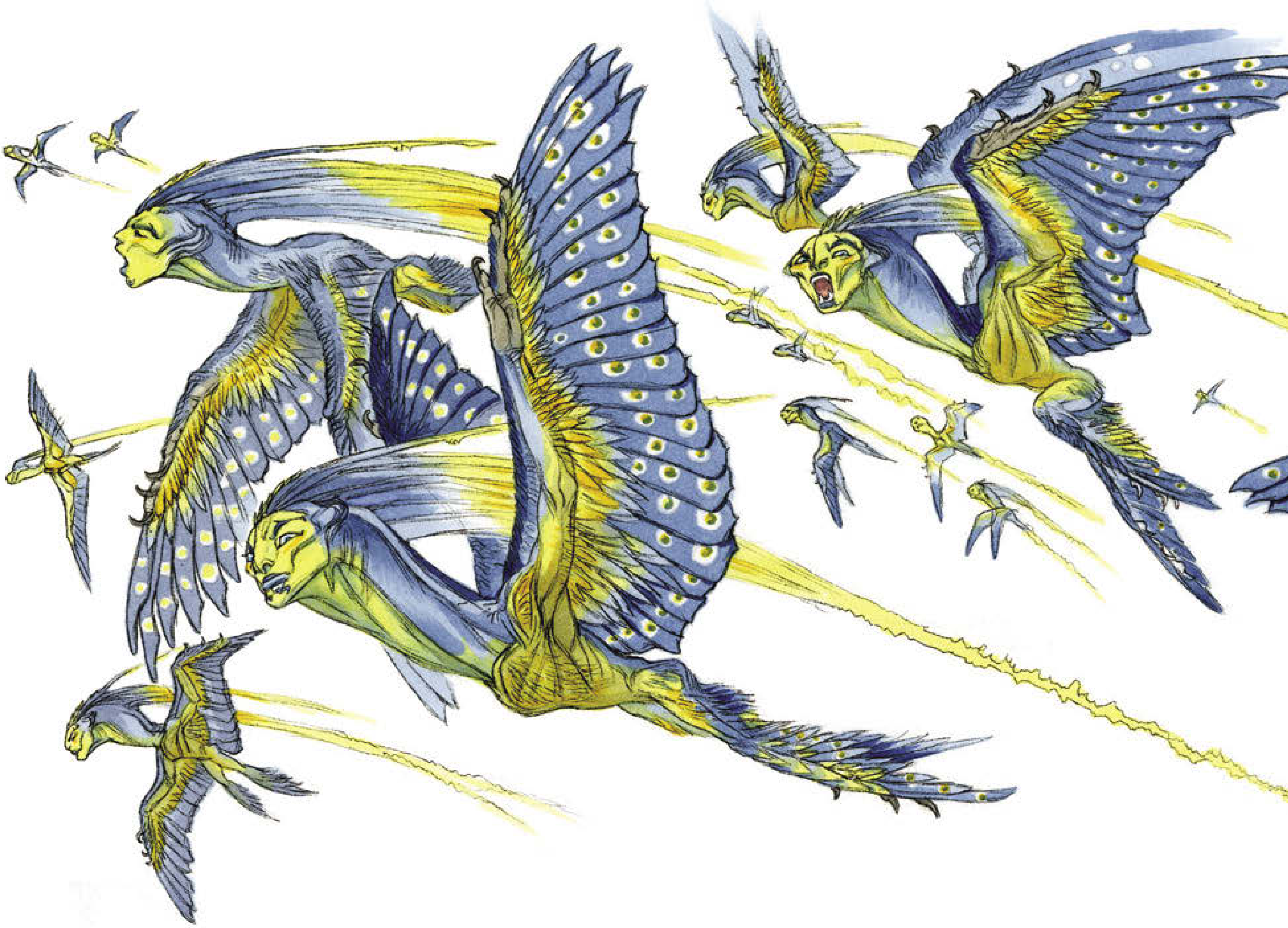
In our hippogriff, the muscles of the back drive the upstroke, and the muscles of the chest power the downstroke, just as in living bats and long-extinct pterosaurs. Birds, in contrast, have both sets of muscles in the chest. With a batlike or pterosaurlike arrangement of the flight muscles, the chest could be a reasonable size. With a birdlike arrangement, in contrast, the chest would have to be so large as to be ungainly. The bat or pterosaur condition is also a more realistic option for the hexapodal body plan, in which the stacked shoulder blades make a birdlike musculature impossible.

HEXAPODAL HIPPOGRIFF ANATOMY



Long, stiff tail similar to that of the pterosaur *Rhamphorhynchus*

Scale to human



DEPICTING THE METAPHYSICAL: Angels of the Bible

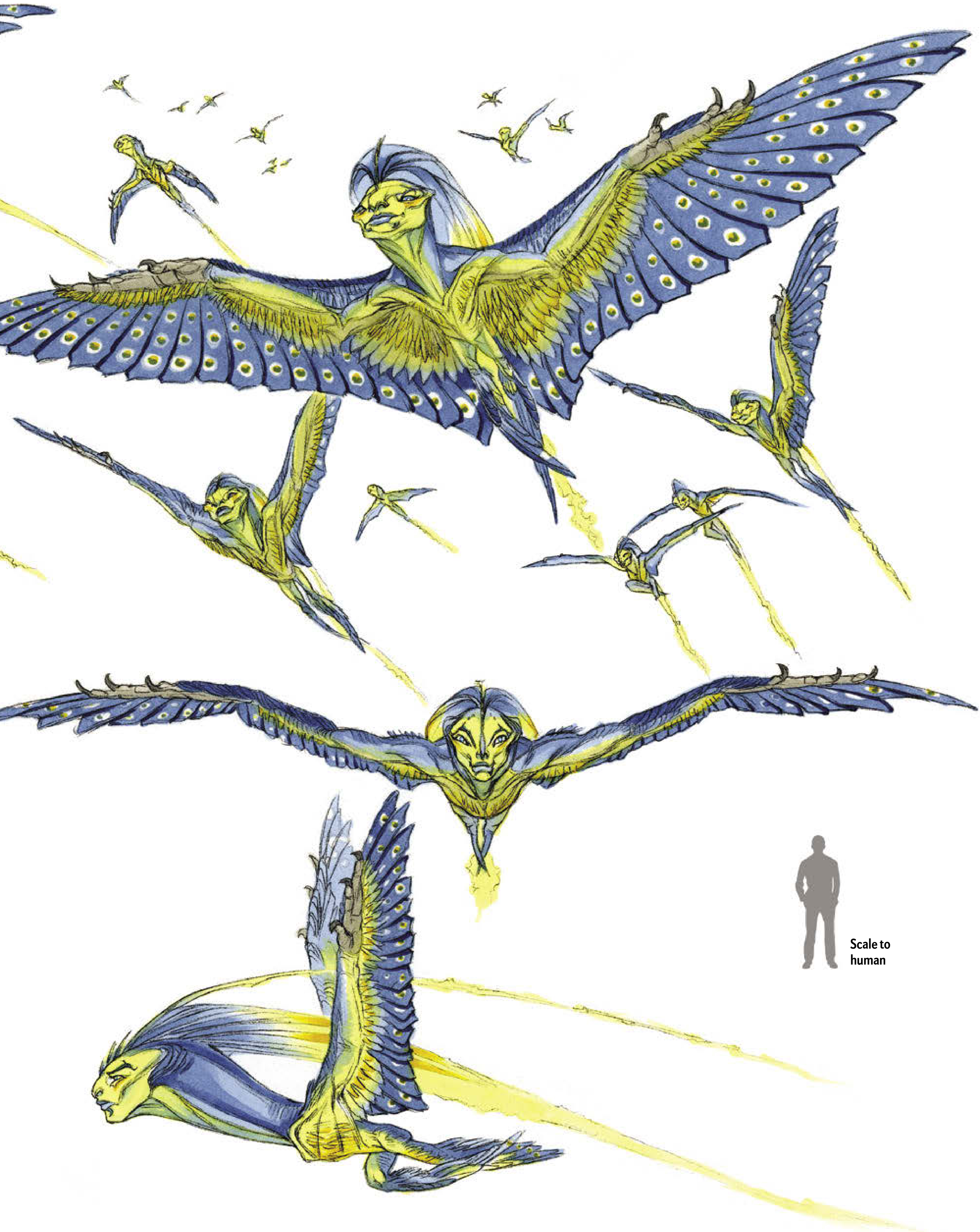
Despite their centrality in Judeo-Christian stories, art and traditions, angels are rarely described in any physical detail in surviving religious texts. In modern interpretations, these heavenly beings are often shown as humans with wings, but the few written descriptions of angels in the Bible suggest much more complex forms: many are described as terrifying to behold, and any human being who encountered them is said to have been overwhelmed by fear. Two books of the Bible—Revelation and Ezekiel—contain the most detailed physical descriptions. Both seem to depict the same four angels, sometimes referred to as the Four Living Creatures.

The descriptions in the two texts agree on some details, but they differ in notable respects. In Revelation, these powerful angels are portrayed as resembling a lion, an ox, a man and an eagle. According to Ezekiel, in contrast, only their faces resemble these creatures. Revelation's angels have three pairs of wings; Ezekiel's have two pairs that are covered with eyes, and their flight is described as "hovering," with abundant thunder, lightning and electrical plasma surrounding the angels as they flutter around the throne of God.

A prominent early interpretation, popularized by third-century bishop and Christian martyr Victorinus of Pettau, equated the four creatures with the Four Evangelists. In this understanding, the lion represents Mark, the ox represents Luke, the eagle represents John, and the man represents Matthew.

We depict Matthew, mostly as described in Ezekiel, though, with a single face as in Revelation (Ezekiel gives each angel four faces). And we dipped into the fossil record for real-world inspiration. For the body plan, we looked to *Microraptor,* a flying dinosaur that had four wings. Recent studies have concluded that *Microraptor* and its relatives probably flew by flapping their forewings and holding their hind wings under the body to help with stability and maneuverability. Accordingly, our Matthew has flapping, propulsive forewings, and he holds his hind wings vertically.

For the overall proportions, we turned to the largest airborne animals known: giant azhdarchid pterosaurs. These flying reptiles included animals such as *Quetzalcoatlus* and *Cryodrakon,* both of which grew to hundreds of pounds in weight and had wingspans in excess of 30 feet. These huge pterosaurs were oddly "front-loaded" animals, with massive heads, necks, chests and arms. Our rendering of Matthew features a humanlike (but distinctly alien) head atop a massive, *Cryodrakon*-style neck. An expanded chest accommodates large flight muscles, and a corresponding forward sweep of the wings aligns the center of lift with the center of mass. The resulting creature is at once magnificent and terrifying—and biomechanically feasible.


Scale to
human

FLYING WITHOUT WINGS: Dragons of Asia

Asian dragons, particularly those of Chinese, Vietnamese and Japanese mythology, are challenging to represent in an anatomically believable way because these creatures are consistently shown flying without wings. They typically have a serpentine body plan, but they are not associated with snakes in traditional lore. Instead these dragons are often described as having features in common with both mammals and fish, especially carp, and they are associated with rivers, rain, lightning and storms.

To find good models from the real world to work with, we turned to living animals that fly without wings. Gliding snakes of the genus *Chrysopelea* do it beautifully, flying tens of feet at a time without any limbs at all. They perform a series of S curves and twisting motions in the air while gliding, which nicely approximates the winding paths flying dragons are often shown taking in traditional Chinese and Japanese art. (Dragon dancers in China work in teams of nine or more individuals to move a dragon on poles in flowing, curving patterns.) *Chrysopelea* also hails exclusively from Southeast Asia, which makes it a regionally appropriate group of snakes on which to model our dragon. Like *Chrysopelea* snakes, our anatomically plausible Asian dragon creates its primary flight surface by flattening its body and forming S curves in the air. To help account for the large size of the dragon, we have added some additional "webbing" along the body and limbs to enlarge the flight surface.

We looked to other unusual serpents from the real world, including the Malagasy leaf-nosed snake (genus *Langaha*), to develop the "whiskers" that are depicted on dragons in traditional art. These snakes have a long, flexible appendage projecting from their snout. By taking such a projection and splitting it, we have created a set of whiskerlike structures for our dragon. Asian vine snakes (genus *Ahaetulla*) inspired its narrow face, horizontal pupils and ridges over its eyes.

This dragon is associated with forest streams. It can swim, climb and glide, making it a fearsome and adaptable predator. All of the snakes we referred to for this build specialize in hunting lizards. Their fangs are located toward the back of the jaw, and their venom paralyzes other reptiles. In fact, the most important predators of lizards and snakes in many regions are other lizards and snakes. With that in mind, we have imagined that the greatest threat to young Western dragons (which is to say dragons with wings) is other dragons—specifically, serpentine, wingless ones from the East. Our use of biological inspiration has thus helped us fill in an entire ecology for our dragon. By considering the relations between form and function in real animals, we can imagine a creature of myth in a new light, in terms of both anatomy and behavior.

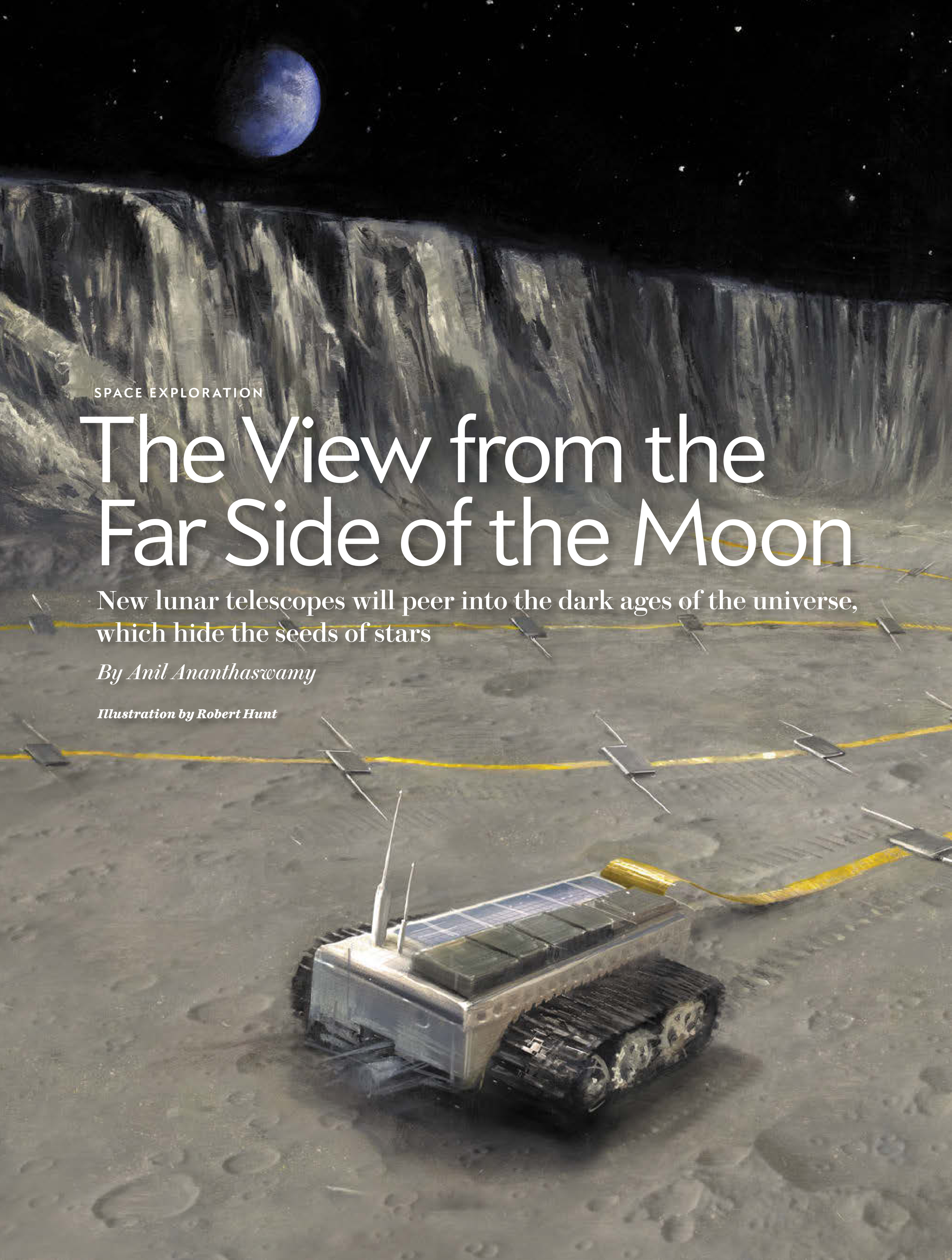
FROM OUR ARCHIVES

Monsters of the Mesozoic Skies. Michael B. Habib; October 2019.

scientificamerican.com/magazine/sa

Detail of Asian dragon head

Size comparisons to hippogriff, human and Western dragon



SPACE EXPLORATION

The View from the Far Side of the Moon

New lunar telescopes will peer into the dark ages of the universe, which hide the seeds of stars

By Anil Ananthaswamy

Illustration by Robert Hunt

RADIO TELESCOPE on the moon's far side (*shown in an artist's depiction*) could detect signals from early hydrogen clouds.

Anil Ananthaswamy is author of *The Edge of Physics, The Man Who Wasn't There* and, most recently, *Through Two Doors at Once: The Elegant Experiment That Captures the Enigma of Our Quantum Reality.*

THE FAR SIDE OF THE MOON IS A STRANGE AND WILD REGION, QUITE DIFFERENT FROM THE FAMILIAR and mostly smooth face we see nightly from our planet. In 1959 the Soviet Luna 3 space probe took the first photographs of this hidden region. Instead of wide plains, the images showed a moonscape spiked with mountains. Observations since then have shown that the far side is also full of rugged craters, and within them there are yet more craters. Soon this rough terrain and the space just above it will have even stranger features: it will be teeming with radio telescopes, deployed by a new generation of robotic rovers and lunar orbiters.

Astronomers are planning to make the moon's distant side our newest and best window on the cosmic dark ages, a mysterious era hiding early imprints of stars and galaxies. Our universe was not always filled with these bright objects that shine across today's skies. About 380,000 years after the big bang, the universe cooled, and the first atoms of hydrogen formed. Gigantic clouds of this element soon filled the cosmos. But for a few hundred million years, everything remained dark, devoid of stars. Then came the cosmic dawn: the first stars flickered, galaxies swirled into existence and slowly the universe's large-scale structure took shape.

The seeds of this structure must have been present in the dark-age hydrogen clouds, but the era has been impossible to probe using optical telescopes—there was no light. And although this hydrogen produced long-wavelength (or low-frequency) radio emissions, radio telescopes on Earth have found it nearly impossible to detect them. Our atmosphere either blocks or disturbs these faint signals; those that get through are swamped by humanity's radio noise.

Scientists have dreamed for decades of studying the cosmic dark ages from the moon's far side, shielded from earthly transmissions and untroubled by any significant atmosphere to impede cosmic views. Now multiple space agencies plan lunar missions carrying radio-wave-detecting instruments—some within the next three years—and astronomers' dreams are set to become reality.

"If I were to design an ideal place to do low-frequency radio astronomy, I would have to build the moon," says astrophysicist Jack Burns of the University of Colorado Boulder. "We are just now finally getting to the place where we're actually going to be putting these telescopes down on the moon in the next few years."

THE HYDROGEN HEARTBEAT

THE IDEA THAT TELESCOPES could detect neutral hydrogen goes back to the 1940s, when Dutch astronomer Hendrik Christoffel van de Hulst predicted that hydrogen atoms can spontaneously emit pulses of electromagnetic radiation. This happens because each atom of hydrogen can flip between two energy states, emitting or absorbing radiation at a wavelength of 21 centimeters (or a frequency of 1,420 megahertz). Such emissions are the "heartbeat" of hydrogen and can add up to detectable signals when clouds of the gas accumulate on cosmic scales.

Such signals should have first emerged about 380,000 years after the big bang, when the universe cooled enough for protons and electrons that previously filled space to coalesce into atoms of hydrogen. Besides forming the raw material from which all subsequent objects would arise, this event had the added benefit of making the universe transparent rather than opaque, liberating the fossil radiation produced by the big bang to stream through the cosmos. We now see this radiation—the big bang's afterglow—as the cosmic microwave background (CMB). Thereafter, neutral hydrogen pervaded the dark universe for perhaps the first few hundred million years, until the break of cosmic dawn, when the first stars and galaxies began to shine.

Cosmologists are particularly interested in the dark ages because they offer a glimpse of the universe when it was relatively pristine, free of confounding astrophysical effects. Back then, the distribution of neutral hydrogen still carried the imprints of primordial quantum fluctuations that had been profoundly magnified by the universe's rapid expansion in the first fractions of a second of its history—unsullied by the emergence of stars, galaxies and galaxy clusters. It is possible that the 21-centimeter signals from the dark ages could carry indications of new physics or deviations from the standard model of cosmology. "It's a playground for testing cosmology," Burns says.

The first radio telescopes on and above the far side of the moon will be simple. They will gather hints of this shadowy slice of otherwise unseen cosmic time. As more sophisticated instrumentation comes online, the 21-cm signals will emerge in richer detail, allowing astronomers to create dynamic, high-resolution maps of hydrogen clouds.

"The nice thing about neutral hydrogen is that it's not just a snapshot in time like the CMB," says Kristian Zarb Adami of the

University of Oxford. By tracking the fluctuating 21-cm signal over cosmic time, telescopes can chart the evolution of the early universe through the dark ages all the way up to the cosmic dawn and even beyond. After the dawn came the epoch of reionization, when the radiation from the first massive stars and other violent astrophysical phenomena sufficiently reheated the remaining neutral hydrogen to transform it back to plasma. That epoch ultimately extinguished the 21-cm signals.

FAR-SIDE PIONEERS

SOME PATHFINDER INSTRUMENTS are already in operation. They are part of China's Chang'e-4 lander on the moon's far side, as well as a lunar orbiter named Queqiao ("Magpie Bridge"), which relays signals from the lander to Earth. Queqiao was launched in May 2018, and Chang'e-4 reached the lunar surface in January 2019. "This was the first time there was a soft landing on the far side of the moon," says Bernard Foing, executive director of the International Lunar Exploration Working Group and a planetary scientist at VU Amsterdam. "It was a great success."

Both Chang'e-4 and Queqiao carried radio antennas. But those on Queqiao, built in collaboration with Dutch scientists, did not extend completely, and Chang'e-4's single antenna is hindered by radio-frequency interference (RFI) coming from the lander's electronics. Future dark-age-surveying lunar spacecraft could include additional shielding to minimize RFI. They could also deploy multiple antennas across tens or hundreds of kilometers of lunar soil.

The next preparatory phase for far-side astronomy is set to begin with the launch of ROLSES (Radiowave Observations at the Lunar Surface of the photoElectron Sheath) this October. ROLSES will travel to the moon within a privately developed lander licensed by NASA as part of the space agency's Commercial Lunar Payload Services program. Although it will touch down in the Oceanus Procellarum region on the moon's near side, ROLSES's task of characterizing the RFI generated by lunar soil is crucial for future work identifying other radio signals on the far side. "This is real," says Burns, who is a member of the ROLSES team. "I have been working on this for 35 years. It's actually happening."

Another mission to characterize the radio-frequency interference on the moon—the Lunar Surface Electromagnetics Experiment (LuSEE)—is slated to launch as early as 2024. "LuSEE is going to the far side," Burns says. "It's going to go to the Schrödinger impact basin." The lander carrying LuSEE may also have another payload: DAPPER (Dark Ages Polarimeter Pathfinder), a telescope for detecting the 21-cm signal from the cosmic dark ages. "DAPPER was originally designed to be an orbiter around the moon, but it may go on this lander," Burns says. "NASA has funded us to work on the mission concept for DAPPER. We'll be ready to go."

Whether in orbit or on the lunar surface, DAPPER will be limited to a set of dipole antennas in one location. But astronomers have more ambitious plans for deploying arrays of antennas on the moon. These arrays, which combine signals from individual antennas spread over large distances, act as telescopes with resolutions far greater than would be possible with a single antenna and can effectively pinpoint sources in the sky.

THE ERA OF ARRAYS

XUELEI CHEN of the National Astronomical Observatories at the Chinese Academy of Sciences thinks lunar orbit is the best near-term site for creating dark-age-mapping lunar arrays. Antennas on a number of satellites could be configured into an array that carries out observations when the satellites are all on the far side. "This is a small experiment with moderate cost, and we could accomplish it with current technology," Chen says.

The tentative plan calls for a fleet of five to eight satellites flying in carefully choreographed formation to form an array. One of the satellites would be a larger mother ship that would host most of the electronics for receiving and combining the signals from other satellites and then relaying the results to Earth. "We want to have them launched as an assemblage, and then they will be released one by one," Chen says.

Putting such an array on the far side's surface will be far more challenging for many reasons, among them the moon's rugged terrain and the spacecraft-threatening chill of the 14-day-long lunar night. To begin preparing for this type of mission, Foing's team is planning to test the deployment of radio antennas using robotic rovers designed by the German Aerospace Center. The test will occur in June on the flanks of Mount Etna, an active volcano in Sicily meant as a proxy for the lunar surface. Scientists will control the rovers remotely; each rover will carry four boxes of antennas. "We will position them in different configurations to show that we will be able to do that in the future on the moon," Foing says.

Another way of deploying a radio array on the moon's far side would be to simply drop antennas from an orbiter to land and unfurl where they may. Adami and his colleagues are working on one such idea: a low-frequency interferometer, designed to precisely measure characteristics of radio emissions, that involves 128 fractal-like "mini stations." Each station has eight arms, and each arm combines 16 spiral antennas. "My idea would be that these fall off from the satellite and all land in different parts on the moon's surface," Adami says.

To minimize the number of moving parts, the team has figured out how to print these antennas as flat sheets that will take their final form after being rolled out on the lunar surface. "You could print antennas as fast as you print newspapers. We've been testing this technology for the past four or five years," Adami says. "We are in the process of prototyping these spiral antennas." The next step, he adds, is for the scientists to design a mini station and drop it from a drone in remote areas, such as an arid region of Western Australia, to see if it unfurls.

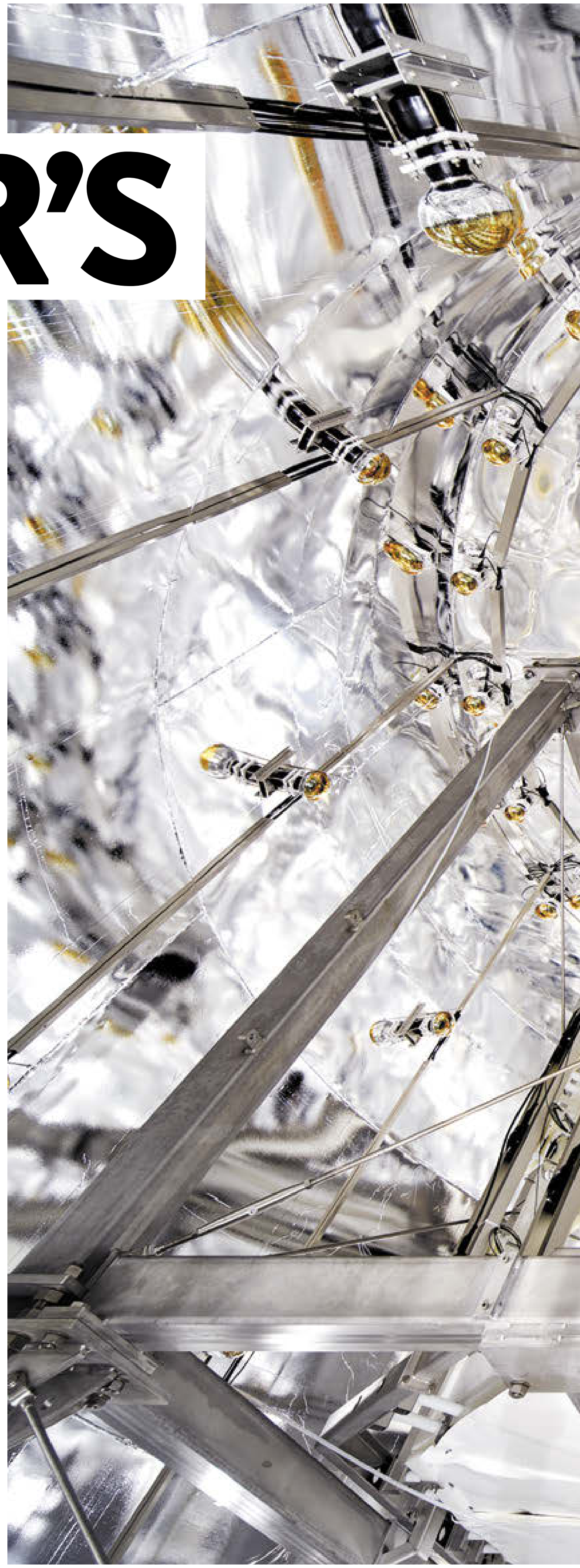
Meanwhile Burns is also leading a NASA-funded concept study for building another lunar radio telescope, aptly called FARSIDE (Farside Array for Radio Science Investigations of the Dark ages and Exoplanets). To design FARSIDE, Burns and co-principal investigator Gregg Hallinan of the California Institute of Technology have teamed up with NASA's Jet Propulsion Laboratory. The scientists are looking to land a payload of four rovers and 256 antennas, totaling about 1.5 metric tons, using lunar landers funded by NASA. The rovers would deploy the antennas, spreading them in four flowerlike petals over a region that is 10 kilometers in diameter. "We can do this with current technology," Burns says. "So this all looks very plausible [for] later in the decade."

FROM OUR ARCHIVES

The Dark Ages of the Universe. Abraham Loeb; November 2006.

scientificamerican.com/magazine/sa

DARK MATTER'S LAST STAND



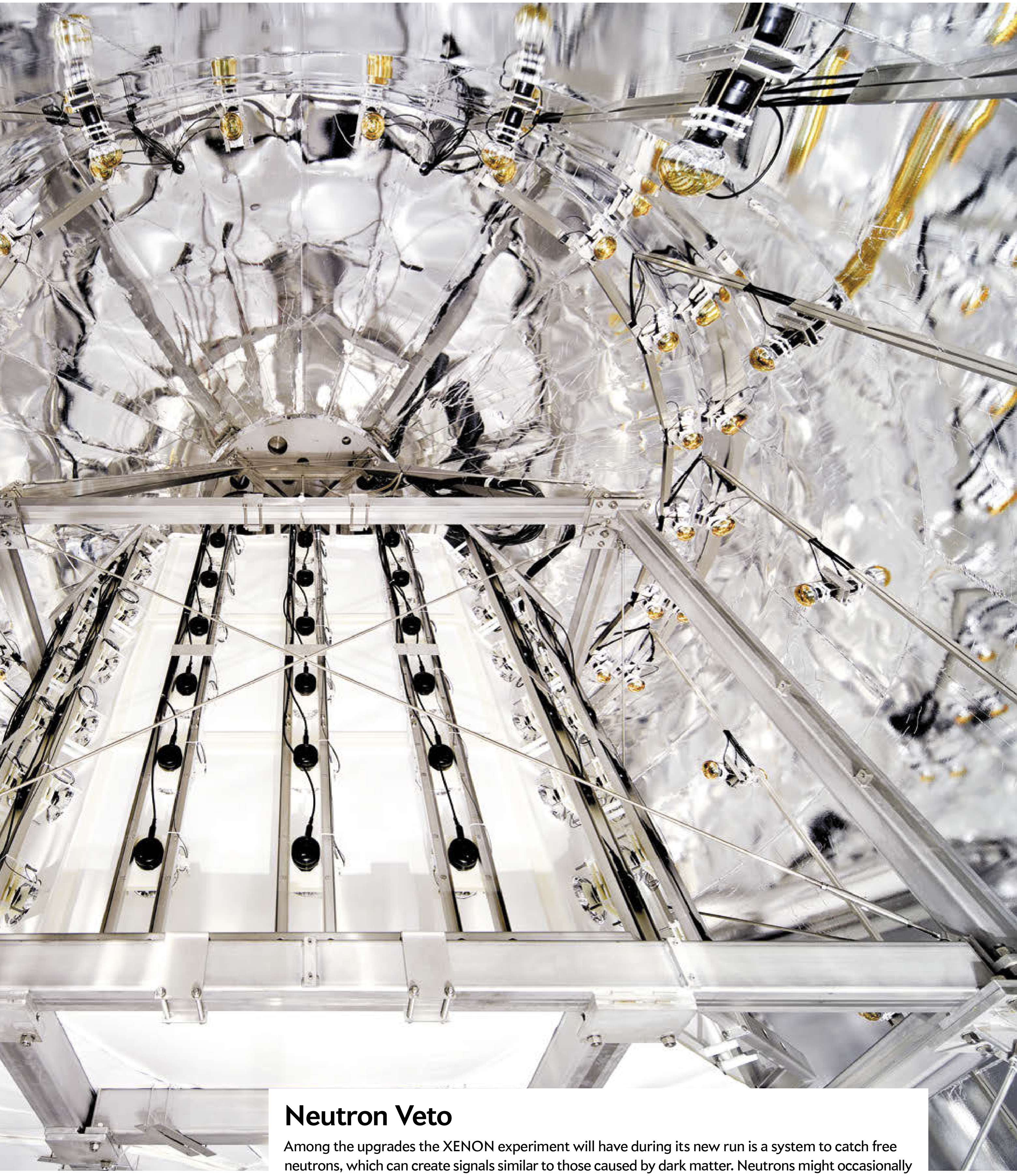
A new experiment could catch invisible particles that previous detectors have not

By Clara Moskowitz

Photographs by Enrico Sacchetti

SCIENTISTS ARE FOND of saying negative results are just as important as positive results, but after several decades of not finding something, researchers can be forgiven for feeling impatient. Back in the 1990s, experiments began trying to detect the particles that make up dark matter, the ubiquitous yet untouchable invisible material that apparently fills the cosmos. Since then, physicists have found more and more evidence that dark matter is real but not a single sign of the stuff itself. A new version of the long-running XENON experiment that started up late last year aims to finally break that pattern.

One of physicists' best guesses about the identity of dark matter has long been that it is made of particles called WIMPs—weakly interacting, massive particles. These elementary bits of matter could be anywhere between the mass of the proton and 1,000 times the mass of the proton, and they would interact with regular atoms only through gravity and the weak nuclear force, which governs radioactivity. But over the years, as experiment after experiment failed to find anything, some of the enthusiasm has faded. "You do start to scratch your head and think maybe that was the wrong horse to bet on," says Rafael Lang, a physicist at Purdue University, who has been working on the XENON experiment at the Gran Sasso



Neutron Veto

Among the upgrades the XENON experiment will have during its new run is a system to catch free neutrons, which can create signals similar to those caused by dark matter. Neutrons might occasionally be released by the stainless steel in the water tank surrounding the detector or by cosmic rays coming from space, causing a false detection. The octagonal neutron veto cage, studded with the backs of photomultiplier tubes that will detect any neutrons present, sits inside the water tank.

National Laboratory in Italy for more than a decade. For now, though, Lang says he is keeping his money on WIMPs, pointing out that the experiments have falsified many of the theories predicting what WIMPs might look like but certainly not all. "If you believed in WIMPs 10 years ago, only half of those WIMPs have been ruled out," he says. "The other half are still alive."

Of course, so are many other dark matter candidates. Another top contender is the axion, a much lighter theorized particle that has lately morphed into a fluid category of possibilities called axionlike particles. Some scientists are excited about the idea that dark matter may be a composite particle—a conglomerate of "dark quarks" and "dark gluons" that stick together just like regular quarks and gluons to create "dark nuclei." It is also possible that dark matter is not a particle at all. One idea still in the running is that the missing matter is made of primordial black holes that formed soon after the big bang.

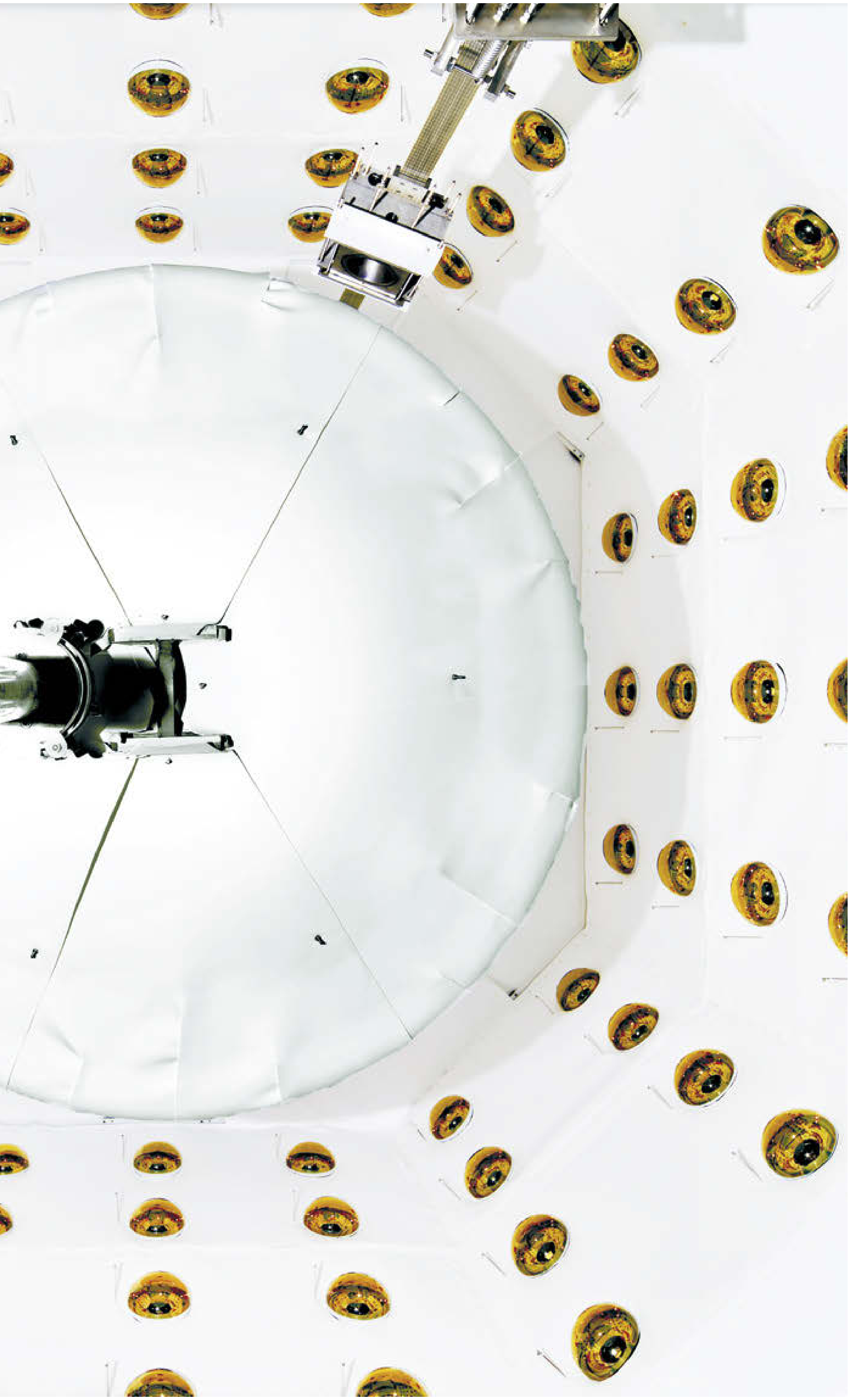
The newest version of the XENON experiment, XENONnT, began collecting data last year. Its goal is to catch dark particles on the very, very rare occasions when they might bump into regular atoms. The atoms in this case are xenon—8.3 metric tons of it, kept in liquid form in a giant vat buried under a mile of rock to shield it from cosmic rays and other contamination. Xenon, with its 54 protons and electrons and even more neutrons, is a good, dense target for dark matter to bump into. If an exotic particle were to hit a xenon nucleus, it might send the nucleus or an electron flying through the liquid, creating a flash of light that photomultipliers on the top and bottom of the vat can detect. This latest iteration of the experiment contains four times more xenon than the previous version, which means it is four times more likely to see a signal.

Other upgrades include improved purification of the xenon and better systems to detect cosmic rays and trace amounts of radioactive elements in the experiment and its housing that could masquerade as dark matter signals. "Every nut and bolt on the detector is custom handmade from carefully selected materials," Lang says, "because if you just buy a stainless-steel bolt at the hardware store, it's too radioactive for what we need."

To the outside world, the years of painstaking work without the reward of a discovery might seem disappointing, but physicists see it differently. "If you're judging by whether it has detected dark matter, they haven't, but in the eyes of the community it is a dramatically successful experiment," says theoretical physicist Dorota Grabowska of CERN, who is not part of the project. Its success, she says, lies in the many possibilities it has ruled out and the ever increasing sensitivities it has achieved.

Now the search for WIMPs stands at a turning point. In the relatively near future, underground dark matter experiments will have searched most of the theoretical landscape they can reach. If they have not found WIMPs, it may mean they do not exist, or it may simply mean they take some form that has managed to escape notice. But scientists are resourceful—they can think of new ideas for what dark matter might be and new ways to search for it faster than they can build detectors. "There is a lot of excitement and creativity around identifying new ways to detect dark matter candidates," says theoretical physicist Tongyan Lin of the University of California, San Diego. One idea she works on involves using crystals to catch dark particles. In crystal form, elements such as silicon might register an interaction with dark matter at lower energies than traditional detectors, opening up a new avenue for discovery.

Although dark matter has proved more elusive than some had initially hoped, physicists are far from giving up. "A lot of people have a view of science that is like *Star Trek,*" says theoretical physicist Tim Tait of the University of California, Irvine. "You see something and take out a tricorder and get an answer. But it's actually a very messy process, and you try lots of things until you find something that works. All the things that didn't work were an important part of the process." ■



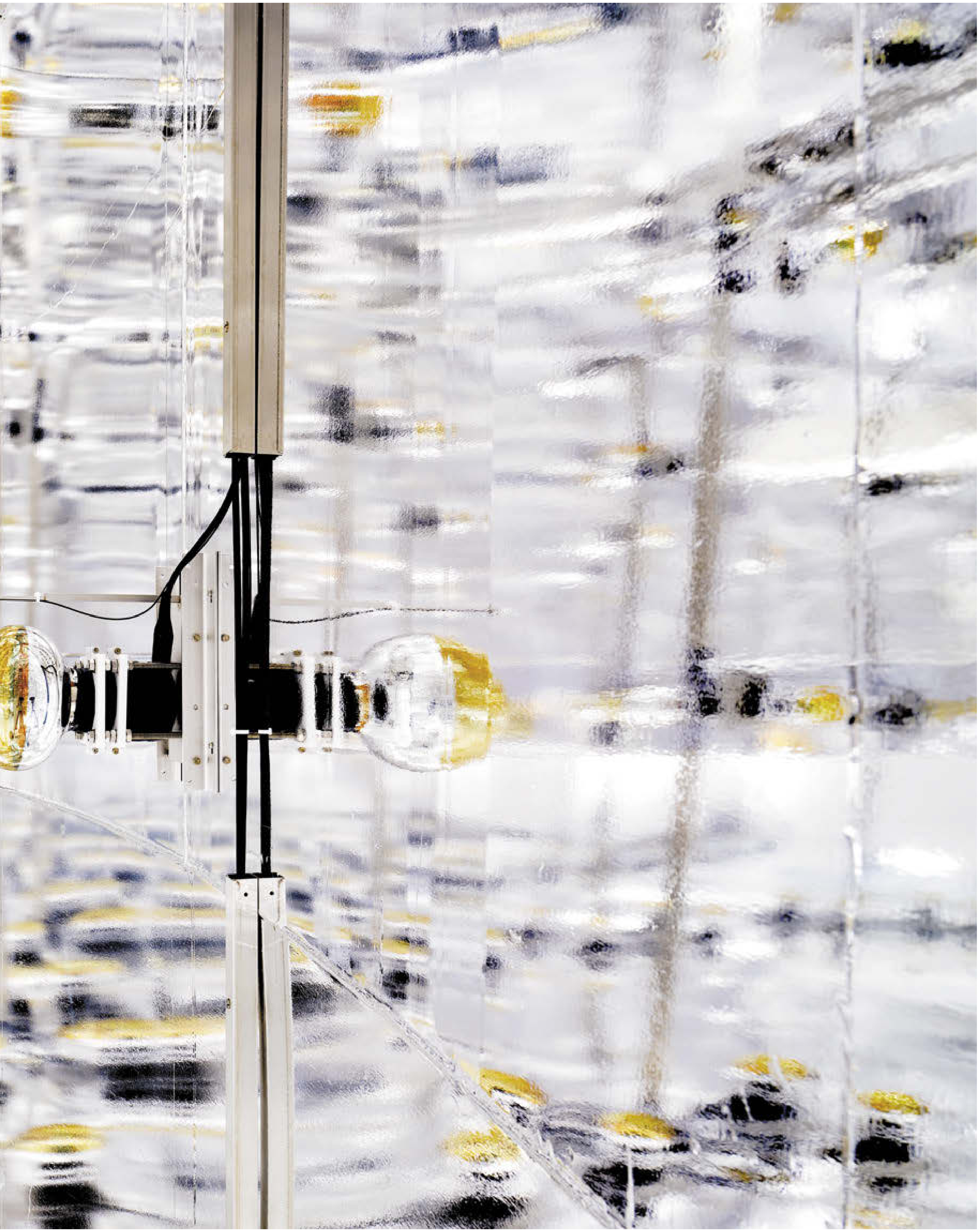
Clara Moskowitz
is a senior editor at
Scientific American,
where she covers
space and physics.

Onion Layers

The XENONnT experiment is structured like an onion, with multiple layers to keep out extraneous particles that might imitate dark matter. The first is the mountain on top of the underground Gran Sasso lab, which stops most cosmic rays from space that might contaminate the results. The next layer is a roughly 10-by-10-meter water tank that encircles the inner contents, blocking most of the particles that are released from radioactivity in the walls and rock surrounding the lab. In the tank is the neutron veto system, which will also be filled with water, shown here from the inside. Nestled within is a white cylindrical outer cryostat—essentially a thermos—that contains an inner cryostat. The inner cryostat surrounds the detector itself, which is filled with liquid xenon.

Mirror Image

Photomultiplier tubes line the water tank, which is covered in reflective foil that creates a double image. The optical instruments are sensitive enough to detect a single photon released by a particle interaction. In this case, the tube is designed to see the signals of muons, which may infiltrate the experiment as cosmic rays. Slightly different photomultiplier tubes line the neutron veto layer and the innermost detector.



Final Check

A technician makes a last sweep through the unfilled water tank. The XENONnT experiment will run for five years before reaching its design sensitivity. At that point, it will have either discovered WIMPs or ruled out more than two thirds of the theoretical WIMP possibilities still on the table. A similar experiment called the LUX-ZEPLIN (LZ) project is being carried out in South Dakota. The two use slightly different setups and will be important checks for each other if either sees a signal of new particles.

FROM OUR ARCHIVES

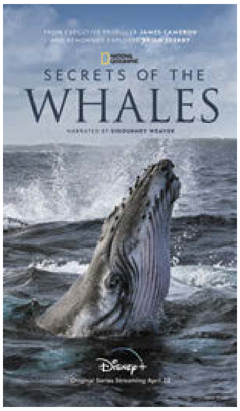
Black Holes from the Beginning of Time. Juan García-Bellido and Sébastien Clesse; July 2017.

scientificamerican.com/magazine/sa

By Andrea Gawrylewski

Secrets of the Whales

by Brian Skerry. Streaming on Disney+, starting April 22



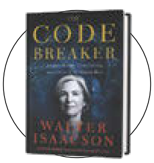
HUMPBACK WHALES are known for their long, complex songs, which carry for miles underwater. The purpose of their music remains a mystery.

Despite being warm-blooded, air-breathing mammals descended from land animals, whales give birth, nurse and raise their young entirely at sea. This sweeping four-part series takes a riveting view of these mysterious and mesmerizing ocean dwellers. Executive produced by James Cameron and narrated by Sigourney Weaver, the series' chief message is that whales are more than sea creatures: they have sophisticated communication, close-knit families and even culture. Photojournalist Skerry journeys alongside different whale species, capturing their specialized hunting tricks, idiosyncratic lingo shared within pods and the heartbreaking grief they carry for their dead. Facing not only the harsh daily travails of life in the deep, these majestic beasts must draw on their uncanny cleverness to adapt to the changing conditions of the open oceans and the planet.

The Code Breaker:

Jennifer Doudna, Gene Editing, and the Future of the Human Race

by Walter Isaacson. Simon & Schuster, 2021 ($35)



What started as a quest to understand how bacteria protect themselves from viruses turned into one of the biggest scientific discoveries of our time: CRISPR, a technique to alter DNA. Biographer Isaacson tells the story behind the breakthrough and profiles one of CRISPR's discoverers: University of California, Berkeley, biochemist Jennifer Doudna. He describes a scientist who revels in the beauty of nature and who also possesses a competitive streak that has helped her navigate the aggressive jockeying among researchers looking to capitalize on the finding. Isaacson expertly plumbs the moral ambiguity surrounding this new technology. "Figuring out if and when to edit our genes," he writes, "will be one of the most consequential questions of the twenty-first century." —*Clara Moskowitz*

Flash Forward:

An Illustrated Guide to Possible (and Not So Possible) Tomorrows

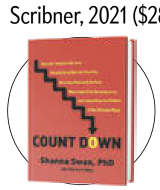
by Rose Eveleth. Abrams ComicArts, 2021 ($24.99)

In her popular podcast, writer and producer Eveleth examines futures for human (and nonhuman) life extrapolated from the latest science and technology. Here she adapts the concept to a new medium with the help of 12 eclectic guest artists. Each section of the book features a short comic set in a speculative future: a handheld device tabulates absolute truth, Venice is under the sea, or a pill removes the need for sleep, among a few examples. Specific details, such as work shifts that stretch to mind-numbing weeks in a society where sleeping is optional, make these vignettes both fascinating and unsettling. Afterward, Eveleth pulls the focus outward and brings scientific research to bear on the future's potential. The comics lend a hard-hitting depth to an otherwise abstract discussion. —*Sarah Lewin Frasier*

Count Down:

How Our Modern World Is Threatening Sperm Counts, Altering Male and Female Reproductive Development, and Imperiling the Future of the Human Race

by Shanna Swan, with Stacey Colino. Scribner, 2021 ($28)



Sperm counts have plummeted over 50 percent in the past 50 years. In a 2017 meta-analysis of counts for more than 40,000 people, epidemiologist Swan and her colleagues documented a dramatic decline among Western men. Here she and journalist Colino survey possible explanations—for example, chemicals such as BPA and PCBs that became prevalent in the 20th century. Their disruption of the endocrine system may be behind decreased sperm motility, lowered sperm concentration, and, potentially, earlier menstruation onset and higher miscarriage rates. What can be done about the impacts on human reproduction is still an open question.

ADAM GEIGER *National Geographic*

Naomi Oreskes is a professor of the history of science at Harvard University. She is author of *Why Trust Science?* (Princeton University Press, 2019) and co-author of *Discerning Experts* (University of Chicago, 2019).

Scientists: Admit You Have Values

Pretending otherwise won't rebuild trust in the scientific enterprise

By Naomi Oreskes

As the U.S. recoils from the divisions of recent years and the scientific community tries to rebuild trust in science, scientists may be tempted to reaffirm their neutrality. If people are to trust us again, as I have frequently heard colleagues argue, we have to be scrupulous about not allowing our values to intrude into our science. This presupposes that value neutrality is necessary for public trust and that it is possible. But available evidence suggests that neither presumption is correct.

Recent research in communications has shown that people are most likely to accept a message when it is delivered by trusted messengers—teachers, for example, or religious or business leaders, or local doctors and nurses. One strategy to build trust, therefore, is for scientists to build links from their laboratories, institutes and academic departments into the communities where they live and work. One way to do this is by partnering with organizations such as the National Center for Science Education, founded to fight creationism in the classroom but now working broadly with teachers to increase understanding of the nature of science itself. To do this, scientists do not need to throw off their personal values; they merely need to share with teachers a belief in the value of education. This is important because research suggests that, even if we try, we can't throw off our values.

It is well known that people are more likely to accept evidence that accords with what they already believe. Psychologists call this "motivated reasoning," and although the term is relatively recent, the insight is not. Four hundred years ago Francis Bacon put it this way: "Human understanding is not composed of dry light, but is subject to influence from the will and the emotions … man prefers to believe that he wants to be true."

Scientists may assume this motivated reasoning explains erroneous positions—such as the refusal to wear a mask to limit the spread of COVID-19—but plays little role in science. Alas, there is little evidence to support such confidence. Some research suggests that even with financial incentives, most people are apparently incapable of escaping their biases. Thus, the problem seems to be not a matter of *will* but of capacity. Great scientists may think because they are trained to be objective, they can avoid the pitfalls into which ordinary people fall. But that isn't necessarily the case.

Does this mean that science cannot be objective? No. What makes it so is not scientists patrolling their own biases but rather the mechanisms used to ensure that bias is minimized. Peer review is the best known of these, though equally if not more important is diversity. As I contend in the new edition of my book *Why Trust Science,* diversity in science is crucial not just to ensure that every person has a chance to develop their talent but to ensure that science is as unbiased as possible.

Some will argue that value neutrality is an ideal toward which we should strive, even if we know it can't be achieved entirely. In the practice of science, this argument may hold. But what is useful in scientific research may be counterproductive in public communication because the idea of a trusted messenger implies shared values. Studies show that U.S. scientists want (among other things) to use their knowledge to improve health, make life easier, strengthen the economy through innovation and discovery, and protect people from losses associated with disruptive climate change.

Opinion polls suggest that most Americans want many of these things, too; 73 percent of us believe that science has a mostly positive impact on society. If scientists decline to discuss their values for fear that they conflict with the values of their audiences, they may miss the opportunity to discover significant points of overlap and agreement. If, on the other hand, scientists insist on their value neutrality, they will likely come across as inauthentic, if not dishonest. A person who truly had no values—or refused to allow values to influence their decision-making—would be a sociopath!

Value neutrality is a tinfoil shield. Rather than trying to hide behind it, scientists should admit that they have values and be proud that these values motivate research aiming to make the world a better place for all. SA

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Illustration by Jay Bendt

50, 100 & 150 YEARS AGO

INNOVATION AND DISCOVERY AS CHRONICLED IN *SCIENTIFIC AMERICAN*

Compiled by Dan Schlenoff

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APRIL

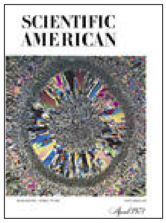
IN MEMORIAM

2021 Dan Schlenoff

With great sadness we share that Dan Schlenoff, the editor of this column for more than 20 years, has died. Dan was a historian who delighted in learning about *Scientific American*'s past and sharing the prescient, surprising or sometimes strange stories he found in our archives. He was a kind, funny, inquisitive and generous colleague and friend, and we will miss him dearly. Our gratitude to Dan lives on. In all that we do, we remember him.

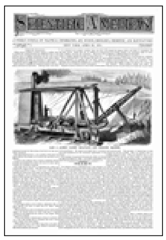
1971 Modern Glass

"A process whereby plate glass of high quality is made by floating it over a bath of molten tin is rapidly replacing the conventional plate-glass process in the U.S. The float process, developed in England about 10 years ago by the glass-making company Pilkington Bros. and introduced into the U.S. by PPC Industries, does away with the mechanical grinding and polishing operations that must be performed in the conventional method. It is therefore a significantly cheaper process. In the float process the glass as it leaves the melting furnace flows horizontally into the float bath, which is an oblong tank more than 100 feet long and broad enough to carry a ribbon of glass of the widest standard commercial size. The ribbon floats on molten tin, which has a perfectly flat surface."



1971

1921



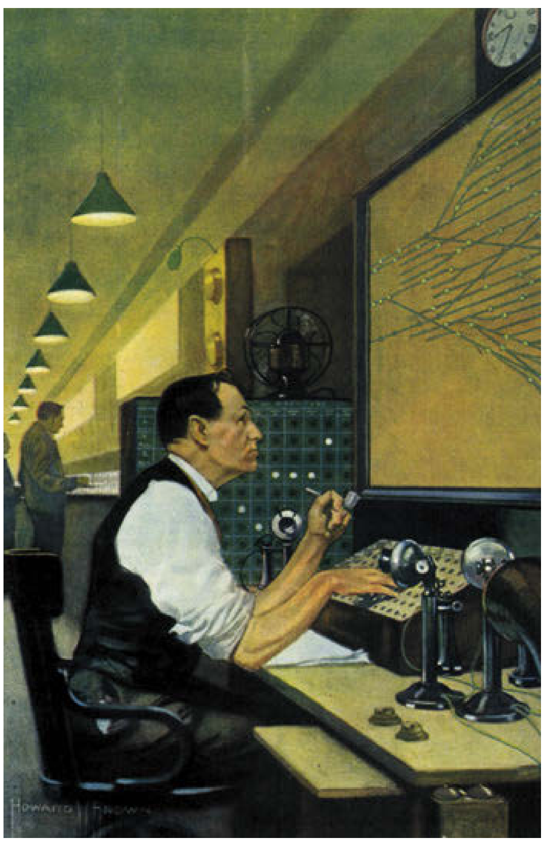
1871

1921 Moving the Masses

"In the Grand Central Terminal, in the heart of New York City, something like six hundred passenger trains are handled daily. These trains must be assigned to the proper tracks in the terminal with all the switching and signaling that such operations involve. And if the long obsolete practice of using stand switches with individual switchmen were still in vogue, it would require many hundred men continually on duty to operate these stands. The present method of operating the switches and crossovers and signals from a central point, known as an interlocking station, has enabled all these operations over an extensive area to be controlled by a small number of men headed by a 'director,' as shown in our illustration."

1871 Earth: Solid or Molten?

"Although the doctrine that the earth is a molten sphere, surrounded by a thin crust of solid matter, was once almost universally taught by geologists, there have of late years been brought forward several arguments to the contrary, which, apparently, are more in favor of its being a solid, or nearly solid mass throughout. For instance, whether it is possible for such a thin crust to remain solid, and not at once to become melted up and absorbed into the much greater mass of molten matter beneath it? In reality, it is evident that no crust could even commence to form on the surface, unless the sphere itself was at the moment actually giving off more heat to the surrounding atmosphere than it could supply from its more central parts."



1921: Before the digital age, electric apparatus helped to direct train operations.

SCIENTIFIC AMERICAN, VOL. CXXIV, NO. 17; APRIL 23, 1921

Working Like a Dog

"French nails, says the *Mechanics' Magazine,* are manufactured at Charleville, partly in large factories by machinery, partly in a multitude of small factories, or rather *atéliers,* scattered about the densely populated villages. These villages, and especially one of them, Neufmanil, are not only inhabited by people, but by an *ouvrier* [working] class of dogs. The labor of these dogs, whose hours are as exactly regulated as those of their human fellow laborers, consists in furnishing motive power to the bellows, which fan the furnaces of the *atéliers.* They get inside a wheel and turn it, just like squirrels in a cage."

Heard It through the Grapevine

"The drying of grapes, for making raisins, is becoming a large industry in California, the highly saccharated juice of the American grapes peculiarly fitting them for the purpose."

Text by Mark Fischetti | Graphic by Jen Christiansen

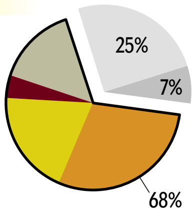
A New You in 80 Days

Cell turnover is vast and swift

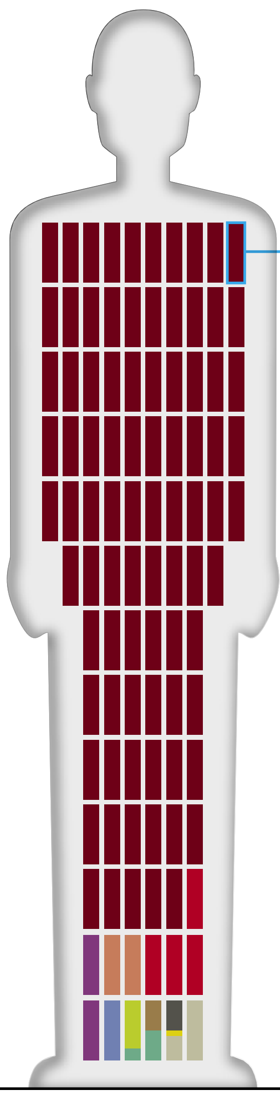
The human body replaces its own cells regularly. Scientists at the Weizmann Institute of Science in Rehovot, Israel, have finally pinned down the speed and extent of this "turnover." About a third of our body mass is fluid outside of our cells, such a plasma, plus solids, such as the calcium scaffolding of bones. The remaining two thirds is made up of roughly 30 trillion human cells. About 72 percent of those, by mass, are fat and muscle, which last an average of 12 to 50 years, respectively. But we have far more, tiny cells in our blood, which live only three to 120 days, and lining our gut, which typically live less than a week. Those two groups therefore make up the giant majority of the turnover. About 330 billion cells are replaced daily, equivalent to about 1 percent of all our cells. In 80 to 100 days, 30 trillion will have replenished—the equivalent of a new you.

Cells in the Body

Mass About 25 percent of body mass is fluid outside of cells, such as plasma; another 7 percent is solids, such as minerals. That leaves 68 percent made of human cells.



Number* A 70-kilogram male has roughly 30 trillion human cells. Fat and muscle cells are large—72 percent of cellular mass—but are only 0.1 percent of the total number. About 87 percent, by number, are erythrocytes—red blood cells—which are extremely small.



Each rectangle represents 1 percent of all 30 trillion cells. That's roughly equivalent to the number of cells the body sheds and produces every day.

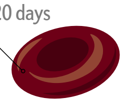
Cell Type

Blood
- Erythrocytes
- Lymphocytes
- Neutrophils
- Monocytes

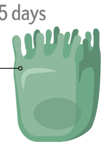
- Endothelial (vessels)
- Lung
- Hepatocytes (liver)
- Gastrointestinal lining
- Skin
- Brain
- Adipocytes (fat)
- Myocytes (muscle)
- Other

Little Cells Rule Large cells tend to live long, so daily turnover is dominated by plentiful, small cells with very short life spans.

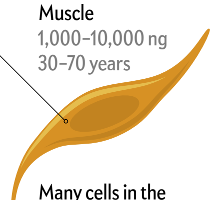
Erythrocytes
Mass:
0.1 nanogram (ng)
Life span:
120 days



Colon epithelial cells
1 ng
3–5 days



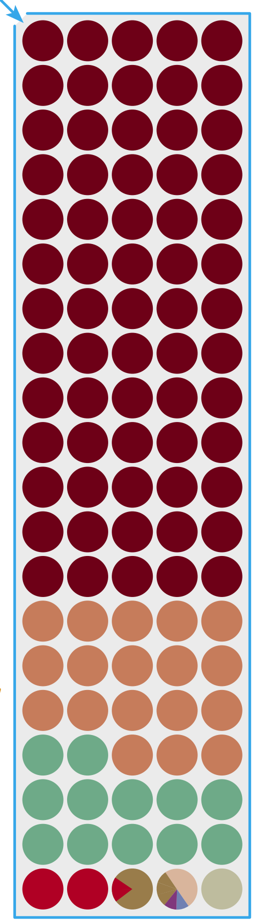
Muscle
1,000–10,000 ng
30–70 years



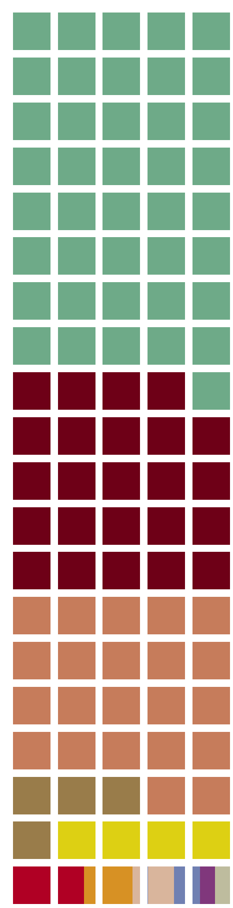
Many cells in the heart, eyes and brain last a lifetime.

Cell Turnover per Day

By Number† Roughly 330 billion cells (+/–20 billion) turn over every day. About 86 percent are blood cells, and 12 percent are gut cells. Other cells are replaced very slowly.



By Mass About 49 percent are blood cells, 41 percent are gut cells, with skin making up 4 percent, fat 4 percent and muscle 1 percent. Daily mass turnover is 80 grams (+/–20).



**This research is rooted in a standard reference person, which historically has been defined as a male, age 20 to 30, weighing 70 kilograms. Cells lost or gained resulting from menstruation were not taken into account. Negligible percentages are not shown.*

†Our bodies harbor another 38 trillion bacteria and many more viruses, but they weigh only 200 to 300 grams (seven to 11 ounces) and are not counted as human.

SOURCES: "REVISED ESTIMATES FOR THE NUMBER OF HUMAN AND BACTERIA CELLS IN THE BODY," BY RON SENDER, SHAI FUCHS AND RON MILO, IN *PLOS BIOLOGY,* VOL. 14; AUGUST 2016 *(total cell data),* AND "THE DISTRIBUTION OF CELLULAR TURNOVER IN THE HUMAN BODY," BY RON SENDER AND RON MILO, IN *NATURE MEDICINE,* VOL. 27; JANUARY 2021 *(cell turnover data)*