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The fight to keep evolution in classrooms
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SCIENTIFIC AMERICAN

THE SEVENTH SENSE

The immune system may work as a sensory organ that helps the brain monitor microbes throughout the body

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VOLUME 319, NUMBER 2

SCIENTIFIC AMERICAN

ON THE COVER

The brain and the immune system were long thought to live separate lives. Recent research has shown that the brain needs the immune system to function properly, however. The immune system's main job may be to detect microorganisms and report on them to the brain. In this way, it could constitute a seventh sense. **Illustration by Mark Ross.**

Photograph by Grant Delin

SCIENTIFIC AMERICAN

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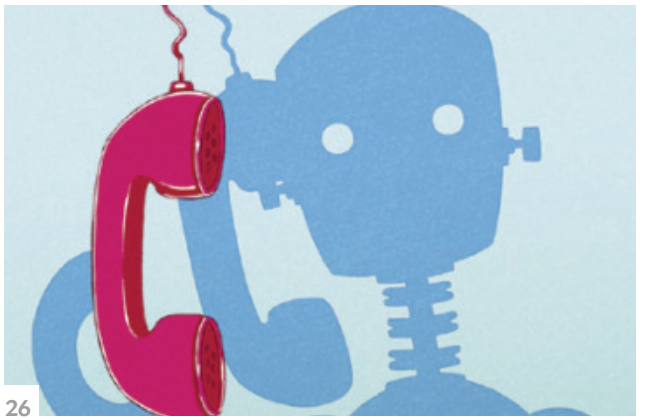

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ON THE WEB

Science on the Hill
Scientific American works with Nature Research and Representative Jerry McNerney of California to educate Congress about AI and robotics and the future of medicine. *Go to www.ScientificAmerican.com/aug2018/congress*

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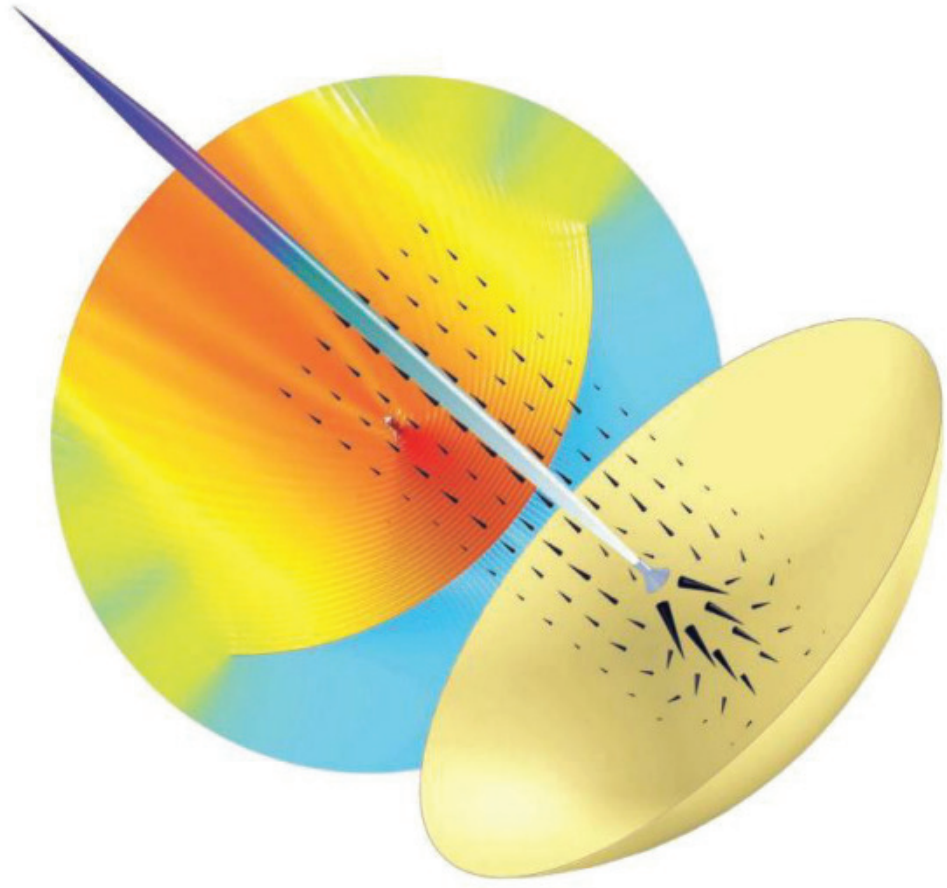
EM simulation could help the Internet of Space lift off.



Visualization of the electric field, power flow, and sharp far-field radiation pattern of a parabolic reflector antenna.

The wired and wireless networks that currently connect people around the world cannot reach everywhere on Earth. To solve the problem, engineers are turning their eyes toward space. The goal is to form a suborbital high-data-rate communications network to revolutionize how data is shared and collected. Before this Internet of Space can be built, design engineers need to optimize their antenna designs.

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

A Sense of Discovery

Sight, hearing, touch, taste, smell, body awareness (formally, proprioception): six of the widely recognized senses in our bodies that help tell us about the world around us. Yet we have other senses as well. And now meet our surprising latest detector: the immune system. What's that you say? The anatomy textbooks show that the brain and the immune system are almost completely isolated from each other? I thought so, too. But, as usual, researchers probing the world have turned up some fresh insights about how things work.

In our cover story, "The Seventh Sense," neuroscientist Jonathan Kipnis describes the relationship between the nervous and immune systems. "Mounting evidence indicates that the brain and the immune system interact routinely, both in sickness and in health," he writes. The immune system may "qualify as a kind of surveillance organ that detects microorganisms in … the body and informs the brain about them, much as our eyes relay visual information and our ears transmit auditory signals." Turn to page 28.

So science giveth, but sometimes it also taketh away. For instance, "Is Dark Matter Real?" ask theoretical physicist Sabine Hossenfelder and astrophysicist Stacy S. McGaugh. This invisible type of matter is thought to accompany the normal matter in the universe to explain how stars orbit in galaxies and how galaxies move in clusters. But astrophysicists have made numerous observations that are difficult to explain with theories about dark matter. Perhaps there's more to gravity than Einstein taught us? The story starts on page 36. The idea that gravity may need to be modified is not widely held, but like the once unquestioned belief in the separation between the brain and immune system, maybe the area is worth a second look. SA

Sustainable Cities

Usually I'm based in one of the world's great cities, New York. But around when this issue appears, I'll be halfway around the planet in the city-state of Singapore to co-emcee an important event run by *Scientific American*'s parent company, Springer Nature: "Science and the Sustainable City." Co-located with the World Cities Summit, which draws 20,000 government and business leaders focused on making cities more livable and sustainable, this meeting brings together global experts in academic research, policy and business to discuss and collaborate on solutions. Cities—which already house more than half of the world's population, rising to two thirds in the next few decades—form crucibles combining both pressing challenges and exciting opportunities. They can be focal points of extreme human stress but also of strong community identity and innovation. And they enable the exploration of new ideas that are impossible to implement in the short term at a national level.

The symposium is part of our Grand Challenges publishing program, which you can learn more about at https://grandchallenges.springernature.com —*M.D.*

Illustration by Nick Higgins


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April 2018

"Programming the emotional mind to feel fear or disgust at the means of killing oneself makes no more difference to a patient's suffering than preventing suicide by strapping someone to a bed."

R. ALLEN GILLIAM *LONGWOOD, FLA.*

MECHANICAL MIND

"The Brain, Reimagined," by Douglas Fox, concerns work by physicists Thomas Heimburg and Andrew D. Jackson, who argue that signals in neurons are conveyed by mechanical waves of expansion and contraction of the cell membrane rather than by electrical spikes, or action potentials, as described by British researchers Alan Hodgkin and Andrew Huxley.

Heimburg's contention is described as being that the Hodgkin-Huxley model is simply wrong. It is astonishing that he would not accept a compromise between the two models. Given, for example, the Hodgkin-Huxley equations' long-standing success in describing action potentials, this argument would require addressing how the new mechanism accounts for the observations of the old. The list of questions could be quite long, and there are several I would ask at a minimum. Among them are how Heimburg's model accounts, quantitatively, for the increased velocity of conduction in myelinated axons and the mechanism by which it leads to transmission across a chemical synapse.

DOUGLAS A. EAGLES *via e-mail*

Fox hints at the possibility that a voltage pulse in a neuron will initiate a mechanical deformation and that a mechanical pulse will generate a voltage. This sounds similar to the way that changes in electric and magnetic fields generate each other to produce a propagating electromagnetic wave. Is it possible that the interaction of electrical and mechanical effects is actually required for neurons to function?

PETER SOCHACKI *Schaumburg, Ill.*

FOX REPLIES: Heimburg, Jackson and their colleagues spent years assembling evidence to place their theory on a sound physics foundation. But Eagles raises a fair point that the theory does not currently explain why myelination increases the speed of nerve pulses or how a mechanical pulse might trigger neurotransmitter release at a synapse. These questions will have to be addressed for the mechanical-wave theory to gain broader credibility. Doing that will almost certainly require that biologists step in to continue the work that physicists have begun.

I would agree with Sochacki: if a mechanical wave is indeed part of nerve conduction, then it seems plausible that the mechanical and electrical signals might entrain and reinforce each other. Lipid membranes have been around since the origin of life, and it appears reasonable to suspect that ion channel proteins, which nestle inside the membranes, have perhaps evolved to not simply tolerate those nanoscale forces but to harness them.

SUICIDE PREVENTION

Lydia Denworth reports on novel ideas and technology used for "Preventing Suicide." As a psychiatrist and researcher, I would like to emphasize that although formal training in how to detect and manage suicide can be very helpful, it is unlikely to reach all of those who potentially work with troubled individuals. A more straightforward option is to become comfortable discussing topics related to suicidal ideation and behavior.

If you are exposed to someone with any risk of suicide, being open to hearing what the person has to say and listening are typically enough to prevent an attempt and create an opportunity for progress, such as a referral to a mental health specialist. Denworth says that 95 percent of young people in a survey indicated that they wanted to be asked about suicide risk. People prefer to live and, if given the chance, without sensing reluctance from the listener, will discuss suicidal thoughts.

BRAD BOWINS *Toronto*

Denworth writes that "the pain and hopelessness that lead a person to want to die can be anticipated, addressed and ameliorated." Yet one of the techniques she describes is to match "suicide-related images—blood, wounds and knives—with aversive pictures of snakes, spiders, and the like." Programming the emotional mind to feel fear or disgust at the means of killing oneself makes no more difference to a patient's suffering than preventing suicide by strapping someone to a bed. Am I the only one who finds it disturbing that a doctor thinks it is acceptable to inflict this kind of emotional conditioning?

R. ALLEN GILLIAM *Longwood, Fla.*

SIGNAL TO NOISE

"Flashes in the Night," by Duncan Lorimer and Maura McLaughlin, discusses the observation and search for fast radio bursts from the distant universe. The article brought back a memory from my days as an undergraduate assistant working on the 300-foot radio telescope in Green Bank, W. Va., in 1968.

Green Bank is in a radio-quiet area, but the local farmers used equipment that the telescope could detect. It was easy to distinguish these signals because they didn't shift four minutes every day, as do the radio sources we were interested in. But one puzzling signal showed up most days at the same sidereal time. We identified it as coming from the noisy starter in a co-worker's car as he showed up for his

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observing run, four minutes later each day. Perhaps we would have called the signal a peryton had we known more about mythology. Instead, in keeping with the designations in the Third Cambridge Catalogue of Radio Sources, we named the source after the driver's initials: 3C-MMD.

ALAN KARP *Palo Alto, Calif.*

CAR BAFFLE

Having retired from designing software systems, I was not a bit surprised by David Pogue's assessment of the sorry state of dashboard controls in "Automotive Touch Screens Are Awful" [TechnoFiles].

I was often struck by the utter arrogance of engineers in my profession when it came to creating user interfaces (UIs). It seemed that the main objective in designing a UI was to produce the cleverest newfangled gadget, without regards to legacy or familiarity on the part of the target users, who were never consulted. Completely forgotten was the idea that a UI should be easily mastered by the most technologically inept operator. I suppose we should be thankful that the steering wheel hasn't yet been replaced by arrows on a touch screen.

TED CARMELY *Los Angeles*

MICROBIAL MOUSER

I am fascinated by Aditee Mitra's "The Perfect Beast," which describes "mixotrophic" plankton, which can use solar energy like plants but can also hunt and eat prey.

The idea that one plankton specializes in preying on a different one makes me wonder if there are any indications of types that attack environmentally damaging species, such as the "toxic *Karlodinium*" or "ecologically damaging, green *Noctiluca*" cited in the article, and if it would thus be possible to encourage growth of the more desirable species in areas prone to blooms of the undesirable ones.

EDWARD J. JAGO *via e-mail*

ERRATUM

"The Perfect Beast," by Aditee Mitra, includes a photograph of a microorganism incorrectly described as *Ceratium* (*Tripos*) *furca*. Although the source of the image had identified it as that species, an expert review clarified that it shows a member of the genus *Protoperidinium*.

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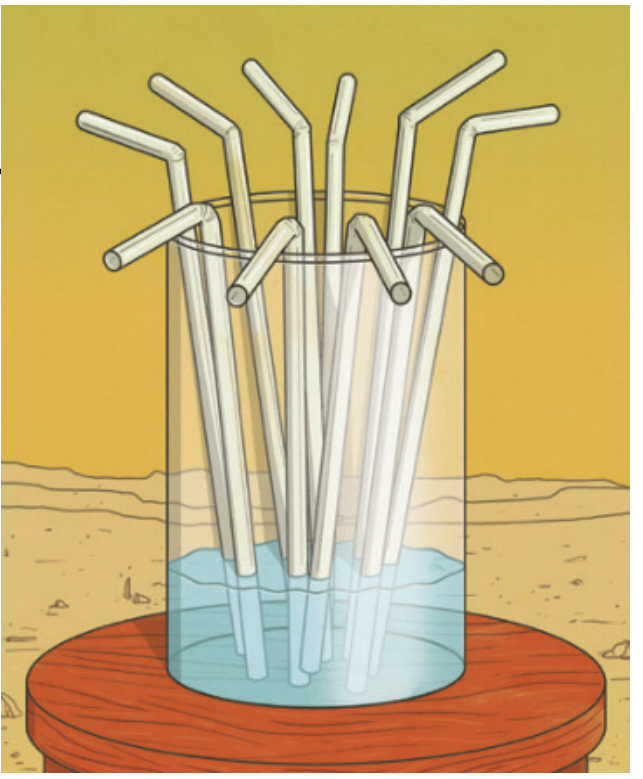
Prepare for Water Day Zero

Cape Town's recent water crisis highlights the need for better urban planning and management

By the Editors



Earlier this year ominous headlines blared that Cape Town, South Africa, was headed for Day Zero—the date when the city's taps would go dry because its reservoirs would become dangerously low on water. That day—originally expected in mid-April—has been postponed until at least 2019 as of this writing, thanks to water rationing and a welcome rainy season. But the conditions that led to this desperate situation will inevitably occur again, hitting cities all over the planet.

As the climate warms, extreme droughts and vanishing water supplies will likely become more common. But even without the added impact of climate change, normal rainfall variation plays an enormous role in year-to-year water availability. These ordinary patterns now have extraordinary effects because urban populations have had a tremendous growth spurt: by 2050 the United Nations projects that two thirds of the world's people will live in cities. Urban planners and engineers need to learn from past rainfall variability to improve their predictions and take future demand into account to build more resilient infrastructure.

How did Cape Town get into a Day Zero situation? The city gets its water from six reservoirs in Western Cape province, which usually fill up during the rainy season, from May through August. But since 2015 the region has been suffering from the worst drought in a century, and the water in those reservoirs dwindled perilously. Compounding the problem, Cape Town's population has grown substantially, increasing demand. The city actually did a pretty good job of keeping demand low by reducing leaks in the system, a major cause of water waste, and has even won awards for its conservation policies. But the government of South Africa was slow to declare a national disaster in the areas hit hardest by the drought, paving the way for the recent crisis.

Cape Town is not alone. Since 2014 southeastern Brazil has been suffering its worst water shortage in 80 years, resulting from decreased rainfall, climate change, poor water management, deforestation and other factors. And many cities in India do not have access to municipal water for more than a few hours a day, if at all. For example, the city of Shimla ran out of drinking water in May, prompting locals to beg tourists to stay away from the popular Himalayan summer retreat. The water infrastructure in many Indian cities is old and leaky, but city governments have not repaired it. Municipalities have, however, given free electricity to farmers for irrigation, depleting local groundwater stocks.

In the U.S., the situation is somewhat better, but many urban centers still face water problems. California's recent multiyear drought led to some of the state's driest years on record. Fortunately, about half of the state's urban water usage is for landscaping, so it was able to cut back on that fairly easily. But cities that use most of their water for more essential uses, such as drinking water, may not be so adaptable. In addition to the problems that drought, climate change and population growth bring, some cities face threats of contamination; crises such as the one in Flint, Mich., arose because the city changed the source of its water, causing lead to leach into it from pipes. If other cities are forced to change their water suppliers, they could face similar woes.

Fortunately, steps can be taken to avoid urban water crises. In general, a "portfolio approach" that relies on multiple water sources is probably most effective. Cape Town has already begun implementing a number of water-augmentation projects, including tapping groundwater and building water-recycling plants. Many other cities will need to repair existing water infrastructure to cut down on leakage.

Metropolitan leaders should be thinking about meeting long-term needs rather than just about daily requirements. Good organization and financial accountability are equally critical. And planning efforts should include diverse stakeholders from the community. One major challenge is providing services to informal areas, which develop haphazardly, without any government foresight. Such regions often lack basic resources—a well-planned water supply among them.

The global community has an opportunity right now to take action to prevent a series of Day Zero crises. If we don't act, many cities may soon face a time when there isn't a drop to drink. SA

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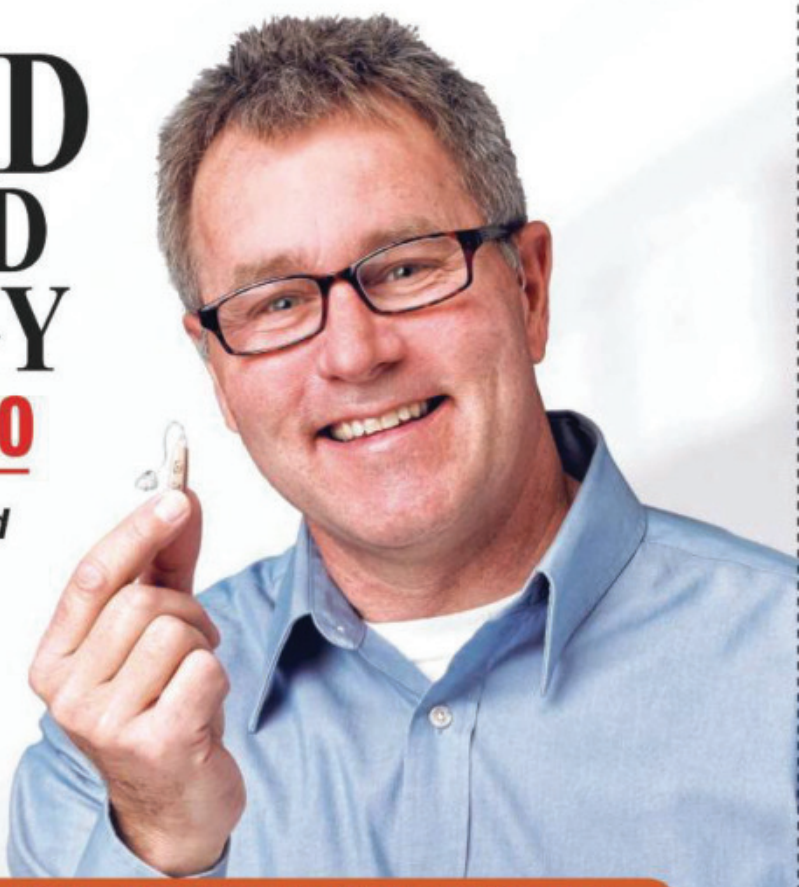

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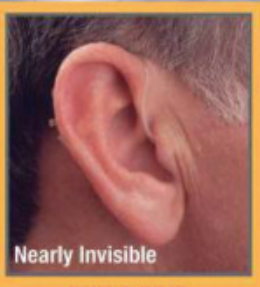

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Madison Freeman is a research associate for energy and U.S. foreign policy at the Council on Foreign Relations.

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Capture That Carbon

Grabbing CO_2 as it exits smokestacks is key to fighting climate change

By Madison Freeman and David Yellen

The conclusion of the Paris Agreement in 2015, in which almost every nation committed to reduce their carbon emissions, was supposed to be a turning point in the fight against climate change. But many countries have already fallen behind their goals, and the U.S. has now announced it will withdraw from the agreement. Meanwhile emissions worldwide continue to rise.

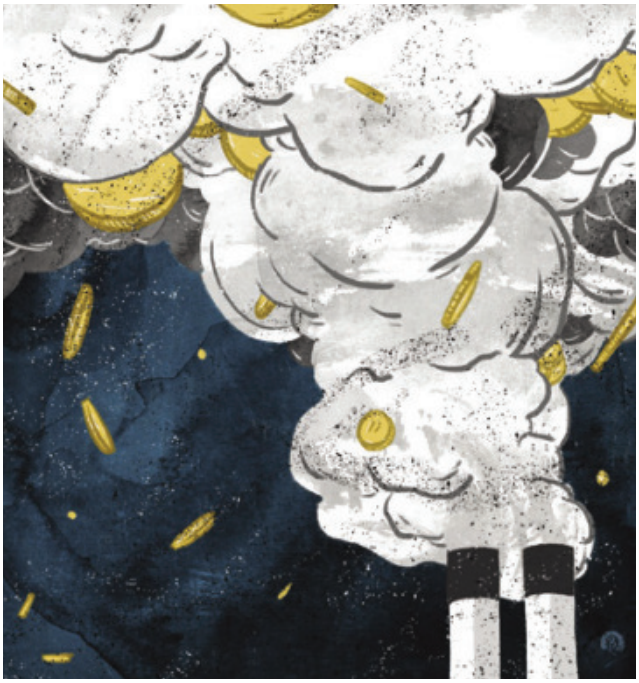
The only way to make up ground is to aggressively pursue an approach that takes advantage of every possible strategy to reduce emissions. The usual suspects, such as wind and solar energy and hydropower, are part of this effort, but it must also include investing heavily in carbon capture, utilization and storage (CCUS)—a cohort of technologies that pull carbon dioxide from smokestacks, or even from the air, and convert it into useful materials or store it underground.

Although CCUS has been opposed as too expensive and unproved, recent gains have made it far more effective. Improvements such as chemical compounds that are more efficient at latching onto carbon could drive the cost down from $100 per ton of captured carbon in 2016 to $20 per ton by 2025, according to a 2016 article in *Science*. Start-ups are also developing new tactics, among them the transformation of trapped carbon into fertilizer, which could spur further savings.

Without CCUS, the level of cuts needed to keep global warming to two degrees Celsius (3.6 degrees Fahrenheit)—the upper limit allowed in the Paris Agreement—probably cannot be achieved, according to the International Energy Agency. By 2050 carbon capture and storage must provide at least 13 percent of the reductions needed to keep warming in check, the agency calculates.

Three primary CCUS paths lead us to this goal: retrofitting existing power plants to strip carbon dioxide from the exhaust produced by fossil-fuel electricity plants; reducing emissions in industries that cannot run on renewable energy; and directly removing carbon from the air. Cutting emissions from existing electric power stations with CCUS could be made more appealing in a future with a circular carbon economy, in which captured carbon could be resold and recycled for other uses—for instance, serving as a raw material for making concrete or plastics.

CCUS technologies can also help decarbonize emissions in heavy industry—including production of cement, refined metals and chemicals—which accounts for almost a quarter of U.S. emissions. In addition, direct carbon-removal technology—which captures and converts carbon dioxide from the air rather than from a smokestack—can offset emissions from industries that cannot readily implement other clean technology, such as agriculture.



The basic idea of carbon capture has faced a lot of opposition. Skepticism has come from climate deniers, who see it as a waste of money, and from passionate supporters of climate action, who fear that it would be used to justify continued reliance on fossil fuels. Both groups are ignoring the recent advances and the opportunity they present. By limiting investment in decarbonization, the world will miss a major avenue for reducing emissions both in the electricity sector and in a variety of industries. CCUS can also create jobs and profits from what was previously only a waste material by creating a larger economy around carbon.

For CCUS to succeed, the federal government must kick in funding for basic research and development and offer incentives such as tax breaks for carbon polluters who adopt the technology. The Trump administration has repeatedly tried to slash energy technology R&D, with the Department of Energy's CCUS R&D cut by as much as 76 percent in proposed budgets. But this funding must be protected.

There is hope for doing that. The FUTURE Act, the provisions of which were passed with the February 2018 budget bill and which was championed by a bipartisan coalition in the Senate, contains tax incentives that are important steps toward making CCUS economical. The same bipartisan group of senators has proposed the USE IT Act, which would amplify support for CCUS technology by directly funding research and development and by setting up a prize competition to reward deployment.

The transition to clean energy has become inevitable. But that transition's ability to achieve deep decarbonization will falter without this wide range of solutions, which must include CCUS. SA

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Illustration by Benjamin Currie

ADVANCES

NASA's OSIRIS-REx spacecraft is one of two probes en route to asteroids to gather samples for analysis.

INSIDE

NASA'S GODDARD SPACE FLIGHT CENTER

SPACE EXPLORATION

Collecting Space Rocks

Two asteroid missions could yield discoveries about the origins of life

If all goes according to plan, two spacecraft will commence close encounters of the curious kind with two separate asteroids by the end of August. Their goal: to retrieve samples that may contain organic materials dating back to the solar system's birth. These building blocks may be key to understanding the origins of the planets and of life on Earth—and could also make future space prospectors very rich.

As of this writing, Japan's Hayabusa2 probe was on track to arrive at a kilometer-wide asteroid called Ryugu around June 27. On August 17 a NASA craft, OSIRIS-REx, is scheduled to arrive within sight of a roughly 500-meter-wide asteroid called Bennu. These space rocks will be the focus of approximately two years of sensor surveys and efforts to collect samples for scientists back on Earth to analyze.

"There are going to be so many groups around the world that are going to be able to study the samples for decades to come," says Nancy Chabot, a planetary scientist at the Johns Hopkins University Applied Physics Laboratory, who is not affiliated with either mission. The new data, she says, are "really going to revolutionize what we understand about the composition and the makeup of these primitive bodies from the early solar system." Hayabusa2 and OSIRIS-

REx will not be the first missions to retrieve an asteroid sample. That honor went to Japan's first Hayabusa spacecraft, which in 2010 returned to Earth with a tiny sample from the asteroid Itokawa after an unplanned crash on its surface. Itokawa is representative of so-called S-type asteroids, which consist primarily of stony materials.

In contrast, Ryugu and Bennu fall into the carbonaceous (C-type), or carbon-containing, class of asteroids—the most common space rocks in the solar system. Taken together, samples delivered by OSIRIS-REx and Hayabusa2 could confirm that these asteroids have a composition similar to those of "carbonaceous chondrite" meteorites discovered on Earth. Such meteorites contain organic compounds, in addition to water locked inside hydrated minerals. But these meteorites may have been contaminated by Earth's surface. If the composition of the asteroids matches that of the meteorites, it would suggest the compounds could have been brought here from space.

Carbonaceous meteorites "very well may have been, at least in part, the source of water on Earth and the compounds that lead to life," according to a joint statement by Harold Connolly, a co-investigator and mission sample scientist for OSIRIS-REx, and Shogo Tachibana, a mission sample scientist for Hayabusa2. This hypothesis could be reinforced by bringing back the first pristine samples from carbonaceous asteroids.

Launching two very similar missions may seem redundant—but it could be informative, Chabot explains. "If the samples [from both asteroids] turn out to be identical, that would be telling us something very fundamental about how homogeneous materials were in the solar system," she says. "But my money is on the samples showing us some surprising differences."

The two missions also have distinct operational phases. Beyond surveys and collecting samples, Hayabusa2 will attempt to place up to three robotic rovers and a European-built MASCOT lander on Ryugu to explore its surface. The Japanese mission also plans to fire a two-kilogram copper projectile at the asteroid; in this way, scientists hope to create a crater that would reveal its internal composition.

The first Hayabusa mission brought back less than a milligram of asteroid dust from its historic and harrowing journey. The new missions could retrieve a far larger haul of pristine space rock, making it easier for researchers to share and analyze samples.

Hayabusa2 aims to collect three samples from different locations on Ryugu, netting approximately 100 milligrams. OSIRIS-REx will attempt to collect up to two kilograms from a single spot on Bennu's surface. Scientists from both missions plan to exchange samples and cooperate closely throughout: Connolly even works on both OSIRIS-REx and Hayabusa2.

These missions may also provide valuable information for asteroid-mining operations, Chabot says. She serves as a scientific adviser for Planetary Resources, an aspiring asteroid-mining company based in Redmond, Wash. It is one of several firms hoping to eventually harvest minerals from space rocks, as well as water, which they could convert into rocket fuel to power future missions in the distant solar system.

Hayabusa2 and OSIRIS-REx are not scheduled to return to Earth until 2020 and 2023, respectively, but the payoff will almost certainly be worth the wait. Many labs are still squeezing new science out of the Apollo lunar samples decades later, as improving techniques and instruments allow investigators to reanalyze old specimens. —*Jeremy Hsu*

ASTROBIOLOGY

Astro Worms

A tiny species of nematode can withstand major *g*-forces

Caenorhabditis elegans would make an ace fighter pilot. That's because the roughly one-millimeter-long roundworm, a type of nematode that is widely used in biological studies, is remarkably adept at tolerating acceleration. Human pilots lose consciousness when they pull only 4 or 5 *g*'s (1 *g* is the force of gravity at Earth's surface), but *C. elegans* emerges unscathed from 400,000 *g*'s, new research shows.

This is an important benchmark; rocks have been theorized to experience similar forces when blasted off planet surfaces and into space by volcanic eruptions or asteroid impacts. Any hitchhiking creatures that survive could theoretically seed another planet with life, an idea known as ballistic panspermia.

STEVE GSCHMEISSNER *Science Source*

Tiago Pereira and Tiago de Souza, both geneticists at the University of São Paulo in Brazil, spun hundreds of roundworms in a device called an ultracentrifuge. After an hour, the researchers pulled them out, convinced that the animals would be dead. But they were "swimming freely as if nothing had happened," Pereira says. More than 96 percent were still alive, and the survivors did not exhibit any adverse physical or behavioral changes. "Life tolerates much more stress than we typically think," as Pereira puts it. His team's results were published online in May in the journal *Astrobiology.*

Still, this extreme test does not replicate the full brunt of an interplanetary journey, the researchers concede. For one thing, it took roughly five minutes for the ultracentrifuge to build up to these massive *g*-forces—whereas rocks blasted off a planet would reach them within a 1,000th of a second. Nor did the experiment replicate the harsh conditions of space. "Other factors, such as temperature, vacuum and cosmic radiation, should also be tested," says Cihan Erkut, a biochemist at the European Molecular Biology Laboratory in Heidelberg, Germany, who was not involved in the research. Pereira says his team's work is a starting point for other experiments to develop "an understanding of the limits of life." —*Katherine Kornei*

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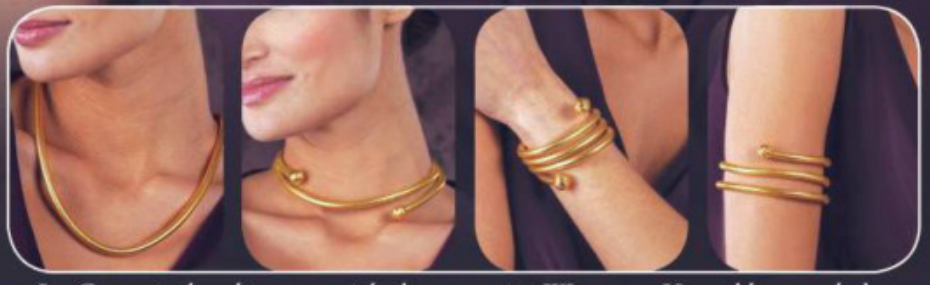

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BIOLOGY

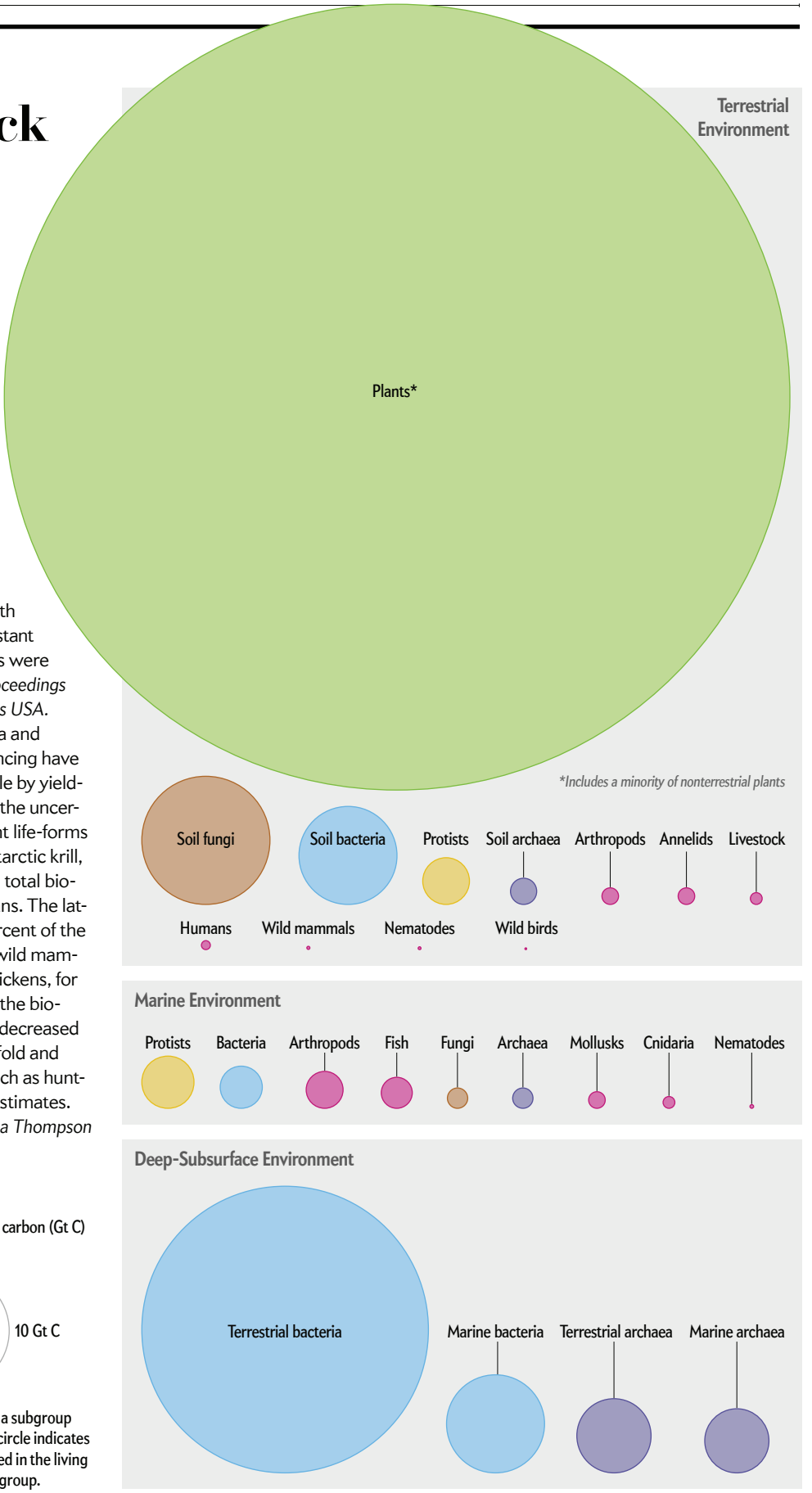
Taking Stock of Life

A new survey breaks down Earth's biomass by organism

Plants rule the planet—at least in terms of sheer mass. Many tallies of Earth's life use biodiversity as a measurement and simply count the number of species. A new census, based on biomass, compiled data from hundreds of studies to determine which kingdoms, classes and species carry the most global heft. The results show that plants (primarily those on land) account for 80 percent of the total biomass, with bacteria across all ecosystems a distant second at 15 percent. The findings were published online in May in the *Proceedings of the National Academy of Sciences USA*.

Higher-resolution satellite data and improvements in genomic sequencing have made such measurements possible by yielding more accurate estimates, but the uncertainty is still high for hard-to-count life-forms such as microbes and insects. Antarctic krill, a type of small crustacean, have a total biomass comparable to that of humans. The latter makes up only a 100th of a percent of the total, but it still dwarfs that of all wild mammals. Livestock also dominate: chickens, for example, account for three times the biomass of wild birds. Humans have decreased the biomass of wild mammals sixfold and plants twofold through actions such as hunting and deforestation, the study estimates.

—*Andrea Thompson*



Each circle represents a kingdom of life or a subgroup of a particular kingdom. The area of each circle indicates how many gigatons of carbon are contained in the living tissue of all the organisms in the specified group.

SOURCE: "THE BIOMASS DISTRIBUTION ON EARTH," BY YINON M. BAR-ON ET AL., IN *PROCEEDINGS OF THE NATIONAL ACADEMY OF SCIENCES USA*. PUBLISHED ONLINE MAY 21, 2018

Graphic by Amanda Montañez

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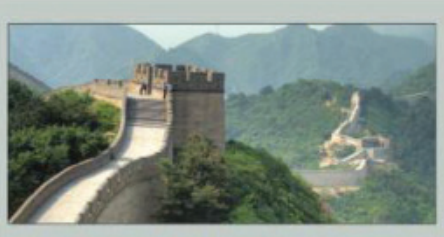

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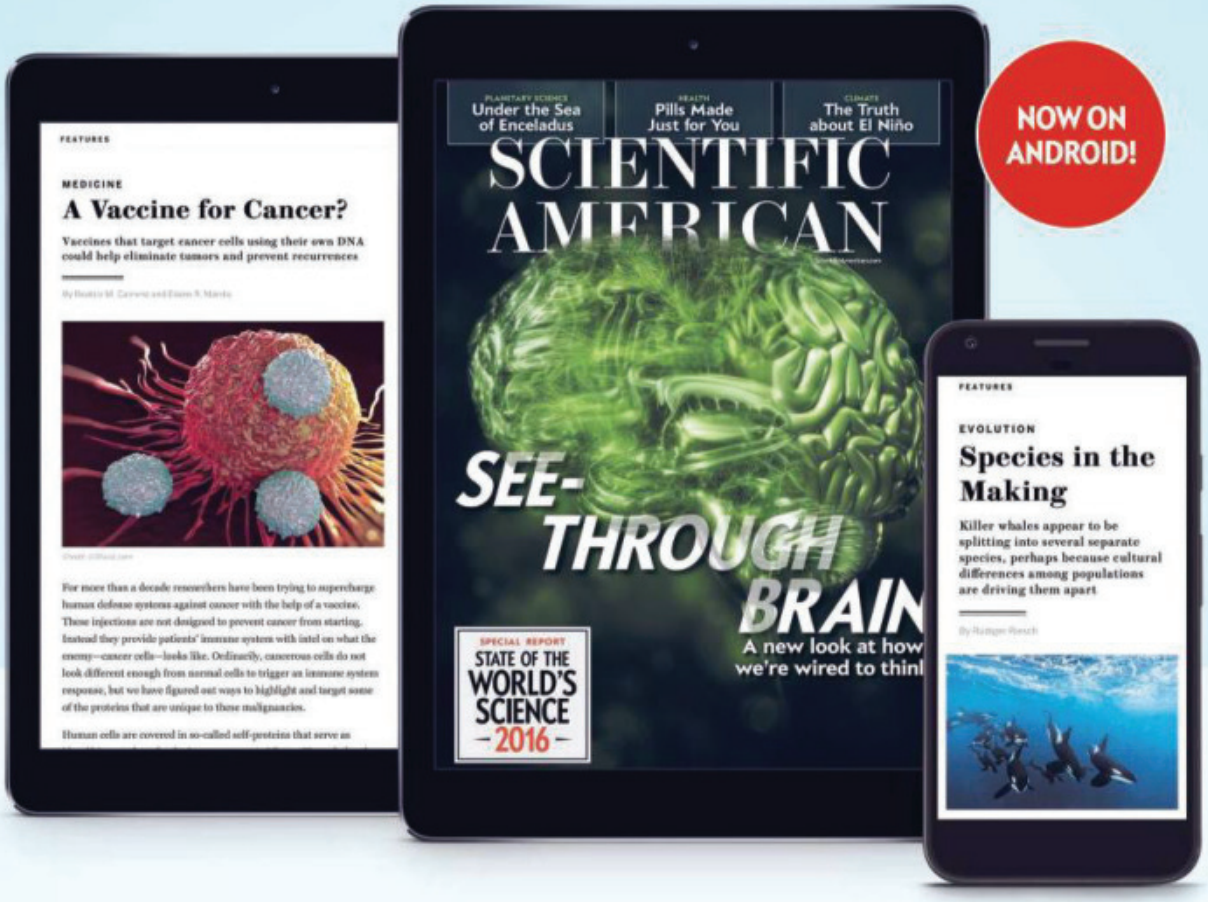

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ECOLOGY

Bloodthirsty

Dehydrated mosquitoes may bite more frequently

Mosquitoes are the world's deadliest animals, transmitting diseases that kill hundreds of thousands of people annually. Only the females bite, to acquire protein to make their eggs. But blood can also serve as a refreshing beverage on a hot, dry day.

A new study finds that dehydrated mosquitoes are more aggressive, land more often on hosts and feed more frequently than those with ready access to water. In quenching their thirst, they may also increase the spread of disease, says Joshua Benoit, a biologist at the University of Cincinnati and senior author of the study, published in May in *Scientific Reports*.

Because some mosquitoes lay their eggs on water, researchers have long assumed that wetter conditions lead to more mosquito-borne illness. Yet recent studies have hinted at the opposite, linking increased transmission of diseases such as West Nile fever to droughts. Benoit and his colleagues' discovery helps to resolve these counterintuitive findings.

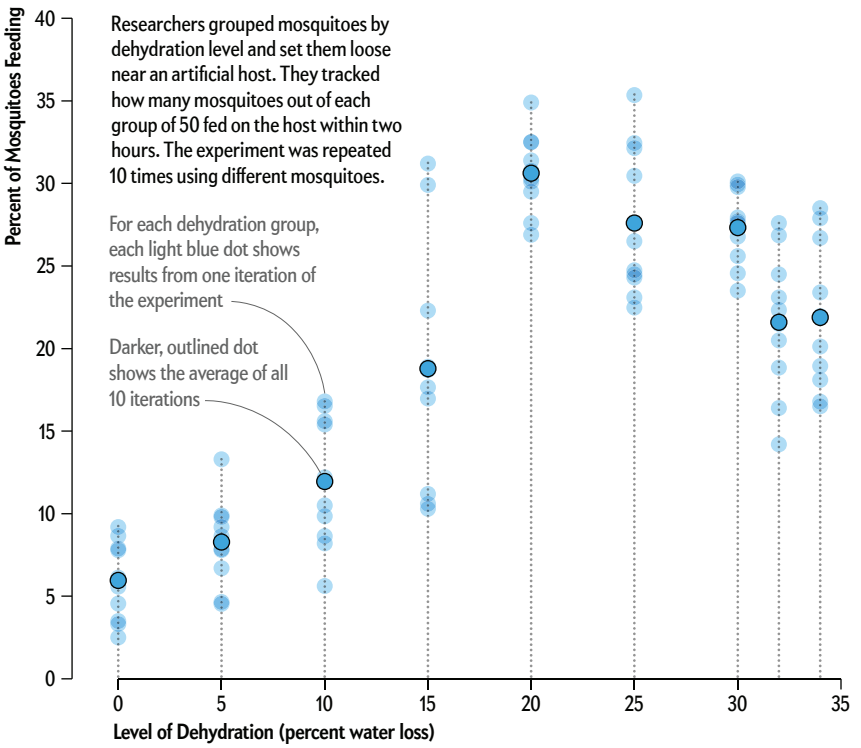
"It's not just as simple as saying, 'If it's wet, there will be more mosquitoes and more disease transmission,'" Benoit says.

His laboratory became interested in the impact of dehydration on mosquito-feeding behavior by accident: a worker dropped a container of water-deprived mosquitoes and noticed that they dive-bombed him with much greater vigor than usual.

The researchers studied three mosquito species that transmit yellow fever, Zika or West Nile fever. They exposed hundreds of insects to different temperatures and humidity levels in cages with or without access to water and nectar (mosquitoes' preferred sugar source). They then tested how often the pests chose to bite a "host": a warm, waxy plastic membrane coated in artificial sweat and filled with chicken blood.

Within a few hours up to 30 percent of mosquitoes without water fed on their host's blood—compared with 5 to 10 percent of those that had water. "Even short periods of dehydration can have profound effects," Benoit says.

These "very interesting" findings have real-world applications for predicting rates of disease transmission, says Chloe Lahondere, an entomologist at Virginia Tech, who was not involved in the study: "To develop new tools to efficiently fight these insects, it is essential to have a better understanding of their biology." —*Rachel Nuwer*



SOURCE: "DEHYDRATION PROMPTS INCREASED ACTIVITY AND BLOOD FEEDING BY MOSQUITOES," BY RICHARD W. HAGAN ET AL., IN *SCIENTIFIC REPORTS*, VOL. 8, ARTICLE NO. 6804; MAY 1, 2018

Graphic by Amanda Montañez

HUMAN BEHAVIOR

Is the Friend of My Friend My Double?

A Stanford scientist explains how social networks can reveal hidden traits

People generally spend time with others who are like them, making it easy for data scientists to infer individuals' attitudes or personality attributes by analyzing their online and real-world social networks. Researchers call this tendency to seek out like-minded people "homophily." Think of the old adage "birds of a feather flock together," says Johan Ugander, a management science and engineering researcher at Stanford University, who studies this topic.

But in a surprising twist, Ugander and his graduate student Kristen M. Altenburger have found that some people are consistently drawn to those with certain dissimilar attributes. The researchers call the variation introduced by this phenomenon "monophily." Scientists previously assumed that heterogeneity would make it harder to draw conclusions about people based on friend networks. But Ugander and Altenburger's research demonstrates that monophily produces an effect whereby a person's friends of friends are similar to them in ways that immediate friends may not be. This could make it easier than anticipated for scientists to infer personal characteristics that might otherwise remain hidden—and it is one more way for data miners to trace personal information.

In a study published online in March in *Nature Human Behaviour,* Ugander and Altenburger analyzed three different types of networks: an online social network, a network of political blogs and a well-studied terrorist communication network. SCIENTIFIC AMERICAN spoke with Ugander about the research and its implications for individual privacy. An edited excerpt follows. —*Andrea Anderson*

Did the idea that "opposites attract" lead you to study monophily?

What led us to this project was the basic puzzling fact that there is barely any gender homophily, or consistent gender clustering, in online social networks. There is a lot of age clustering. The fact that there is almost no gender homophily has consequences for information diffusion and for data privacy. It turns out you can still predict people's gender based on the gender of their friends of friends by harnessing variability in the network—which is the counterintuitive starting point we spend most of the study trying to unpack and explain.

Is having Facebook friends with different political views an example of monophily?

With respect to political affiliation, you tend to surround yourself with similar others. That said, we did see a statistically significant amount of friend dissimilarity when it came to political affiliations in blogger networks. There are some people who are crossovers: they run liberal blogs but tend to link to conservative blogs, or vice versa.

Have you seen changes in how social networks are being studied in light of privacy concerns?

I view myself as somebody who tries to sound alarms and look at all the ways it is possible to predict things about individuals. There has been a healthy public conversation recently about the importance of protecting the information contained in connections in these online social networks. [Disclosure: Ugander was affiliated with Facebook Data Science from 2010 to 2014.]

On the other hand, there are benefits to understanding people better based on their position in a social network. A lot of social sciences research is focused on identifying authentic causal relationships and ruling

CONSERVATION

Caterpillar Heartbeats

Stressed butterflies reveal the problem with roadside habitats

Every year millions of breeding monarch butterflies in the U.S. and southern Canada search for milkweed plants on which to lay their eggs. Concern over dwindling habitat has prompted conservationists to create monarch-friendly spaces along roadsides, which are abundant within the butterflies' range and usually publicly owned. But traffic noise stresses monarch caterpillars out, a new study finds. They eventually do become desensitized to it—but that might spell trouble for them later on, too.

Noise pollution is known to disrupt the lives of birds, whales and other creatures. But until recently, scientists had never tested whether it triggers a stress response in insects. When Andy Davis, a conservation physiologist at the University of Georgia, noticed online videos of roadside monarch caterpillars apparently shuddering as cars zoomed by, he wondered how the constant clamor might affect them. Davis built a custom caterpillar heart monitor, fitting a small sensor into a microscope to precisely measure monarch larvae's heart rates as they listened to recordings of traffic sounds in the laboratory.

The hearts of caterpillars inundated with highway noise for two hours beat 17 percent faster than those of caterpillars in a silent room. But the heart rates of the noise-exposed group returned to baseline levels after hearing the traffic sounds nonstop for their entire 12-day larval development period, Davis and his colleagues reported in May in *Biology Letters.*

This desensitization could be problematic when the caterpillars become adults, Davis says. A rapid stress response is vital for monarch butterflies on their two-month journey to spend winters in Mexico, as they

JIM MCKINLEY *Getty Images*

out confounding factors. I am interested in understanding the extent to which we can describe individuals when we maybe don't have demographic data but do have this very rich network of social relationships.

Are you concerned that your research could be used for nefarious purposes?
Always. When one builds tools, one has a responsibility for how those tools are used. The main algorithm we study has been in the scientific literature since 2009. It was previously assumed that this method works for predicting an individual's attitudes or attributes if there are between-friend similarities in the network. But we are showing you do not need homophily, or likeness, for this approach to be effective.

narrowly escape predators and fight wind currents. "What I think is happening [on roadsides] is their stress reactions get overwhelmed when they're larvae and [could be] impaired when they travel to Mexico," Davis says.

Whether a noisy larval period reduces monarchs' survival rates remains unknown, notes Ryan Norris, an ecologist at the University of Guelph in Ontario, who was not involved in the study. But in any case, he believes roadside patches almost certainly drive up the butterflies' mortality as a result of collisions with cars. "There is so much potential road habitat for monarchs and other insects—it would be such a nice thing to capitalize on," Norris says. "But you just can't get around the traffic."

Davis adds: "I think roads and monarchs just don't mix." —*Erica Tennenhouse*

Illustration by Thomas Fuchs

ENVIRONMENT

Can Logging Help Jaguars?

Well-regulated forestry operations may conserve the big cats

Carefully logged forests can serve as critical habitat corridors for jaguars.

GETTY IMAGES

Jaguars, the largest big cats in the Americas, need a lot of space. One male can roam a territory spanning tens of square kilometers in search of mates and prey. But as ranching, crop farming and other forms of development encroach on tropical forests, these fearsome predators are losing ground.

A study published in the April issue of *Biological Conservation* offers hope. Scientists at the San Diego Zoo, the Wildlife Conservation Society, and Peru's National Forest and Wildlife Service found that in some lightly logged forests in Guatemala and Peru—certified by independent experts as "well managed"—jaguar densities were comparable to those in protected areas or other high-quality habitats. The study adds to a growing body of evidence that such forests can serve as important habitat corridors for the wide-ranging felines.

The researchers examined logging concessions in Guatemala's Maya Biosphere Reserve, an internationally recognized conservation area with three levels of protection: a core of national parks; a buffer zone that allows farming and ranching; and a multiuse area that allows limited logging but excludes livestock. All forestry operations in the reserve must be certified by the independent nonprofit Forest Stewardship Council (FSC). Established by an international consortium of conservation and industry groups in 1993, the FSC sets standards that permit very low intensity timber harvesting. Hunting in the forest areas studied is strictly banned, and access roads are guarded, although some subsistence hunting does occur elsewhere in the reserve.

The scientists used camera traps and a multispecies computational model to determine that jaguar density in the Maya Biosphere Reserve was comparable to that in similar habitats in the Gran Chaco region in Bolivia and Emas National Park in Brazil. In Peru, the researchers applied the same techniques to FSC-certified forests in the Amazon basin's Madre de Dios region and found even greater jaguar densities. In both Guatemala and Peru, they detected over 20 other mammal species, including prey for the big cats. The newly opened canopy may have encouraged growth of the plants they eat.

Anand Roopsind, a postdoctoral research fellow at Boise State University, who was not involved in the new study, says these findings reaffirm other research demonstrating the value of lightly logged forests for jaguar conservation. The FSC enjoys significant support among conservationists. But some have criticized aspects of the program, such as potential conflicts of interest; certifiers are hired directly by logging companies.

Nevertheless, both Roopsind and study co-author John Polisar, coordinator of the Jaguar Conservation Program for the Wildlife Conservation Society, stress that lightly logged areas can act as vital conduits between more heavily protected areas. "If we manage forests really well, the impact on big mammals is minimal, and it's much better than conversion to ranchland or agriculture," Roopsind says. Polisar goes a step further: "If jaguar densities are good," he says, "you know the forest is well managed." —*Amy Mathews Amos*

The Answer Physicists Don't Want You to Know

THE PROBLEM. In 1935 Erwin Schrödinger proposed an experiment to lampoon the current interpretation of Quantum Mechanics:

"One can even set up quite ridiculous cases [see figure below]… One would say that the cat still lives if meanwhile no atom has decayed. The [wave-function] of the entire system would express this by having in it the living and dead cat (pardon the expression) mixed or smeared out in equal parts."

Schrödinger's cat soon came to epitomize a class of problems known generically as the *measurement problem* ("the most controversial problem in physics today"). The problem arises because QM does not offer a picture of reality when no one is looking. Instead there are particles that are both here and there, equations that only give probabilities, and states that are in superposition. What was needed is a picture of reality at every moment—a believable picture.

THE ANSWER. In 1949, after completing his Nobel award–winning work on renormalization, Julian Schwinger felt that a new approach to Quantum Field Theory was needed:

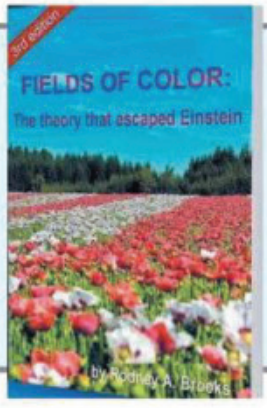
"The pressure to account for those [experimental] results had produced a certain theoretical structure that was perfectly adequate for the original task, but demanded simplification and generalization; a new vision was required… Like the silicon chip of more recent years, the Feynman diagram was bringing computation to the masses… But eventually one has to put it all together again, and then the piecemeal approach loses some of its attraction… Quantum field theory must deal with Bose-Einstein fields and Fermi-Dirac fields on a fully equivalent footing… There was my challenge."

Schwinger's challenge led to a series of six papers titled "A Theory of Quantized Fields," published in 1951–54. This theory provides a believable picture of reality at every moment:

- Reality is made of fields. There are no particles.
- Field strength is described by Hilbert algebra, not by simple numbers. (Schwinger called it measurement algebra.)
- The use of Hilbert algebra leads to field quantization: The fields are made of independent units called quanta. Each quantum lives a life and dies a death of its own.
- The state of a system, or of a region of space, is described by giving the (expectation value of) field strength for each quantum at every point within that region.
- The quanta evolve and interact according to the field equations.
- There are no superpositions other than the use of Hilbert space to describe field strength.
- When a quantum is absorbed it collapses; that is, it disappears everywhere instantaneously, a process not described by the field equations. Collapse also violates the principle of locality (what happens at a given location can only be affected by events at that location). However, collapse has been shown experimentally to occur. This is not the first time physics has had to accept a counterintuitive result. At least QFT provides a reason: each quantum is an indivisible unit. (Quantum collapse was covered more fully in Schwinger's later development of source theory.)
- If two quanta are created in the same event, their properties are correlated or entangled; if one collapses, so does the other.

Schwinger's theory provides a believable picture of reality at every moment, and a simple answer for Schrödinger's cat: The cat is alive until a radiated quantum collapses into an atom in the Geiger counter; after that the cat is dead. Unfortunately, Schwinger's formulation of Quantum Field Theory is mostly unknown, and few physicists have read these papers. Instead it is Richard Feynman's version, based on particles and virtual particles, that has come to the fore—a theory that Feynman himself called "absurd."

The above material is excerpted from my article "A Physics Tragedy," which is on the arXiv website but was rejected by a physics journal. The reason given was that the theory is too controversial. Well, I don't think a theory developed by a Nobel laureate physicist who was once called "the heir apparent to Einstein's mantle"—a theory that solves the measurement problem and many other problems in Quantum Mechanics and Relativity—should be considered "controversial." That's why I'm paying for this ad—to tell as many people as possible that physics does make sense. More discussion and insight about this wonderful theory can be seen by reading my article (Google "A physics tragedy") or better yet, by reading my book "Fields of Color"(go to quantum-field-theory.net and click on "Look Inside"), the third edition of which has a 4.8 star rating on Amazon.



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ENGINEERING

I(KEA), Robot

A new machine can assemble a DIY chair

IKEA furniture is no problem for this bot.

NANYANG TECHNOLOGICAL UNIVERSITY

Anyone who has spent an afternoon puzzling over IKEA furniture parts will appreciate how tempting it would be to let a robot do the job. The Swedish company's complex DIY kits are something of a benchmark for roboticists, who have worked for years to build automatons smart and dexterous enough to fit screws and wood pegs into holes.

Engineers at Nanyang Technological University in Singapore have now assembled a STEFAN chair using a two-armed robot, whose sensors and programming enabled it to fit most of the pieces together without human help. The team reported its feat in April in *Science Robotics.* Using its arms, parallel grippers, sensors and 3-D camera, the machine followed about 50 steps of instructions to complete the chair's frame in about 20 minutes.

Furthermore, the robot was made of off-the-shelf parts that "are already mass-produced, so the technology we developed here can be deployed in actual factories in the very near future," says Quang-Cuong Pham, an assistant professor of mechanical and aerospace engineering, who built the robot with Francisco Suárez-Ruiz and Xian Zhou, both then at Nanyang.

The engineers programmed the robot using conventional computer code instead of training the device to assemble parts via machine learning. They focused on the robot's perception, planning and control capabilities rather than the more abstract reasoning enabled by artificial intelligence, Pham says.

The robot's arm movements may look slow and tedious, but its ability to fit pegs into holes addresses "a superhard problem in robotics," says Ross Knepper, an assistant computer science professor at Cornell University, who was not involved in the Nanyang research. Knepper was part of a Massachusetts Institute of Technology team that in 2013 built the "IkeaBot" system of autonomous robots, which successfully assembled the furniture company's LACK side tables.

"Whereas my work used vision to solve the peg-in-a-hole problem, the Nanyang researchers are doing it through tactile feedback—feeling whether or not the peg went into the hole," Knepper says. "The applications [of these two approaches] are both for IKEA furniture, but the contributions to robotics are very different."

The Nanyang team's technology is meant to be reprogrammable for different tasks—including possibly assembling other kinds of furniture. "The dream," Knepper says, "is still to have one robot system that can assemble IKEA's entire catalog—but we're not there yet." —*Larry Greenemeier*

MEDICAL TECH

Body Sense

Experimental technique restores an amputee's lost sense of limb position

Close your eyes and touch two fingers together. The sense that enables this gesture is proprioception—feedback that tells your brain where body parts are and what they are doing. "Proprioception is essential to all human movement," says Tyler Clites, a biomedical engineer at the Massachusetts Institute of Technology.

Scientists have made huge strides in controlling robotic limbs with the nervous system, but providing such sensory feedback has proved more challenging. Now, however, a team led by biomechanical engineer Hugh Herr, also at M.I.T., has created a prosthetic leg with proprioception. "That's one of the fundamental pieces of prosthetics that has been missing," says biomedical engineer Paul Marasco of the Cleveland Clinic, who was not involved in the study.

Muscles that are linked so that one stretches when the other contracts are central to a sense of limb placement. In a traditional amputation, surgeons tie the remaining muscles to bone, limiting movement and breaking this dynamic relationship. The new technique, described in May in *Science Translational Medicine,* involves grafting new muscle pairs onto the amputation site of a patient with below-knee amputation. Skin electrodes pick up electrical activity in the grafted muscles and use it to control motors in the prosthetic leg's ankle, and sensors in the prosthetic foot transmit proprioceptive feedback to the muscles. "Returning that back into the system that's built for handling it is a pretty big deal," Marasco says.

The procedure restored near-natural limb control. When climbing stairs, the patient unconsciously flexed his robotic foot like uninjured people do. "This is a first demonstration of emergent reflexive behaviors—these important yet unintentional behaviors that come out as we walk on difficult terrains," says Clites, the study's lead author. In another first, the researchers showed that including feedback from torque sensors in the ankle allowed the patient to more precisely control how hard he pushed on a pedal. "What's new here is the ability to provide feedback the brain knows how to interpret as sensations of position, speed and force," Clites explains.

These sensations appear to imbue a sense of ownership. "The patient said things that describe an embodiment, like 'The robot has become part of me' and 'I have my leg back,'" says Herr, who is an amputee himself. When the patient's daughter asked him if he felt like a cyborg, he told her, "No, I felt like I had a foot." —*Simon Makin*

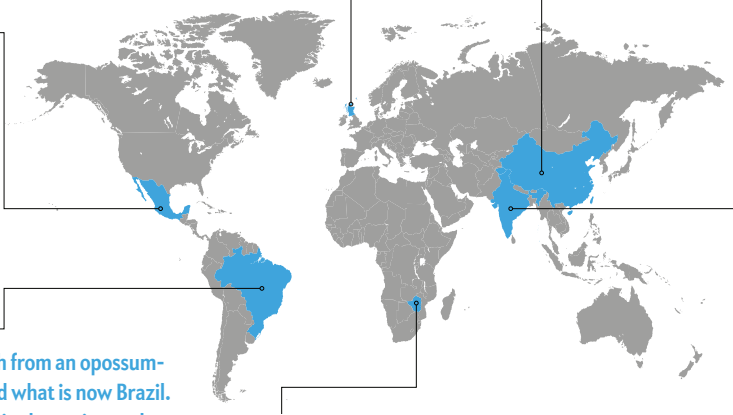
IN THE NEWS

Quick Hits

SCOTLAND
Microsoft has begun installing computer servers on the seafloor near Scotland's northern islands as an alternative to data farms on land. The idea is that the water will create a cool environment for the servers.

CHINA
The Chinese government announced it will take on a new role in monitoring scientific misconduct. Such cases, previously handled by institutions, will be maintained in a national database and could disqualify scientists from applying for certain research opportunities and jobs.

MEXICO
Cavers and scientists in the Mexican state of Oaxaca discovered that the world's ninth-largest known cave is deeper than previously thought. With a depth of 5,118 feet, it houses dozens of species not found anywhere else.



INDIA
Solar power is on the rise in India. In the first quarter of 2018, newly installed panels produced 3,269 megawatts. Solar power now accounts for 6.3 percent of India's total power output.

BRAZIL
Archaeologists discovered a tooth from an opossum-sized creature that once inhabited what is now Brazil. The oldest known mammal found in the region to date, it lived sometime between 87 million and 70 million years ago, when *Tyrannosaurus rex* still roamed.

ZIMBABWE
The oldest African baobab tree (roughly 2,500 years of age) died within the past decade, researchers found. Nine of the 13 oldest baobabs—all in Africa—have perished since 2005, possibly as a result of unprecedented climate change.

—Maya Miller

For more details, visit
www.ScientificAmerican.com/aug2018/advances

Ba-Boom! There Goes Your Hearing

New discoveries offer hope for noise-induced hearing loss

By Claudia Wallis

The most common injury to American troops is silent and invisible. And I don't mean PTSD: hearing loss and tinnitus—ringing in the ear—top the list of service-related disabilities for veterans. They are an unsung consequence of prolonged exposure to roaring environments, such as the deck of an aircraft carrier, or, increasingly, to the sudden blast of a roadside bomb. One fifth of veterans of the Iraq and Afghanistan wars are affected, according to a 2017 analysis. Hearing loss has enduring social and economic impacts, harming one's ability to earn a living and the quality of relationships. The Department of Defense is in the process of calculating the enormous financial costs.

Noise trauma is a civilian problem, too. Up to 24 percent of U.S. adults have a hearing loss consistent with damage from noise, and, shockingly, 20 percent of teenagers have hearing issues, although whether it is caused by blaring earbuds or something unrelated to booming sounds is unknown. Now a major step has been taken toward understanding the precise mechanisms of injury from loud blasts. Along with that discovery comes an intriguing opportunity to intervene and preserve hearing.

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*.

The inner ear, which processes sound, is protected by one of the densest bones in the body, the otic capsule, making it difficult to visualize its tiny structures with conventional imaging. But a tool developed a few years ago by John Oghalai, then at Stanford University and now chair of otolaryngology at the University of Southern California's Keck School of Medicine, uses a laser-based technology called optical coherence tomography (OCT) to get the picture. OCT is already used to look at the retina of the eye. "We built this into a special microscope so that we could look inside the cochlea, the auditory portion of the inner ear," Oghalai explains.

Using OCT in mice, Oghalai and his colleagues were able to see for the first time what happens when the ear is exposed to an explosive blast—akin to a roadside bomb—and reported the results in a recent paper. First, the shock wave overwhelms the tiny hair cells that line the snail-shaped cochlea. The delicate hairs of these cells "can detect very quiet sounds," Oghalai says, "and when you have a big blast wave, it's just going to break them." In the wake of the destruction, potassium ions build up in the inner ear fluid called endolymph, pulling in more liquid by osmosis. The resulting swelling begins to damage the synapses linking surviving hair cells to auditory neurons. In the mouse model, the hair cells lose about half their connections to auditory nerve fibers, which means they cannot send proper signals for the brain to interpret as sounds.

When the brain loses sound input, it fills the gap with the buzzing din known as tinnitus. At least that is the leading theory. Oghalai likens tinnitus to phantom limb pain. It can be temporary, as often occurs after an earsplitting rock concert, or infuriatingly constant.

In his mouse studies, Oghalai saw a chance to intervene in the window between the instant harm to hair cells and the delayed destruction of nerve synapses. His team was able to protect the latter by injecting a very salty solution through the eardrum, which reversed the buildup of fluid in the cochlea.

Could this approach lead to a battlefield intervention? A lot more research is needed, but saving neural connections, even if some hair cells are lost, could potentially make a functional difference in hearing. Past research suggests that lost synapses may lead to the common conundrum of being able to detect faint sounds on a hearing test and yet not being able to distinguish speech in a noisy environment—an issue that hearing aids do not fix very well.

"It would be great to have the ability to intervene in the minutes or hours or days after an exposure," says Sharon Kujawa, director of audiology research at Massachusetts Eye and Ear. Currently the remedy for sudden hearing loss—such as after a firecracker mishap on the Fourth of July—is to treat with corticosteroids.

Better treatments are a priority for the U.S. military, as reflected in the 2012 founding of the Department of Defense's Hearing Center of Excellence. A variety of new therapies are in early stages of development to prevent and even reverse damage, says Tanisha Hammill, who coordinates research at the center.

Perhaps the most exciting thing about Oghalai's work, Kujawa says, is the advent of a "new and powerful technique" to peer into the living ear and watch hidden events unfold. The audiology world is all eyes and ears for the opportunities it will open. SA

Illustration by Celia Krampien

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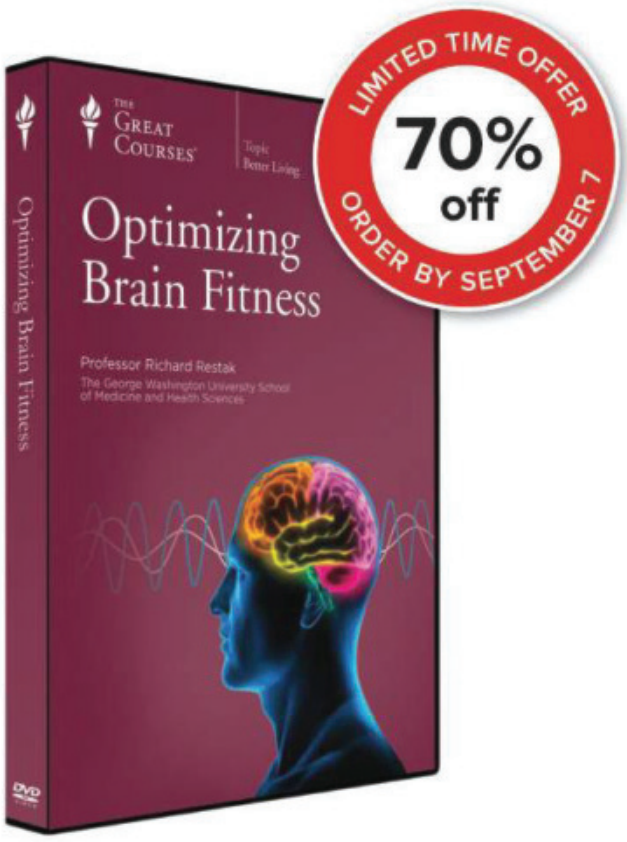

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I'll Have My AI Call Your AI

Google's new assistant sounds almost scarily human

By David Pogue

"Any sufficiently advanced technology is indistinguishable from magic," Arthur C. Clarke famously wrote. That line must have zoomed through 5,000 audience brains when, at Google's developer conference in May, CEO Sundar Pichai demonstrated a new artificial-intelligence product called Google Duplex.

What Duplex does is to make reservations at restaurants and hair salons—by placing a phone call to their human receptionists. It perfectly impersonates a human voice, complete with "ums," hesitations and realistic inflections. Here's an excerpt from the demo:

Duplex AI: "Hi. I'm calling to book a woman's haircut for a client. Um, I'm looking for something on May 3?"
Human receptionist: "Sure. Give me onnne second…."
AI: "Mm-hmm."
Human: "Sure, what time are you looking for, around?"
AI: "At 12 P.M."
Human: "We don't have 12 available. The closest we have to that is a 1:15."
AI: "Do you have anything between 10 A.M. and, uh, 12 P.M.?"
Human: "Okay, we have a 10 o'clock."

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

But here's the key: in the examples Pichai played onstage, the receptionists clearly didn't know they had been talking to an AI. Many in the Twittersphere were aghast. "I am genuinely bothered and disturbed at how morally wrong it is for the Google Assistant voice to act like a human and deceive other humans," tweeted @BridgetCarey. "This is horrible and so obviously wrong," tweeted @Zeynep. Nobody wants to be duped by a robot.

After the demo, however, I interviewed Rishi Chandra, vice president for home product management at Google. "We're gonna be spending a bunch of time on different ways we can let the restaurant know," he reassured me. "We want to be very transparent that this is coming from Google." In states where it is required, Duplex will also inform the human that the call is being recorded.

The other worry, of course, is that once this technology is out in the wild, it will be a handy tool for scammers, robo callers and other sinister social engineering hacks. But that fear, too, is overblown. Duplex is incredibly limited; it must be individually coded for each kind of situation. For now, all it can do is call restaurants (where it anticipates queries such as "How many in your party?" and "Any vegetarians?") and hair salons ("Is this for a man's cut or a woman's cut?"). Duplex can't call a dentist, a nail salon or an airline, let alone voters or potential customers.

Duplex is also in its very earliest stages. Google plans to proceed with what it calls a "small experiment," using only the hair salon and restaurant routines (plus one that asks businesses of any kind for their hours). Meanwhile Duplex really does fill a need. "The reality is that many businesses today are not digital businesses," Chandra says. "How do we bridge this notion that I want a haircut or I want to order a pizza, but my local pizza joint's not online? [Today] a very narrow, small number of people can have personal assistants doing all these things for them. Now can we make that accessible to everyone?"

Look, it's natural to fear new technology. Our minds always leap to dystopian extremes. We once feared the automobile, the airplane and the microwave oven, too. But we work it out. We test, we observe side effects, we design guidelines and we accept the technologies that are worth accepting.

Google Duplex will quickly stop seeming scary. Receptionists will become accustomed to getting calls from Duplex just as we got used to speaking to other AI voices, such as Siri on our phones or automated menu systems on customer service hotlines. YouTube will probably fill up with recordings of pranksters trying to lead Duplex conversationally astray. We'll tell our grandchildren about how we used to have to spell our last name six times on the phone.

Someday small businesses will get their own versions of Duplex so they don't have to waste time on phone calls, either. Your AI will call their AI—no human interaction required. Then the only question is, What will we do with all our new free time? SA

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Illustration by Jay Bendt


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NEUROSCIENCE

THE SEVENTH SENSE

Long thought to be divorced from the brain, the immune system turns out to be intimately involved in its functioning

By Jonathan Kipnis

Illustration by Mark Ross

Jonathan Kipnis is a professor and chair of neuroscience and director of the Center for Brain Immunology and Glia at the University of Virginia School of Medicine. His research focuses on interactions between the nervous and immune systems.

FOR DECADES ANATOMY TEXTBOOKS TAUGHT THAT THE TWO MOST COMPLICATED systems in the body—the brain and the immune system—existed in almost complete isolation from each other. By all accounts, the brain focused on the business of operating the body, and the immune system focused on defending it. In healthy individuals, the twain never met. Only in certain cases of disease or trauma did cells from the immune system enter the brain, and when they did so, it was to attack.

But in recent years a rush of new findings has revolutionized scientists' understanding of the two systems. Mounting evidence indicates that the brain and the immune system interact routinely, both in sickness and in health. The immune system can help support an injured brain, for example. It also plays a role in helping the brain to cope with stress and aids such essential brain functions as learning and social behavior. What is more, the immune system might qualify as a kind of surveillance organ that detects microorganisms in and around the body and informs the brain about them, much as our eyes relay visual information and our ears transmit auditory signals. In other words, the brain and immune system do not just cross paths more often than previously thought—they are thoroughly entwined.

IN BRIEF

Conventional wisdom long held that the brain and the immune system do not interact in healthy individuals. **In recent years,** however, researchers have amassed ample evidence that the two systems are closely connected. **Scientists still have** much to learn about this new field of neuroimmunology, but its findings could lead to new insights into—and therapies for—a number of neurological diseases.

Researchers are still in the early stages of studying this burgeoning new field of neuroimmunology. But already it is becoming clear that the brain's response to immunological information and how that information controls and affects brain circuitry could be the key to understanding many neurological diseases—from autism to Alzheimer's—and developing new therapies for them. Efforts to treat such disorders have typically met with disappointing results because most drugs cannot easily penetrate the brain. The findings from neuroimmunology raise the tantalizing possibility that targeting the immune system might be a more effective tactic.

RECEIVED WISDOM

TO UNDERSTAND THE SIGNIFICANCE of these discoveries, it helps to know a bit about how the brain and immune system are structured and how they work. The brain is our supercomputer and master regulator. Working with the spinal cord and several cranial nerves, which together constitute the central nervous system (CNS), it controls all the body's functions. Given the vast scope of the brain's responsibility, it is perhaps no surprise that the organ is incredibly intricate. Its basic functional units are neurons, which occupy roughly half of the brain. The human brain contains an estimated 100 billion neurons interlinked by approximately 100 trillion connections called synapses. The neurons, along with various types of nonneuronal cells called glia, make up the brain's parenchyma, the functional tissue responsible for processing information. Other key players include stromal cells, which physically support the parenchymal tissues, and endothelial cells, which compose the blood vessels that supply the brain and form the blood-brain barrier, which limits the passage of substances from other parts of the body into the brain.

For its part, the immune system has two major components, innate immunity and adaptive immunity. Innate immunity is the more primitive element, having evolved about a billion years ago in the first cells to detect and dispatch enemy forces quickly but without much precision. It is the body's first line of defense against pathogens, consisting of physical and chemical barriers to them, as well as cells that kill them. Innate immunity initiates the inflammatory response, in which white blood cells swarm the site of infection and churn out proteins that induce heat and swelling to confine and destroy pathogens. Adaptive immunity, which evolved after the innate component, consists mainly of cells called T lymphocytes and B lymphocytes, which can recognize a specific pathogen and mount a corre-

spondingly targeted attack against it. In a perfect world, all adaptive immune cells would take aim only at external pathogens and would not touch the body's own proteins or cells. But in about 1 percent of the population, adaptive immunity loses control and attacks cells in the individual's own tissues, causing autoimmune diseases such as multiple sclerosis, arthritis and certain forms of diabetes, among many others. Still, the system has an impressive success rate, targeting foreign invaders exclusively in some 99 percent of individuals.

Researchers long thought that the immune system worked by simply distinguishing an organism's own constituents from nonself ones. But eventually more complex theories began to emerge. In the 1990s Polly Matzinger of the National Institute of Allergy and Infectious Diseases proposed that the immune system recognizes not only foreign invaders but also damage to tissues. This notion gained support from the subsequent identification of molecules that are released by injured, infected or otherwise damaged tissues. These molecules attract the attention of the immune cells, triggering a cascade of events that lead to activation of the immune system, recruitment of immune cells to the site of injury, and elimination (or at least an attempt at elimination) of the alarm-causing invader or injury. In addition, experiments have found that suppression of adaptive immunity accelerates the development and growth of tumors and slows down the healing process in damaged tissues. Such findings show that the immune system—once considered to be laser-focused on protecting the body from foreign invaders—actually has a far greater purview: regulating the body's tissues to help them to maintain equilibrium in the face of all manner of insults, whether from without or within.

But until recently, scientists were quite sure that this purview did not extend to the brain. As early as the 1920s, researchers observed that although the healthy brain harbors immune cells native to the CNS called microglia, immune cells from elsewhere in the body (so-called peripheral immune cells) are not usually found there. The blood-brain barrier keeps them out. In the 1940s biologist Peter Medawar, who won a Nobel Prize for his research, showed that the body is slower to reject foreign tissue grafted onto the brain than grafts placed elsewhere in the body. The brain was "immune privileged," Medawar argued, impervious to the immune system. Peripheral immune cells do appear in the parenchyma and spinal cord of patients with brain infections or injuries, however. And mouse studies demonstrate that these cells cause the debilitating paralysis associated with the disease. Based on such findings, scientists suggested that the brain and immune system have nothing to do with one another except in cases of pathologies that allow immune cells to enter the CNS and wage war on neurons.

(Exactly how the immune cells breach the blood-brain barrier in such instances is uncertain. But it may be that the barrier gets activated during brain diseases in ways that allow immune cells to cross over. In a seminal study published in 1992, Lawrence Steinman of Stanford University and his colleagues found that in mice with a condition similar to multiple sclerosis, peripheral immune cells make a protein called $\alpha 4\beta 1$ integrin that allows them to penetrate the barrier. A drug that inhibits the interaction between the integrin and the endothelial cells, Tysabri, is one of the most potent treatments for multiple sclerosis patients.)

The theory that the brain and immune system lead separate lives prevailed for decades, but it was not without skeptics. Some wondered why, if the immune system is the body's main fighting force against pathogens, the brain would give up ready access to such a system of defense. Supporters of the theory responded that the blood-brain barrier prevents the entry of most pathogens into the brain, so the brain has no need to accommodate the immune system, especially if it could cause problems by being there—doing battle with neurons, for instance. The skeptics pointed out that several viruses, as well as some bacteria and parasites, can access the brain. And far from ignoring these transgressions, the immune system responds to them, rushing to the brain to manage the invading agent. Perhaps the scarcity of pathogens in the brain is not because the blood-brain barrier is so effective at filtering them out but because the immune system is so efficient at fighting them. Indeed, studies have shown that immunosuppressed patients suffer complications that often affect the CNS.

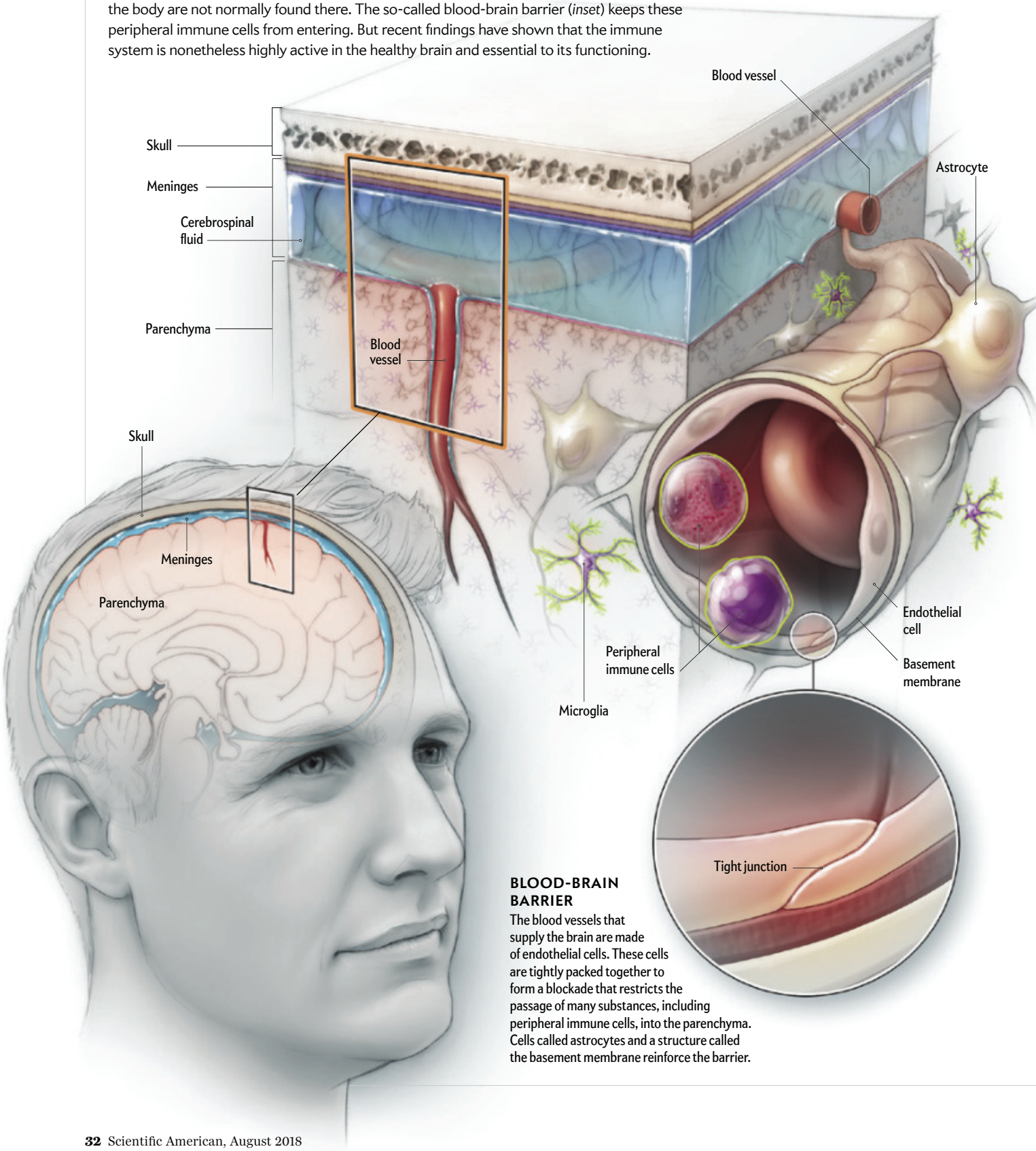
Mice lacking adaptive immunity showed not only impaired spatial learning behavior but also compromised social behavior.

REWRITING THE TEXTBOOKS

EVENTUALLY SUCH ARGUMENTS and a growing appreciation of the immune system's role in supporting damaged bodily tissues prompted researchers to reexamine its role in the CNS. When they took a closer look at the CNS in rats and mice with spinal cord injuries, they found it overrun with infiltrating immune cells. In experiments carried out in the late 1990s, Michal Schwartz of the Weizmann Institute of Science in Rehovot, Israel, showed that eliminating immune cells after injury to the CNS worsens neuron loss and brain function, whereas boosting the immune response improves neuron survival. More recently, studies led by Stanley Appel of Houston Methodist Hospital and

The Brain-Immune Connection

The healthy brain was long thought to be off-limits to the immune system. Although the brain harbors native immune cells known as microglia, immune cells that originate elsewhere in the body are not normally found there. The so-called blood-brain barrier (*inset*) keeps these peripheral immune cells from entering. But recent findings have shown that the immune system is nonetheless highly active in the healthy brain and essential to its functioning.



BLOOD-BRAIN BARRIER
The blood vessels that supply the brain are made of endothelial cells. These cells are tightly packed together to form a blockade that restricts the passage of many substances, including peripheral immune cells, into the parenchyma. Cells called astrocytes and a structure called the basement membrane reinforce the barrier.

CIRCUMVENTING THE BARRIER

Until recently, researchers thought that the membranes surrounding the parenchyma, called the meninges, functioned mainly to carry the cerebrospinal fluid that buoys the brain **A**. New findings show there is more to the story **B**. The meninges turn out to contain lymphatic vessels that remove toxins and other waste from the parenchyma and can relay information about brain infections to the immune system. The meninges also house an array of peripheral immune cells that can communicate with the brain by means of proteins they manufacture called cytokines. Cerebrospinal fluid from the meninges enters the parenchyma through spaces surrounding the blood vessels supplying the brain and can thus carry cytokines from the peripheral immune cells deep into the brain to influence neuron behavior.

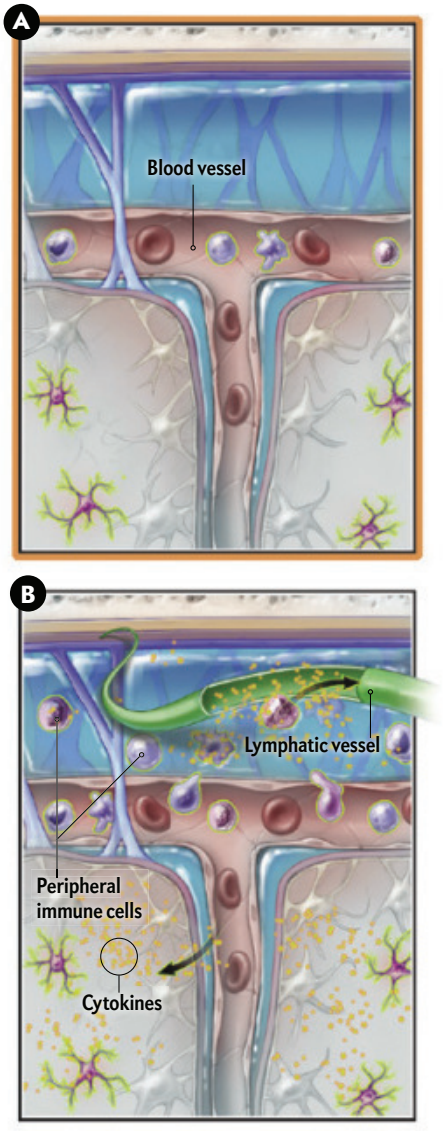


Illustration by David Cheney

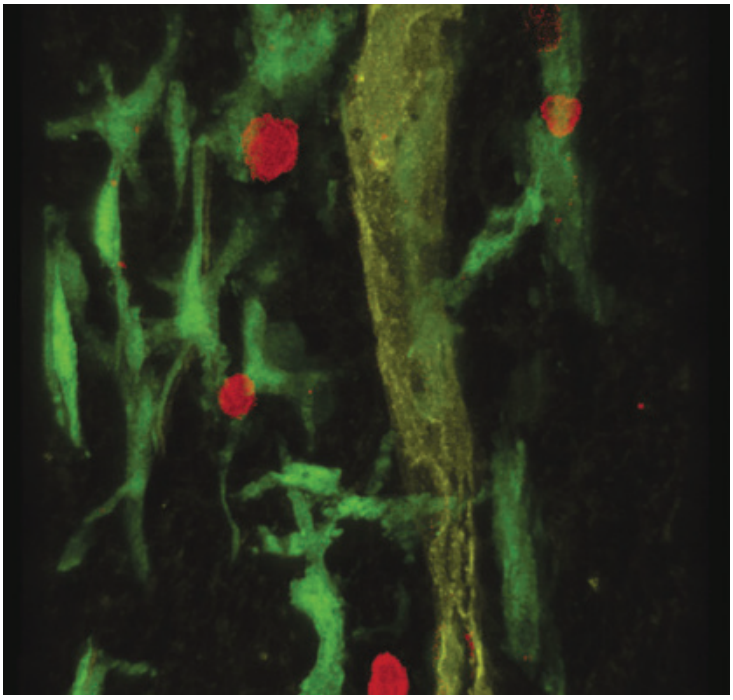
Mathew Blurton-Jones of the University of California, Irvine, have found that amyotrophic lateral sclerosis and Alzheimer's disease develop more severely and rapidly in mice engineered to lack adaptive immunity than in normal mice. Restoring adaptive immunity slows the progression of such diseases. These results indicate that immune cells help neurons rather than only hurting them, as was previously supposed.

At first glance, the immune system's intervention to protect the injured CNS does not make sense. When the CNS sustains trauma, the immune system mounts an inflammatory response, releasing toxic substances to eliminate pathogens and, in some cases, to remove damaged cells, which thereby restores equilibrium. The inflammatory response is a blunt instrument, however, taking out some of the good guys along with the bad. In other tissues, such collateral damage is tolerable because the tissues regenerate readily. But CNS tissue is limited in its ability to grow back, which means that damage from the immune response is typically permanent. Given the potential for immune activity to wreak havoc in the brain, the costs of intervention could often outweigh the benefits. But maybe the immune response observed after CNS injury is simply an extension of the immune response that aids brain function under normal conditions.

Recent studies support this notion. My collaboration with Hagit Cohen of Ben-Gurion University of the Negev in Israel and Schwartz revealed that mice that experience stressful stimuli, such as exposure to the smell of their natural predators, develop an immediate stress response—in this case, hiding in a maze rather than exploring it. In 90 percent of cases, the stress response disappears within hours or days. But for the other 10 percent, the response persists for days to weeks. Mice in the latter group can thus serve as an animal model for post-traumatic stress disorder (PTSD). Interestingly, when mice lacking adaptive immunity are compared with mice that have a normal immune system, the incidence of PTSD is increased severalfold. These results provided the first indication that the immune system supports the brain not only during infections and injuries but also during psychological stress. Moreover, some evidence links the immune system to PTSD in humans.

Though not as nerve-racking as exposure to a predator, tasks that require learning are also stressful. Think of preparing for an exam or even cooking a new recipe. Could an inability to deal with stress hinder the learning process itself? To test this hypothesis, my colleagues and I compared the performance of mice lacking adaptive immunity with that of a control group in various behavioral tests. We found that mice without adaptive immunity, unlike the controls, performed poorly in tasks requiring spatial learning and memory, such as figuring out the location of a platform hidden in a large pool of water. We have since shown that the mice lacking adaptive immunity exhibit not only impaired spatial learning behavior but also compromised social behavior, preferring to spend their time with an inanimate object rather than another mouse.

As evidence that the immune system plays important roles in different brain functions has accumulated, new unknowns have emerged. How the immune system exerts its influence in the CNS is one. After all, apart from microglia, no immune cells are present within the parenchyma of healthy individuals. Clues have come from proteins called cytokines, which are made by immune cells and influence the behavior of other cells. Cytokines released by peripheral immune cells can affect the brain. They presumably gain entrance through brain areas that lack the regular blood-



STAINED TISSUE highlights T cells (*red*) and macrophages (*green*), as well as a lymphatic vessel (*yellow*), in the meninges.

ANTOINE LOUVEAU *University of Virginia School of Medicine*

brain barrier and could directly impact the brain through the vagus nerve, which runs from the brain to the abdomen. The available evidence suggests that the immune cells within the meninges—the membranes that surround the brain—are also the source of the cytokines that may affect brain function. How these immune cells enter the meninges, how they circulate there and how they produce their cytokines are currently subjects of intensive research.

Recently my colleagues and I made an intriguing discovery that bears on these questions: It has to do with how the body gets rid of toxins and waste. The tissues in the body contain two types of vessels. Just as a house has two types of pipes that serve it, one for water and the other for sewage, our tissues have the blood vessels that carry oxygen and nutrients to them and the lymphatic vessels that remove toxins and other waste materials that the tissues produce. The lymphatic vessels also ferry antigens—substances capable of inducing an immune response—from the tissues into tissue-draining lymph nodes, where they are presented to immune cells to be inspected for information on the draining tissue. On detecting a problem, such as injury or infection in the tissue, the immune cells activate and migrate to the affected tissue to try to resolve the problem.

Because of the enduring belief that the healthy brain is disconnected from the immune system and because the parenchyma does not contain lymphatic vessels, scientists long assumed that neither the brain nor the rest of the CNS is serviced by the lymphatic network. Yet this assumption presented a conundrum: Why would the brain not report to the immune system about potential problems that might be affecting it and that the immune system might help solve? And how does the immune system nonetheless receive information on brain infections? Furthermore, studies have found that brain injuries provoke a strong immune response in lymph nodes located outside the brain. How is that possible?

Fascinated by the immune activity in the meninges and its effects on brain function, my colleagues and I decided to take a closer look at those membranes. In doing so, we made a serendipitous discovery: it turns out they house lymphatic vessels. Several other research groups have since made similar findings in fish, mice, rats, nonhuman primates and humans. The results confirm earlier proposals for a link between brain and lymph system that were made some 200 years ago but largely dismissed. These vessels represent a bona fide lymphatic network that drains the CNS, a missing link that can relay information about brain infections and injuries to the immune system.

The presence of both lymph vessels and immune cells in the meninges means researchers need to rethink the exact function of these membranes. The traditional explanation holds that they simply carry the cerebrospinal fluid, which buoys the brain. But considering how densely packed the brain's constituent cells are and how sensitive its neurons are when they fire their electrical signals, perhaps moving all of the brain's immune activity to its meningeal borders was evolution's solution to the problem of allowing the immune system to serve the entire CNS without interfering with neuron function.

The discovery of the brain's lymphatic vessels revealed how the immune system receives information about tissue damage in the CNS. For insights into how the meningeal immune cells actually communicate with the parenchyma and affect it from afar, however, we have to turn to another branch of the brain's waste-removal system. In addition to the lymphatic network that we discovered, the CNS also has a network of channels in the parenchyma through which the cerebrospinal fluid gets access to the brain. Maiken Nedergaard of the University of Rochester has dubbed this network the glymphatic system. The fluid enters the parenchyma through spaces surrounding the arteries that pipe into the brain from the meninges and washes through the tissues until it is recollected in the spaces surrounding the veins and then returned to the pool of cerebrospinal fluid in the meninges. This flow of fluid presumably carries immune molecules such as cytokines from the meninges into the parenchyma, where they can exert their influence.

Studies of cytokines have illuminated how they modulate behavior. For example, Robert Dantzer, now at the University of Texas MD Anderson Cancer Center, and Keith Kelley of the University of Illinois at Urbana-Champaign have determined that interleukin-1 beta ini-

tiates sickness behavior, the name given to the constellation of behaviors people typically exhibit when ill, such as sleeping excessively, eating less and withdrawing from social contact. And my own team has recently shown that interferon gamma, a cytokine produced by meningeal T cells, interacts with neurons in the brain's prefrontal cortex, which, among its other functions, is involved in social behavior. Surprisingly, this cytokine does not exert its influence via the brain's resident immune cells (the microglia) but rather those neurons that control the circuits associated with social behavior. In fact, the cytokines are essential for proper functioning of these circuits: in the absence of T cells or their interferon gamma, these neurons fail to regulate the circuits correctly, and circuit hyperactivity ensues—a disturbance linked to social deficits. Thus, a cytokine produced by immune cells in the meninges can change the activity of neurons, thereby altering the function of the circuit and changing the underlying behavior.

Interferon gamma is not the only immune molecule that affects brain function. Mario de Bono of the MRC Laboratory of Molecular Biology in England and his colleagues have shown that another cytokine, IL-17, activates sensory neurons in the roundworm *Caenorhabditis elegans* and changes the creature's oxygen-sensing behavior. And recent work in mice by Gloria Choi of the Massachusetts Institute of Technology and her collaborators has demonstrated that IL-17 can interact with neurons in the brain's cortex and alter behaviors related to autism spectrum disorder.

ANOTHER SENSE ORGAN?

ONE MIGHT WONDER why an organ as powerful as the brain needs to be controlled or supported by the immune system to function property. I have developed a hypothesis for why the two systems are so closely linked. We have five established senses—smell, touch, taste, sight and hearing. The sense of position and movement, or proprioception, is often referred to as the sixth sense. These senses report to the brain about our external and internal environments, providing a basis on which the brain can compute the activity needed for self-preservation. Microorganisms abound in these environments, and the ability to sense them—and defend against them when needed—is central to survival. Our immune system excels at exactly that, with innate immunity's ability to generally recognize patterns and types of invaders and adaptive immunity's talent for recognizing specific invaders. I propose that the defining role of the immune system is to detect microorganisms and inform the brain about them. If, as I suspect, the immune response is hardwired into the brain, that would make it a seventh sense.

There are ways to test this hypothesis. Because the brain's circuits are all interconnected, interference with one circuit tends affect others as well. For instance, food tastes different when our sense of smell is impaired. Evidence that interference with immune input disturbs other circuits would support the idea that the immune response is a hardwired seventh sense. One possible example comes from sickness behavior. Perhaps an overwhelming input of signals from the seventh sense informing the brain of pathogenic infection spills over and disrupts the circuits that modulate sleepiness, hunger, and so on during illness, leading to this characteristic set of behavioral changes that develop in affected individuals. Alternatively, the microorganism information relayed to the brain by the immune sensory system may prompt the brain to initiate sickness behavior as a means of protecting the sick individual by minimizing exposure to other pathogens and conserving energy.

Our knowledge of the relationship between the brain and the immune system is still in its infancy. We should not be surprised if new discoveries in this field over the next 10 or 20 years reveal the two systems in a completely different light. I hope, though, that the fundamental understanding we possess today will be enriched by the results of such research rather than overturned altogether. One research priority will be mapping how the immune components and neural circuits connect, interact and interdepend in health and disease. Knowing those relations will allow investigators to target immune signaling in their treatment of neurological and mental disorders. The immune system is an easier drug target than the CNS, and it is plausible that one day repair of the immune system through gene therapy or even the replacement of a flawed immune system via bone marrow transplantation will be a viable means of treating brain disorders. Given the myriad immune alterations in brain disorders, research on neuroimmune interactions will probably continue for decades to come and gradually reveal to us even deeper mysteries of the brain. SA

If the immune response is hardwired into the brain, that would make it a seventh sense.

MORE TO EXPLORE

Structural and Functional Features of Central Nervous System Lymphatic Vessels. Antoine Louveau et al. in *Nature,* Vol. 523, pages 337–341; July 16, 2015.

Multifaceted Interactions between Adaptive Immunity and the Central Nervous System. Jonathan Kipnis in *Science,* Vol. 353, pages 766–771; August 19, 2016.

Immune System: The "Seventh Sense." Jonathan Kipnis in *Journal of Experimental Medicine,* Vol. 215, No. 2, pages 397–398; February 2018.

FROM OUR ARCHIVES

Brain Drain. Maiken Nedergaard and Steven A. Goldman; March 2016.

scientificamerican.com/magazine/sa

ASTROPHYSICS

IS DARK MATTER REAL?

Astrophysicists have piled up observations that are difficult to explain with dark matter. It is time to consider that there may be more to gravity than Einstein taught us

By Sabine Hossenfelder and Stacy S. McGaugh

Illustration by Monodolithic Studios

Sabine Hossenfelder is a theoretical physicist at the Frankfurt Institute for Advanced Studies in Germany, who researches physics beyond the Standard Model. She is author of the physics blog Backreaction and the book *Lost in Math: How Beauty Leads Physics Astray* (Basic Books, 2018).

Stacy S. McGaugh is an astrophysicist at Case Western Reserve University. His research focuses on low-surface-brightness galaxies, which provide strong tests of modified gravity and dark matter.

THE STARS STILL HAVE SECRETS. WE KNOW WHY THEY SHINE, AND WE KNOW WHY THEY twinkle, but we still do not know why they move the way they move. The problem has been with us for the better part of a century. In the 1930s Swiss astronomer Fritz Zwicky observed that some galaxies in a cluster of about 1,000 fly surprisingly fast around their common center of mass. Even with generous estimates of the individual galaxies' masses, they did not add up enough to account for this motion. Zwicky fixed the mismatch by conjecturing the existence of a new kind of matter: "dark matter."

In the 1970s American astronomer Vera Rubin, who died in 2016, saw the same thing happening in single galaxies. The velocities of stars far out from the center of a galaxy remained roughly the same as those closer in, when astronomers would have expected them to slow down because of the dwindling gravity at the galaxy's far reaches. Again, the visible mass alone was not sufficient to explain the observations. Rubin concluded that in galaxies, too, dark matter must be present.

Since then, even more evidence has accumulated that we must be missing something. The tiny temperature fluctuations in the cosmic background radiation astronomers see pervading space, as well as the gravitational bending of light around galaxies and galaxy clusters and the formation of the cosmic web of large-scale structure throughout space, confirm that normal matter alone cannot explain what we see.

For many decades the most popular hypothesis has been that dark matter is composed of new, so far undetected particles that do not interact with light. The alternative explanation that we have the right particles but the wrong laws of gravity has received little attention.

Thirty years ago this stance was justified. The idea of particle dark matter gained traction because back then physicists had other reasons to believe in the existence of new particles. Around the 1950s and 1960s physicists realized that the protons, neutrons and electrons that make up atoms are not the only particles out there. Over the next decades particle accelerators started turning up new particles left and right; these came to make up the Standard Model of particle physics and opened theorists' minds to even more possibilities. For instance, efforts to unify the fundamental forces of nature into a single force

IN BRIEF

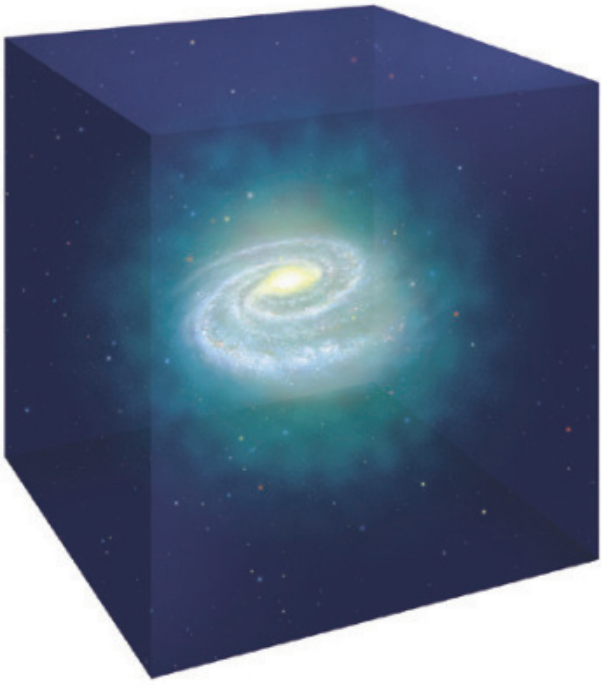
Scientists have long assumed that some invisible "dark matter" particles must accompany the normal matter in the universe to explain how stars orbit in galaxies and how galaxies orbit in clusters. An alternative idea that there is no extra matter and that our equations of gravity need updating has received much less attention.

But numerous experiments have failed to find evidence for dark matter particles, and the possibility remains that gravity must be modified.

Lately, in fact, some astrophysical evidence, such as recent observations of gravitation in galaxies, favors modified gravity theories over dark matter. It is time that physicists let go of their prejudices and reexamined this underdog idea.

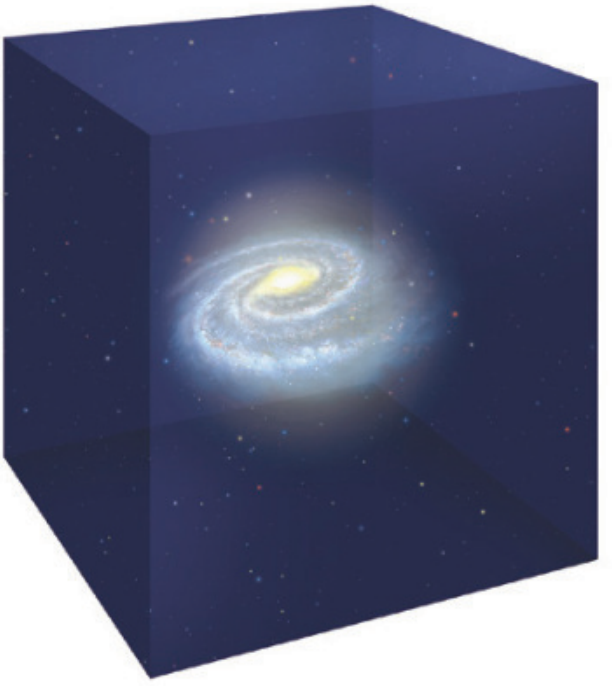
Dark Matter vs. Modified Gravity

Astronomers noticed long ago that the universe seems to be missing mass. Theorists suggested that some kind of hidden particles, dubbed "dark matter," must inhabit the universe to explain how stars move in galaxies and galaxies move in clusters. But experiments have failed to find dark matter. An alternative idea—that our equations of gravity need modifying—deserves a second look.



With Hidden Particles

The dark matter hypothesis suggests that invisible particles swarm around galaxies and clusters, far outweighing the visible matter. Around every galaxy, for instance, a spherical "halo" of dark particles would engulf the visible stars and gas, contributing a huge bulk of extra mass that would explain why stars at the edges of galaxies move nearly as fast as those toward the centers.



Without Hidden Particles

If dark matter does not exist, then scientists could tweak the laws of gravity to explain the speeds of stars at the edges of galaxies. Modified gravity theories revise Einstein's equations of general relativity to account for what we observe. Instead of an invisible dark matter halo surrounding galaxies, the visible objects are all there is.

required theorizing a set of new particles, and the concept of supersymmetry, developed in the 1970s, predicted a mirror particle for every known particle in the universe. Some of these theorized particles would make good dark matter candidates. Another suspect for the role was a particle called the axion, invented to explain the smallness of a parameter in the Standard Model. But after three decades of failed attempts to detect any of these particles, ignoring alternative hypotheses is no longer reasonable.

Meanwhile the idea that dark matter is made of particles has come under pressure from an entirely different direction. New astrophysical data gathered and analyzed by one of us (McGaugh), as well as others, conflict with particle dark matter predictions. It is also becoming increasingly clear that some old problems with the dark matter paradigm persist even after many attempts to resolve them.

Updating the equations of gravity is still a viable way forward. Rather than adding particles to the universe to account for the extra gravity that seems to exist in galaxies and clusters, we can instead stick with the known particles but increase the force they exert on one another. Often dismissed and overlooked, modified gravity, as these theories are called, has never been ruled out. Now is a good opportunity to reconsider the option that we have been looking for the wrong thing in the wrong places. It is time to have a closer look at modified gravity.

TWEAKING GRAVITY

FIRST PUT FORWARD BY Israeli physicist Mordehai Milgrom in 1983, modified gravity changes the mathematical rules that govern how the force of gravity arises from mass. In most cases (that is, in nonextreme situations where Newtonian gravity is a good approximation), we describe this force by the inverse square law: the strength of gravity between

Illustration by Lynette Cook

two objects depends on their masses and decreases with the inverse square of the distance between them. This law is a classic and shows up all over physics, from equations describing how light intensity drops off with distance to rules describing sound pressure. But what if gravity does not always follow the inverse square law? What if the equations, in certain circumstances, should be tweaked?

Milgrom's first proposal—modified Newtonian dynamics (MOND)—dealt only with the Newtonian laws of gravity. But Einstein's general theory of relativity taught us that gravity is not a force and is instead caused by the curvature of space and time. This limitation of the original MOND was likely a key reason many physicists did not take the idea seriously. But we now know several ways to make MOND compatible with general relativity, each using different types of fields that behave slightly differently to describe how gravitational attraction arises from mass. It is these 10 or so more complete theories that we collectively refer to as modified gravity. Dismissing them on purely theoretical grounds is no longer warranted. Another objection to modified gravity is that its mathematical expression appears inelegant from the perspective of particle physics. Not only does it look unfamiliar, it is also more difficult to deal with than particle dark matter, which employs techniques taught as part of the standard curriculum. Although these factors help to explain the idea's unpopularity, they are not scientific grounds for discounting it.

It is becoming increasingly clear that some old problems with the dark matter paradigm persist.

Despite the potential of modified gravity, however, scientists have put almost all their energy on this front into searching for dark matter. Since the mid-1980s dozens of projects have sought the rare interactions predicted between dark matter particles and normal matter. Such experiments place large tanks of liquefied noble gases or carefully prepared solids, kept at extremely low temperatures, in well-shielded environments such as underground mines to avoid contamination from cosmic radiation. Sensitive detectors patiently wait for telltale signs of a dark matter particle bouncing off an atomic nucleus in the liquid or solid target.

The most recent round of dark matter searches just concluded. The very sensitive Large Underground Xenon (LUX) experiment in South Dakota and PandaX-II (for Particle and Astrophysical Xenon Detector) in Sichuan Province in China, like all other dark matter detection experiments before them, recently reported no evidence for particles that could make up dark matter. The first results from XENON1T at Gran Sasso National Laboratory in Italy (an upgrade of XENON100, which was itself an upgrade of XENON10) were also negative. Neither has Super-Kamiokande in Japan seen any signal of protons decaying, which would be evidence for a unification of the fundamental forces and give credibility to the idea that unseen particles must exist. At the same time, scientists at the Large Hadron Collider (LHC) at CERN near Geneva have been looking for novel particles with the right properties for dark matter and have seen no signs of them. Besides the expected Higgs boson, the LHC has seen no new particles at all.

Of course, these negative results do not rule out dark matter. Theories for particle dark matter have become increasingly sophisticated, not to say contrived. To evade conflict with experimental null results, theorists now assume the particles interact with normal matter even less than originally thought. Some researchers have begun to conjecture new forces and additional particle species to go with the original new particles. This proliferation of unseen particles has become so common in the literature that they have been given a collective name: the "hidden sector."

COMPARING THE THEORIES

IN THE ABSENCE OF any signs of new particles, we should ask how well the theories of dark matter and modified gravity, respectively, explain the evidence we do have from nature.

For the most part, the hypothesis that the universe contains about five times as much dark matter as normal matter works well to explain the cosmos around us. Although dark matter's microscopic properties can be complicated, it follows simple equations in bulk. We can describe dark matter as behaving like a fluid without internal pressure, its one variable being the average density of particles in space.

Treating dark matter as a pressureless fluid suffices to reproduce the patterns we observe in the cosmic microwave background. It also does a good job with the formation of large-scale cosmic structures. As the early universe expanded and matter cooled, particle dark matter, because it cannot build up internal pressure, would have begun to clump under the pull of gravity faster than normal matter. Only later would the normal matter collect in the clouds of dark matter to form galaxies. This scenario fits well with some aspects of our observations.

Particle dark matter explains the motions of stars within galaxies when we distribute suitable amounts where needed; clusters of galaxies work out in much the same way. Because theorists can sprinkle dark matter so flexibly, they can make all current observations fit with the predictions of general relativity.

But this flexibility of particle dark matter is also its greatest shortcoming. Galaxies are not particles, and no two are alike. Each galaxy has its own history; each came about in its own delicate dance of billions of stars following the pull of gravitational attraction. Some young galaxies collide and form larger galaxies. Some do not. Some galaxies end up as spinning disks, some as elliptic puff balls. Sometimes dark matter catches a lot of normal matter in its gravitational pull; sometimes it does not. Because of these many variations, you would expect a ratio of dark matter to normal matter that differs from one galaxy to the next. You would expect variety, not strict rules. But the data beg to differ.

In 2016 McGaugh and his colleagues made thousands of measurements in more than 150 galaxies and compared the gravitational pull expected from the normal matter in them with the observed gravitational pull that presumably resulted from the dark matter and normal matter combined. What they found was surprising: a strong correlation between the two. In fact, a simple equation relates the apparent amount of dark matter to the amount of normal matter in each galaxy; deviations from the curve are small and few [*see box on next page*].

This correlation is difficult to reproduce with computer simulations that treat the two types of matter as independent components. Scientists can make the simulations fit the data, but they must insert many parameters that have to be carefully chosen. Modified gravity, in stark contrast, simply predicts this correlation. Because this scenario involves only one type of matter—normal matter—of course the total gravity closely follows the gravity caused by the visible matter. Milgrom even predicted this observation in the early 1980s.

UNUSUAL GALAXIES

THERE ARE OTHER PROBLEMS with the dark matter hypothesis—for instance, "low-surface-brightness galaxies." In these dim galaxies, visible matter is spread more thinly than in galaxies similar to the Milky Way.

The dark matter hypothesis originally led us to expect that galaxies with low surface brightness—that is, low amounts of visible matter—should also generally have low amounts of dark matter. Scientists assumed stars orbiting at large distances from the galactic center would move slower in these galaxies than in normal galaxies of the same size because there was less total gravity pulling the stars along their orbits. But when the data came in, this expectation turned out to be wrong. The outer stars in these unusual galaxies were moving just as fast as they do in normal ones, suggesting that there was actually quite a lot of matter in low-surface-brightness galaxies, despite the sparseness of the stars. It turns out that in these objects, the ratio of dark matter to normal matter must be much higher

NASA/CXC/CfA/M. MARKEVITCH ET AL. (*x-ray*); NASA/STScI AND MAGELLAN/UNIVERSITY OF ARIZONA/D. CLOWE ET AL. (*optical*); NASA/STScI, ESO WFI AND MAGELLAN/UNIVERSITY OF ARIZONA/D. CLOWE ET AL. (*lensing map*)

A Collision Offers Clues

The Bullet Cluster is a pair of galaxy clusters that crashed together long ago. It is a rare instance of a high-speed head-on collision. Images taken in visible and x-ray light (*red*), along with measurements of how gravity is bending light (gravitational lensing) (*blue*), reveal that in each cluster the center of the total mass and gravity is misplaced from the center of the visible mass.

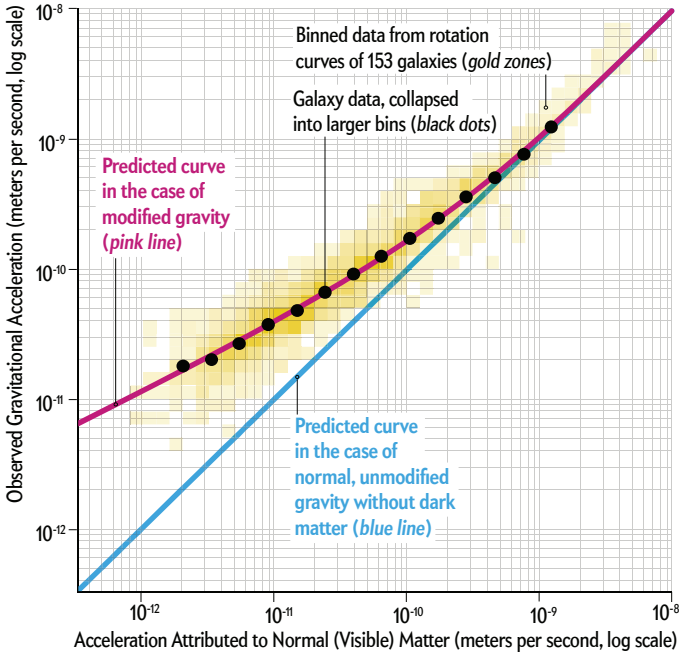
Scientists often claim the Bullet Cluster is evidence for particle dark matter. Because such particles would interact less than normal matter, the collision would have allowed the clusters' dark matter clouds to pass one another while the visible mass interacted with itself and lagged behind. This story matches what we observe, but it is crudely oversimplified.

In modified gravity, too, the point where gravitational attraction focuses can be displaced from the normal mass. This can occur because all forces, including gravity, are thought to be transmitted by a special type of particle. These particles have their own dynamical laws to fulfill. When modified gravity takes into account potential repercussions from these carrier particles, it can also predict what we see in the Bullet Cluster.

More important, this cluster is an extreme event and a statistical outlier. Its mere existence is difficult to explain both with particle dark matter and with modified gravity. Using it as evidence for or against either approach is an exercise in confirming our own biases.

A Problem for Dark Matter

A 2016 study examined stars' movements in galaxies and found that the total gravity present (*y-axis*) is directly proportional to the amount of gravity caused by the visible matter (*x-axis*). This extreme proportionality would be quite surprising if dark matter exists because the number of invisible particles should not depend solely on the amount of visible matter—the different shapes, sizes and gas content of galaxies should cause some variation. Modified gravity theories, however, predict just this relation.



than originally expected. But why should that be?

Originally, the dark matter hypothesis offered no explanation. But as we noted already, it is a very flexible hypothesis, so when theorists sought ways to explain this odd situation, they found them.

To square the findings with the theory, scientists had to fine-tune the amount of dark matter in each galaxy to depend on the surface brightness of the stars: the dimmer the system, the more dark matter. Doing so required some mechanism to rid these galaxies of luminous matter while they formed, so that the matter ratio tilted in favor of dark matter. Currently the most popular method is to add "stellar feedback" to the computer simulations. Stellar feedback is caused by the pressure created when massive stars irradiate their surrounding gas with highly energetic photons, blow strong stellar winds and ultimately go supernova. These giant explosions can blow matter out of galaxies. And because dark matter interacts so weakly, this blowout would affect normal matter more than dark matter. Galaxies that happen to have many supernovae would thus end up with an increased ratio of dark matter.

But although we know stellar feedback plays an important role in the formation of stars and stellar clusters, its role during galaxy formation is less clear. To solve the problem with low-surface-brightness galaxies, supernovae's energy must go almost entirely into pushing matter out of galaxies. Such a high level of efficiency, however, is strikingly implausible for a naturally occurring process. Modified gravity, on the other hand, predicts the observed outcome without involving feedback, just as it predicted the observed rotation speeds of stars in normal galaxies.

MORE PROBLEMS

THE ISSUE WITH low-surface-brightness galaxies is far from the only shortcoming of particle dark matter. The theory predicts, for instance, a highly peaked density of matter in the cores of galaxies, in contrast with what we measure. It predicts many fewer small dwarf galaxies than we observe and fails to predict the way that galaxies and their satellite galaxies align along a single plane. These are just the most prominent disagreements. Modified gravity does better in all these areas.

The lack of density peaks in galactic cores, in particular, fits so badly with the dark matter story that when the data were new, many astrophysicists doubted they were correct. First, the theorists asserted that the resolution of the measurements was inadequate. When subsequent data settled the issue of resolution, they blamed other systematic errors. But after several more generations of observations obtained by multiple groups, the conclusion remains the same: dark matter does a bad job of explaining what we see at the centers of galaxies.

It is true that incorporating stellar feedback and other astrophysical effects into the computer simulations alleviates these issues. Because these extra processes add more parameters to the simulations, researchers can coax the software into producing galaxies that resemble what we observe reasonably well. These simulated galaxies can then also reproduce the observed correlation between the amount of particle dark matter and normal matter. What the computer simulations do not offer, however, is any explanation for the origin of this correlation.

And modified gravity has another advantage. In contrast to dark matter simulations, modified gravity can explain how small galaxies behave when trapped in the gravitational field of larger galaxies. For instance, its calculations have been enormously successful in predicting how a bunch of recently discovered dwarf galaxies swirl around our large neighbor galaxy, Andromeda. These tiny dwarfs are subject to a gravitational pull from their giant host that is stronger than their internal gravity. In such a situation, modified gravity offers a different prediction than it would if the dwarf galaxies were isolated, and it is this unique prediction that we find realized in the observations. Fitting this aspect of the data

SOURCES: FEDERICO LELLI *European Southern Observatory*; "RADIAL ACCELERATION RELATION IN ROTATIONALLY SUPPORTED GALAXIES." BY STACY S. McGAUGH, FEDERICO LELLI AND JAMES M. SCHOMBERT; IN *PHYSICAL REVIEW LETTERS*, VOL. 117, ARTICLE NO. 201101; NOVEMBER 11, 2016

Graphic by Jen Christiansen

with particle dark matter, however, requires adding yet more assumptions to the computer simulations.

But let us be fair: Despite these many predictive successes, modified gravity has serious problems. Although it works across a huge range of different galaxy types, it cannot explain the motion of galaxy clusters very well. And on the behavior of the cosmos as a whole, modified gravity is mute. In these cases, particle dark matter works better. It accounts for the properties of the cosmic microwave background and the distribution of galaxies throughout the universe, where modified gravity has no answers. Yet discarding modified gravity because it does not address these situations misses the point. The theory has made successful predictions. Even if we do not understand why, ignoring it will not help.

MOVING FORWARD

AT THIS POINT, both particle dark matter and modified gravity have advantages and shortcomings. Some recent theoretical developments suggest that maybe the truth is in between: a type of particle dark matter that can masquerade as modified gravity.

In 2015 Justin Khoury of the University of Pennsylvania and his colleagues found that some types of particle dark matter can become superfluids—fluids that flow with no resistance, in which quantum effects are dominant. When the superfluid dark matter collects in galaxies, its quantum properties can generate a long-range force that resembles modified gravity. The superfluid itself has a gravitational pull, but according to Khoury's hypothesis, most of the effect we now assign to dark matter comes not from gravity but from the superfluid's direct interaction with normal matter. This phenomenon would explain why the force we witness acting on normal matter in galaxies is hard for gravity to account for: it is not caused by gravity.

The idea that dark matter is a type of superfluid that mimics modified gravity also clarifies why modified gravity does not work well for galaxy clusters. Throughout most clusters, gravity is not strong enough to make the particles superfluid. In these situations, they behave like a normal fluid—that is, they behave like particle dark matter.

And as one of us (Hossenfelder) noticed by accident, the superfluid concept matches another line of research, pioneered by Erik Verlinde of the University of Amsterdam. Verlinde uses ideas from string theory to argue that the impression that the universe contains more matter than we can see is an illusion caused by the reaction of space to the presence of mass. Although this notion sounds entirely different from Khoury's superfluid hypothesis, the key equation in both cases is almost the same.

This line of research is young and might turn out to be a dead end. But it exemplifies how having a closer look at modified gravity may help overcome the current phase of stagnation in the search for dark matter.

And new data should be available soon that will help determine the truth. Traditional particle dark matter, modified gravity and superfluid dark matter all make different predictions for low-surface-brightness galaxies that may become testable in the near future. The Dark Energy Survey currently identifies such galaxies, and the Large Synoptic Survey Telescope should find them by the hundreds when it comes online next year. The theories also differ when talking about the early universe, when the first galaxies were forming. These galaxies should be observable by the James Webb Space Telescope, which is set to launch in 2020, and future long-wavelength radio observations will probe the dark ages at still earlier epochs.

The advent of gravitational-wave astronomy is also giving us new clues. The Laser Interferometer Gravitational-Wave Observatory (LIGO) recently detected gravitational waves caused by the collision of two neutron stars. At the same time, various telescopes observed light in different wavelengths emitted by the same event. These observations show, to excellent precision, that gravitational waves travel at the same speed as light. This finding has ruled out some, but certainly not all, variants of modified gravity.

Maybe the truth is in between: a type of dark matter that can masquerade as modified gravity.

Right now a few dozens of scientists are studying modified gravity, whereas several thousand are looking for particle dark matter. Perhaps modified gravity is wrong, but perhaps the scientific community is not putting in a good faith effort to know for sure. The universe has had a habit of surprising us; we should be prepared to greet what future data reveal with open minds. The stars may still have secrets, but they are under close surveillance. SA

MORE TO EXPLORE

Radial Acceleration Relation in Rotationally Supported Galaxies. Stacy S. McGaugh , Federico Lelli and James M. Schombert in *Physical Review Letters,* Vol. 117, No. 20, Article No. 201101; November 11, 2016. Preprint available at **https://arxiv.org/abs/1609.05917**

Covariant Version of Verlinde's Emergent Gravity. Sabine Hossenfelder in *Physical Review D,* Vol. 95, No. 12, Article No. 124018; June 15, 2017. Preprint available at **https://arxiv.org/abs/1703.01415**

FROM OUR ARCHIVES

Does Dark Matter Really Exist? Mordehai Milgrom; August 2002.

Mystery of the Hidden Cosmos. Bogdan A. Dobrescu and Don Lincoln; July 2015.

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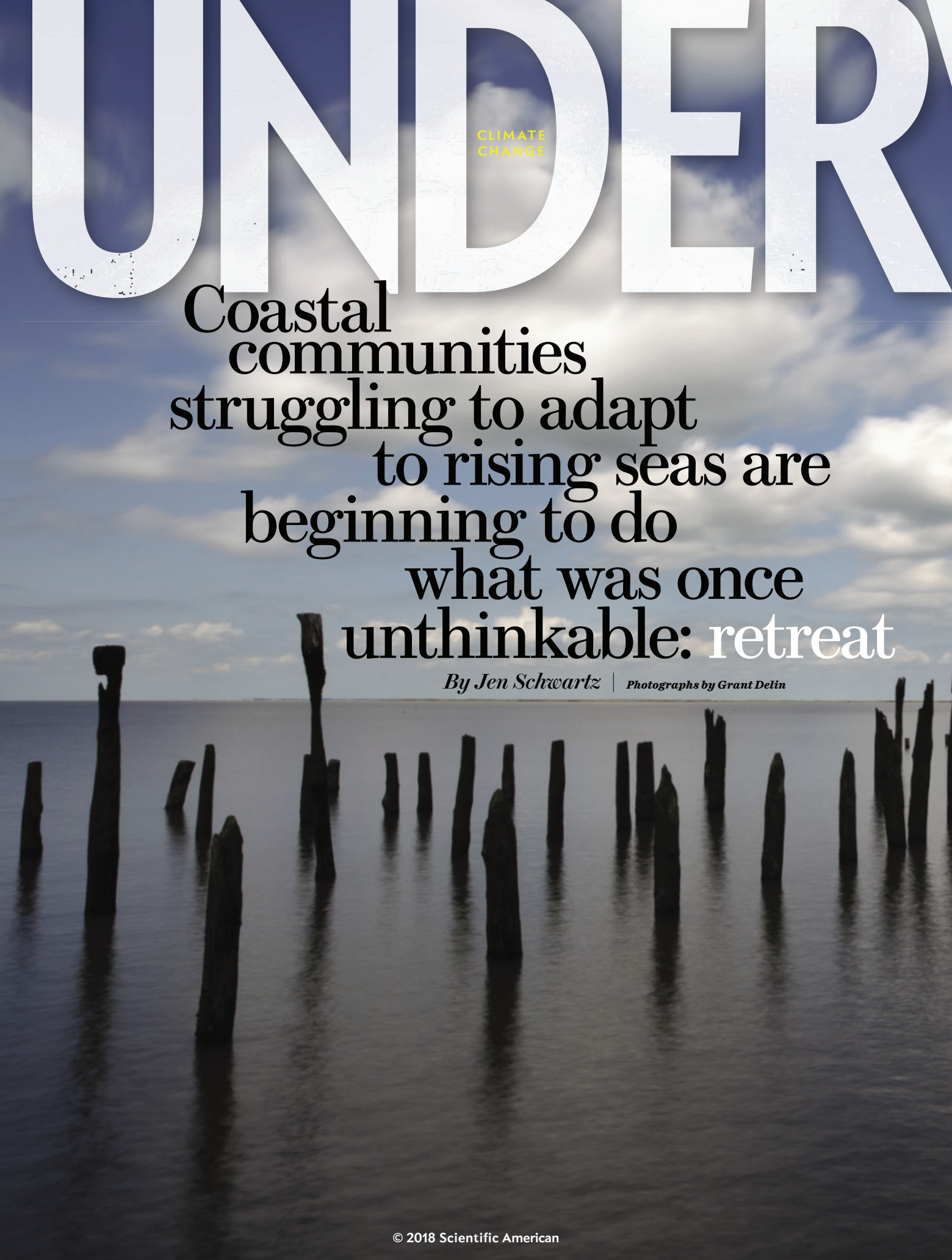


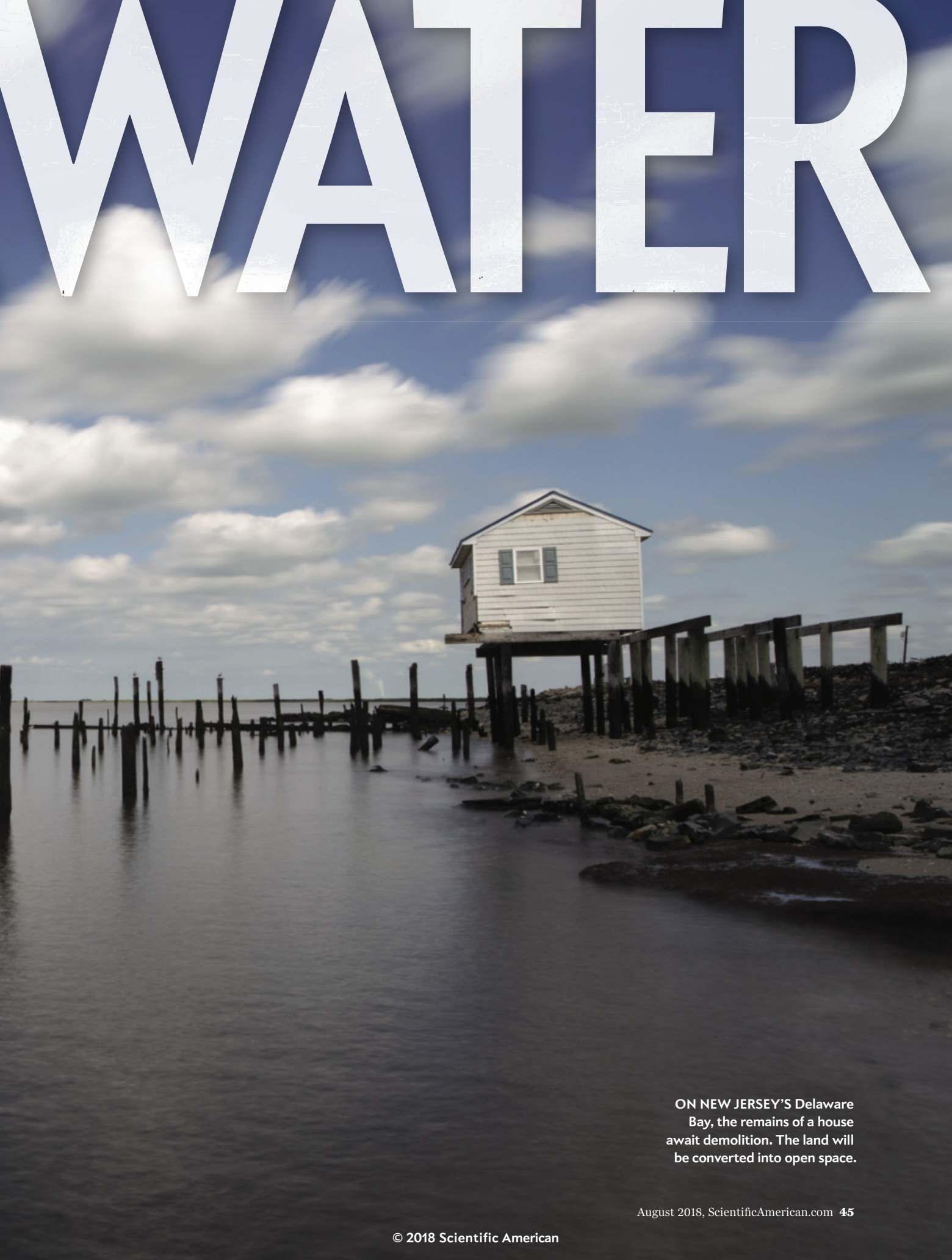
CLIMATE CHANGE

UNDER

Coastal communities struggling to adapt to rising seas are beginning to do what was once unthinkable: retreat

By Jen Schwartz | *Photographs by Grant Delin*

WATER



ON NEW JERSEY'S Delaware Bay, the remains of a house await demolition. The land will be converted into open space.

Jen Schwartz is a senior editor at *Scientific American* who writes about the intersection of science and society.

MONIQUE COLEMAN'S basement was still wet with saltwater when the rallying began. Just days after Superstorm Sandy churned into the mid-Atlantic region, pushing a record-breaking surge into the country's most densely populated corridor, the governor of New Jersey promised to put the sand back on the beaches.

The "build it back stronger" sentiment never resonated with Coleman, who lived not on the state's iconic barrier islands but in a suburban tidal floodplain bisected by 12 lanes of interstate highway. Sandy was being billed as an unusual "Frankenstorm," a one-in-500-year hurricane that also dropped feet of snow. But for Coleman and many residents of the Watson-Crampton neighborhood in Woodbridge Township, the disaster marked the third time their houses had been inundated by floodwaters in just three years. Taxed by the repetitive assault of hydrodynamic pressure, some foundations had collapsed.

As evacuees returned home for another round of sump pumps and mold, Coleman considered her options. Woodbridge sits in the pinched waist of New Jersey, where a network of rivers and creeks drain to the Raritan Bay and then to the Atlantic Ocean. She heard that the Army Corps of Engineers wouldn't be coming to build a berm or tide gate; the area had recently been evaluated, and such costly protections seemed unlikely. Spurred by previous storms, Coleman had already learned a bit about the ecological history of her nearly 350-year-old township. She discovered that parts of her neighborhood, like many chunks of this region, were developed atop low-lying wetlands, which had been elevated with poorly draining "fill" back around the early 20th century. As Coleman researched more deeply, a bigger picture emerged. "I started to realize that, in a sense, we were victims of a system because we were living in a neighborhood that should have never been built," she says.

Although she had flood insurance—her mortgage required it—Coleman knew that her premiums would soon go up, and she worried that her property value would go down. She and her husband liked their house, a prewar colonial. Best of all, it was affordable, a rare find in a town so close to New York City. Coleman had only discovered she would be living in a "special flood hazard area" once she was reading the closing paperwork in 2006. That made her nervous. She recalls her attorney waving it off by saying that at the rate we're going, everyone in New Jersey will live in a floodplain. That might be true in spirit, as a future-looking thought experiment, but it was severely misleading given the circumstances. Desperate to move her family away from a block in Newark with increasing drug activity, Coleman signed away one type of risk for another.

For four uneventful years, the marsh near the bottom of her street was an attractive amenity, a place where her three young sons could play freely. Then the drainages that wrapped around her neighborhood like a wishbone were overwhelmed by a nor'easter in 2010. And by Hurricane Irene in 2011. And again, by Sandy, in 2012.

When federal recovery money started trickling into New Jersey after Sandy, Coleman learned that she could apply for an elevation grant. But raising her house on stilts seemed silly if her car and the road were still on the ground. During Irene, she had witnessed what happens during a storm surge. "The high tide rushes in, and water envelops the entire area in no time at all," she says. "The street becomes a river within a river." Coleman didn't want to be "made whole," in the parlance of disaster-recovery law, if it meant rebuilding in place. Her stress levels spiked every time it rained during high tide. She didn't feel safe, physically or financially.

While commiserating with a neighbor, Coleman heard about a program called Blue Acres. Its premise struck her as radically sensible: The government would "buy out" her repeatedly flooded property at its prestorm value instead of paying to repair it yet again. Demolition crews would then knock down the house and remove other markers of human habitation. She would transfer the deed to the state, and redevelopment would be blocked, forever.

Compared with selling her house, this process seemed overwhelming. But even if she could find a willing buyer, how could she ethically transfer this vulnerability to someone else? "All of us who live in high-risk flood zones were taken advantage of somewhere along the line," Coleman says. "This was a way to end that cycle."

IN BRIEF

As sea levels rise, some coastal communities are confronting a future of both chronic and extreme flooding. Retreat—permanently moving people and property away from the water—is radical, but in some places, it is inevitable.

Even well-managed retreat is messy and painful. It has rarely been tried at all. One New Jersey town is experimenting with moving a cluster of people out of harm's way and turning the newly open land into a flood buffer to protect the rest of the community.

Planning for how and when communities will need to retreat involves many variables. New Jersey could see up to 12 feet of sea-level rise by 2100. Social, political and economic factors add to the complexity.

LAND where Monique Coleman's house stood is now planted with saplings. The house to the left will go through the same process.

RETREATING FROM THE COASTS, in concept or practice, is not popular. Why would people abandon their community, the thinking goes, unless no better alternatives remained? To emergency responders, retreat is a form of flood mitigation. To environmental advocates, it's ecological restoration. To resilience planners, it's adaptation to climate change. Everyone agrees, however, that retreat sounds like defeat. It means admitting that humans have lost and that the water has won. "American political institutions, even our national mythology, are ill-suited to the indeterminacy and elasticity of nature," wrote journalist Cornelia Dean nearly two decades ago in her book *Against the Tide*. "It would almost be un-American to concede … that it is we who must adapt to the ocean, not the other way around."

The U.S. has occasionally experimented with retreat on a tiny scale by offering voluntary buyouts to waterlogged families. The outcome is rarely promising. "Buyouts are extremely expensive, extremely disruptive, and many of the attempts have not gone well," says Craig Fugate, former administrator of the Federal Emergency Management Agency (FEMA). They invoke fear among citizens in every political stratum, bringing to mind land grabs, racist resettlement projects, class warfare, and, depending on your ideology, either federal overreach or federal abandonment. Because they require coordination among politicians, homeowners, lawyers, engineers, banks, insurers and all levels of government, they are enormously complicated to execute, even poorly. At their worst, buyouts break up community support systems, entrench inequality and leave a checkerboard of blighted lots in their wake. At their best, they avoid these things and still displace people from their homes.

Yet anyone who has looked at a map that forecasts sea-level rise can see that in low-lying neighborhoods exposed to the tides, some amount of retreat is inevitable. Regardless of how much and how quickly humans cut greenhouse gas emissions, climate change is already producing effects that cannot be reversed. Within a few decades, as saltwater begins to regularly block roads, kill wetlands, disrupt power supplies, bury popular beaches, undermine houses and turn common rainstorms into perilous floods, the most vulnerable pockets of coastal towns will become uninhabitable. As the National Oceanic and Atmospheric Administration has warned, "today's flood is tomorrow's high tide."

Buyouts, however, are not designed for adapting to climate change. Past beneficiaries were almost exclusively riverine communities in the U.S.'s rural interior—people who lived too close to the overflowing Mississippi and Red rivers, for instance, were relocated nearby. The government didn't even begin promoting buyouts as a form of disaster recovery until the 1990s, and since then, they have been conducted as one-off reactions to hurricanes. With multiple federal agencies involved, yet no one tak-

FAWN MCGEE, director of the Blue Acres Buyout Program, has purchased hundreds of houses in New Jersey, including this one. It will soon be demolished.

ing charge, "it's amazing how much we're still making this up as we go," says Alex Greer, an expert in disaster science at Oklahoma State University. Until recently, retreating from the coasts was practically unheard of.

Superstorm Sandy changed that. The hurricane made sea-level rise, an abstract, future problem for far-flung places, manifest in the form of drowned subway lines and a roller coaster tossed into the waves. It communicated both the experience and evidence of future flooding in a way that probabilities never could. "It's Global Warming, Stupid," said the cover of *Bloomberg Businessweek*. Political leaders in New York State and New Jersey, sensing a tonal shift, realized they couldn't just talk about rebuilding without also talking about resiliency, the rising buzzword of disaster preparedness.

Environmental types were also acknowledging that they could no longer fixate solely on the problem of carbon emissions. Rob Moore was executive director of the Environmental Advocates of New York back in 2012. "We didn't want to talk about adaptation, because we saw it as a distraction from mitigating climate change," he says. "But Sandy made it unavoidable." A few months later Moore took a job at the Natural Resources Defense Council (NRDC) to work on how the country would cope with rising seas. Climate scientists who study the acceleration of sea-level rise felt a similar urgency, and many emerged from their silos to produce better projections. "Now the geophysical people are talking to the atmospheric people and to the economists and the sociologists," says Robert E. Kopp, director of the Institute of Earth, Ocean, and Atmospheric Sciences at Rutgers University and a lead author on major climate reports. This interdisciplinary approach has led to localized forecasting. Instead of only one number—the global mean—we now know that sea-level rise will vary significantly from region to region.

As flooding worsens, a few massive seawalls will likely be built to protect densely populated economic centers, such as lower Manhattan. But there is only so much money, and time, for cement enclosures. Residents in places such as Tangier Island in Virginia and Isle de Jean Charles in Louisiana—and globally from Bangladesh to the Maldives to Senegal—are coping with the same reality as Coleman and her neighbors in Woodbridge Township: a wall isn't coming to save them, and the floods are already here.

NEW JERSEY'S CHIEF OF LAND ACQUISITION clasps her hands on the approach to Bay Point, a peninsula that is disappearing into the Delaware Bay. This is the site of the state's first beachfront buyout, a hard-won success for Fawn McGee. Of the 31 properties she has acquired here, most were recently demolished. Some of the houses were already long gone, leaving behind skeletons of whittled pilings repurposed by nesting ospreys. "It's bittersweet," says McGee from atop a mound of makeshift riprap, residents' last-ditch attempt to stop the erosion. "Even when you can be excited that we bought all these homes, and now we're going to restore the land, everybody is miserable that they had to leave."

When it comes to the unsustainable development of the American coastline, New Jersey owns the honor of being the first and worst. It was here that the tempestuous beach environment,

long feared and avoided until industrial times, was rebranded as a summer vacationland. Atlantic City and Cape May were tourist destinations by the mid-1800s, escapes from the undignified swelter and infectious diseases of Philadelphia. The Lenape people had long done the same—a seasonal migration to the shore—but they came to fish, not to conquer the sand with an arsenal of hotels and boardwalks. To hold everything in place, New Jersey was the first state to try to wrest control of coastal sediment flows from nature by erecting seawalls and jetties and bulkheads, and today virtually none of its coastline is untouched by human intervention. It's no surprise that the first speculator to see dollar signs on the sandbar that became Miami Beach was a New Jerseyan.

For the communities McGee works with, retreat has gone from a strategy of last resort to the only option left in the span of about a decade. Climate change drove that shift. But the reason people are in this predicament in the first place is because of the unchecked hubris of coastal engineering, coupled with general human tendencies to love the water and ignore the future. The government gave a huge boost to coastal development in 1968 by introducing the National Flood Insurance Program—an exemplar of moral hazard that allowed homeowners to rebuild over and over in risky areas while keeping their premiums artificially low. Fifty years later that program has accumulated $36.5 billion of debt while effectively trapping people who might prefer to escape to higher ground, NRDC's Moore explains.

Coastal systems, by their tidal nature, are always dynamic and occasionally volatile. The harder we tried to make them stay put, the less stable they became. In the 1960s, when scientists discovered that beaches armored with hard structures actually eroded faster and recovered slower than natural ones, the Army Corps of Engineers began dredging sand from the continental shelf and pumping it back to the shore. Before long, a storm would wash it away, and the dredging would begin anew. Today the Eastern seaboard has a Sisyphean dependence on the "nourishment" cycle. As sea-level rise rapidly accelerates, beach towns are increasingly desperate for fresh infusions of sand, which the corps must travel farther offshore to find. Geologists warn that we are running out of usable sediment faster than the planet can replace it. Wealthy homeowners in Florida are now stealing sand from public beaches to fill in their private ones.

Just as New Jersey pioneered the quixotic development of the coasts, it is leading an acceptance of what it wrought. Twenty-three years ago the state's Department of Environmental Protection (NJDEP) launched the Blue Acres Buyout Program, using state money to purchase a handful of routinely flooded houses here and there. McGee, who runs the program now, was its first leader to leverage federal money from FEMA and other agencies, turning Blue Acres into one of the country's very few standing buyout departments to deal with rising tides. Florida and Louisiana don't even have their own versions. Blue Acres, McGee says, has three major goals: permanently move people and property out of harm's way; open the land for public access; and restore the natural ecology so that the ground becomes a sponge, mitigating flood risk for the rest of the community.

After Superstorm Sandy, McGee prioritized buyout eligibility for entire clusters of houses over individual ones. In that way, the open space created would be big enough to have a real impact on managing floods. She looked for towns based on where enough homeowners had expressed interest in the process *and* the local government was willing to part with a portion of its tax base. After all, when the houses disappear, so, too, goes the tax contribution. Homeowner participation is voluntary, with an ability to pull out at any stage before signing the final contract. That means that families in a "buyout zone" will ultimately have to make a profoundly personal decision about whether or not to uproot in the context of both their neighbors' choices and their town's vision for the future.

The year before Superstorm Sandy, McGee tried pulling off her first large round of buyouts in the aftermath of Hurricane Irene. It didn't go well. "On paper, buyouts make a world of sense, but in practice, that is absolutely not true," Greer, the disaster scientist, says. McGee scrutinized how the process got disjointed and stalled out, making it nearly impossible for anyone to make decisions. It took more than a year for the funding to align, leaving desperate homeowners in a lurch. Some people were upside down on their mortgages, which disqualified them from the program. Or they couldn't afford to keep living in temporary housing while waiting for answers. As disaster amnesia began to set in, many decided just to pursue the readily available methods of rebuilding or elevating. "I realized this went way beyond land acquisition," McGee says. She tasked her tiny Blue Acres team with anticipating the adjacent challenges. "When Sandy hit and the big federal money came in, we were ready," she says.

But advocating for large buyouts of clustered properties meant McGee was pushing for something novel at a moment when New Jersey was in triage mode. The state administration wanted to recover as quickly as possible. "I think they looked at me as a troublemaker for challenging us to think beyond black-and-white," she says. McGee was arguing to disrupt the cycle of hasty rebuilding in areas where she knew the water would rise again. After many persistent meetings (her approach was "confidence, not confrontation," she says) and assurances that she could navigate through the bureaucracy, McGee convinced the state to give her plan the go-ahead.

Immediately McGee asked to borrow 33 staffers from other areas of the NJDEP. "In addition to my GIS [geographical information system] people, I brought in four paralegals, six project managers to do grant writing and deal with the feds, and eight case managers to walk families through the process," she says. "Then title people. Appraisers. Surveyors. Accountants. We had bookkeepers just to go through shoeboxes of Home Depot receipts from homeowners and cross off things like Snickers bar, water, couch." With each snag that threatened the buyouts, McGee found herself filling some unexpected role. She played a therapist to storm victims experiencing trauma, illness and divorce. When McGee saw how many homeowners were upside down on their mortgages, she facilitated short sales that amounted to more than $5.4 million of debt forgiveness—which resulted in 67 additional bought-out homes. When the issues went beyond her scope, she outsourced. "Hoarders! They literally can't get out of their houses," she says. "We had to bring in specialists to help them let go of their stuff."

Most important, McGee sensed that buyouts were a deeply communal decision. She figured neighbors would be looking at their options together over a bottle of wine, so she assigned case managers according to social groups. Case studies of buyouts show that individual considerations play only a limited role in whether a family leaves or stays. "The implication here is that

Flooding Up Close

When people think about sea-level rise (SLR), the first thing that comes to mind is the beach—narrow, sandy environments that are visibly exposed to surging water and powerful waves. Although New Jersey is known for its Atlantic coastline, much of it composed of barrier islands that are engineered to stay in place, it has a tidally influenced shoreline spread across 20 of its 21 counties. As SLR accelerates through this century, it will make tidal flooding more common and storm flooding more extreme, causing economic, environmental and social upheaval in all types of tidal communities, from bay-shore wetlands to barrier islands to suburbia. These are not problems for the next generation. According to a June 2018 report by the Union of Concerned Scientists, 250,000 homes in New Jersey, together valued at $108 billion, are at risk of chronic flooding within the next 30 years.

FROM A DISTANCE

These maps show what areas will likely be inundated by high tide at 2050 and 2100. Whether we severely cut emissions or keep polluting as usual matters little for 2050 projections; existing effects aren't reversible. (The choices we make today *will* have a big difference on how much the seas swell after 2050.) Another major factor for New Jersey is subsidence: the land itself will sink by about 0.4 feet by 2050. Relative to the baseline sea level from 2000—the average high tide from 1991 to 2009—the New Jersey coast is likely to see one to 1.8 feet of rise by 2050, according to research by Rutgers University climate scientist Robert E. Kopp and his colleagues. There is a 50 percent chance that high tide will reach or exceed the median projection of 1.4 feet above the 2000 baseline within three decades.

New Jersey Sea-Level Projections

2050

- 1.4 feet of sea-level rise (high emissions, "business as usual")

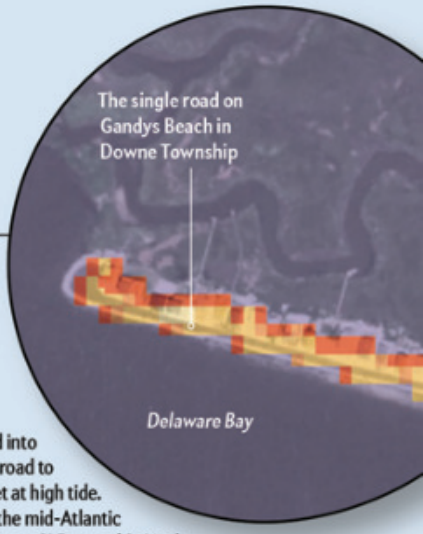
2100

- Lower emissions; more stable Antarctic
- Lower emissions; less stable Antarctic
- High emissions; more stable Antarctic
- High emissions; less stable Antarctic

New Jersey

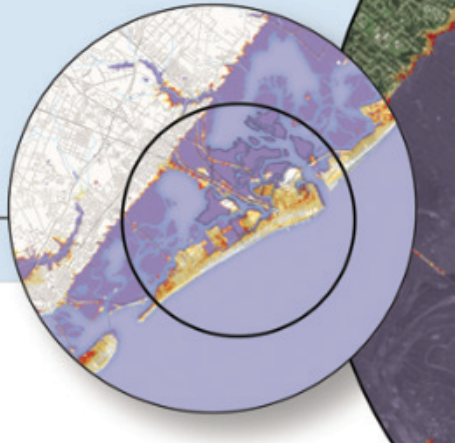
GETTING LOCAL

Zoom in, and the range of near-future threats becomes clear. Houses will routinely flood. High tide will cut off intercoastal access roads. Popular tourist beaches and protective wetlands could disappear. And these higher water levels will be intensified by every full moon, rainstorm, nor'easter and tropical storm. "Increasingly, the research is based on compound threats of flooding instead of the single factor of sea-level rise," says Bryan Jones, a geographer who models climate migration.



BAY WETLANDS

Gandys Beach hosts a single row of homes propped up on pilings, some of which are now always over the water. In May 2018 a portion of the island's road had collapsed into the waves, and the access road to the mainland is already wet at high tide. Many coastal wetlands in the mid-Atlantic region will not likely survive an SLR rate of 0.4 inch a year, which could occur here between 2030 and 2040. Without these natural buffers, communities lose one of the most effective protections against storm surges and tidal flooding.

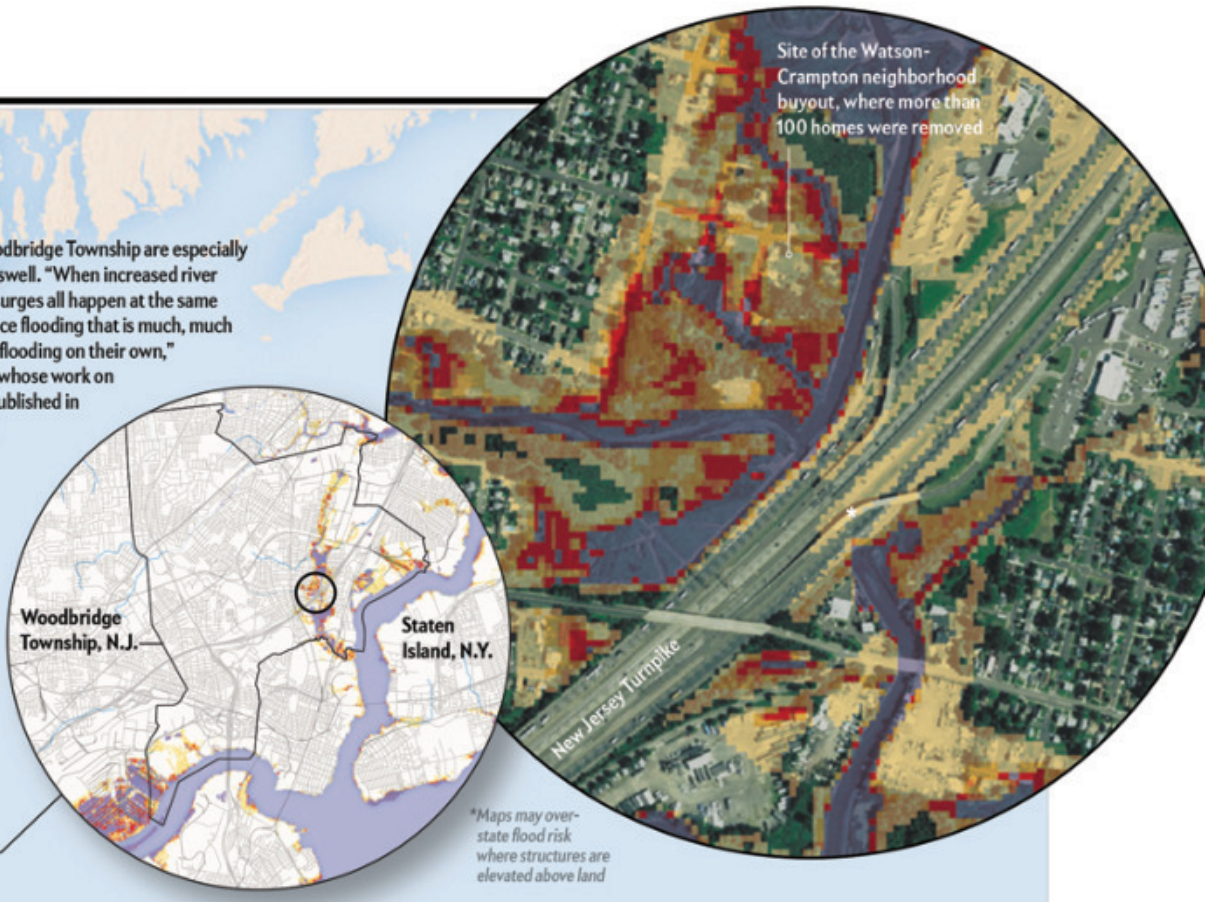


Map by Mapping Specialists, Graphic by Jen Christiansen

SOURCES: CLIMATE CENTRAL (*base flood maps*); "EVOLVING UNDERSTANDING OF ANTARCTIC ICE-SHEET PHYSICS AND AMBIGUITY IN PROBABILISTIC SEA-LEVEL PROJECTIONS," BY ROBERT E. KOPP ET AL., IN *EARTH'S FUTURE*, VOL. 5, NO. 12; DECEMBER 2017 (*sea-level projections*); ROBERT E. KOPP (*flood height*); U.S. DEPARTMENT OF AGRICULTURE (*base satellite imagery*)

URBAN FLOODPLAIN

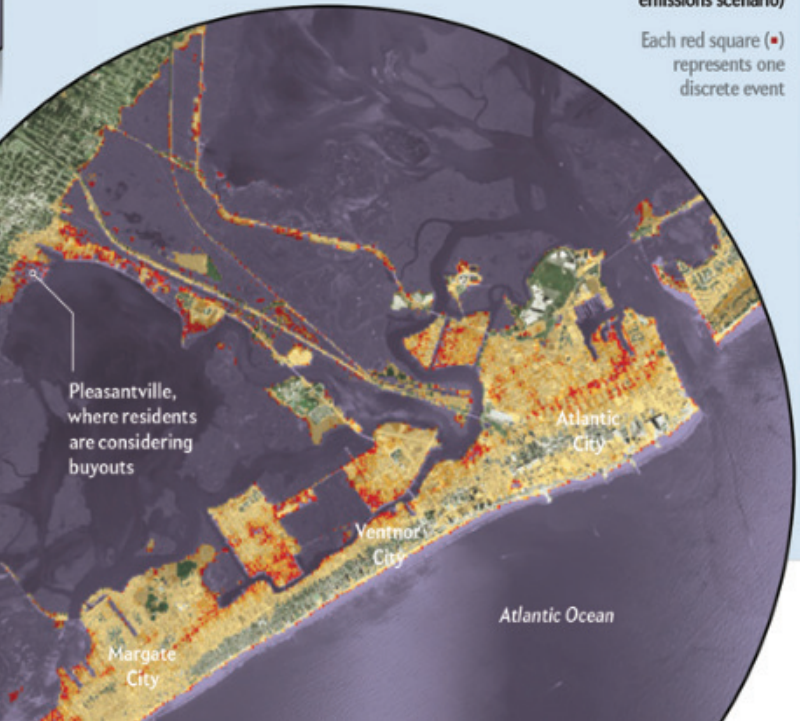
Dense residential areas such as Woodbridge Township are especially vulnerable as their tidal waterways swell. "When increased river discharge, precipitation and storm surges all happen at the same time, coastal regions often experience flooding that is much, much worse that just storm surge or river flooding on their own," says oceanographer Thomas Wahl, whose work on so-called compound flooding was published in *Nature Climate Change* in 2015.



*Maps may overstate flood risk where structures are elevated above land

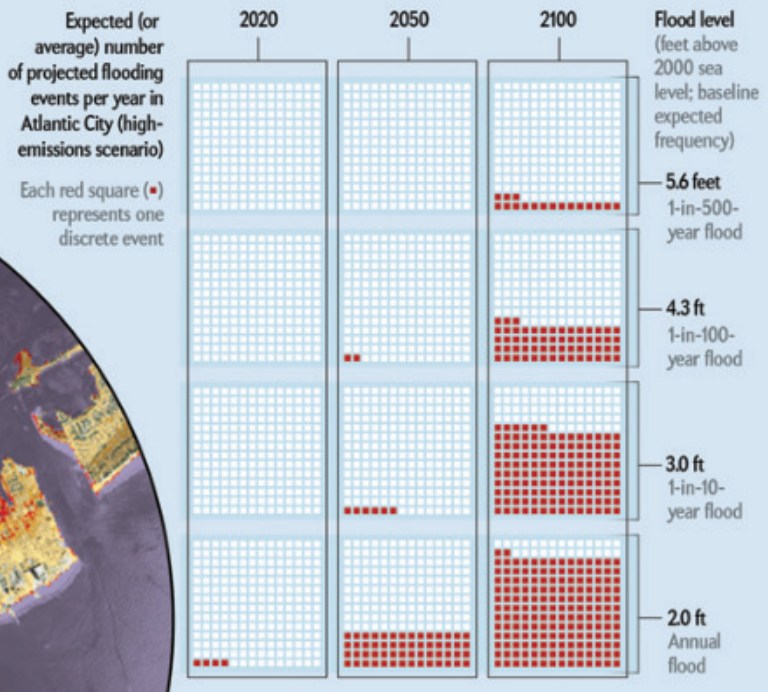
BARRIER ISLANDS

Long before popular beach towns such as Atlantic City, Ventnor City and Margate City (*shown below*) are permanently drowned, the effects of climate change will dismantle them in other ways. "Most people perceive the value of the beach as the sand itself," says Craig Fugate, former head of FEMA. When there is not enough space between the built environment and the water's edge to host sunbathers, will housing prices plummet? Without a sandy beach, will the town itself still have an economic raison d'être? "The question for the Jersey Shore is, Do you start thinking about giving up that first row of homes, businesses and streets in order to get the beach back?" Fugate asks. "Or will we climb up a seawall and walk directly into the water?"



A FUTURE OF REGULAR FLOODING

The maps here show projections of how the baseline sea level will change in the future, inundating currently dry land during high tide. Just because a certain block or property isn't getting wet every day doesn't mean it will be desirable, or even possible, to live and work there. Tidal flooding, sometimes called "nuisance" or "sunny day" flooding, will occur regularly because the baseline water height is getting higher. And when storms arrive, their surges and waves will be more destructive and far-reaching. This chart shows how the frequency of flood events at a given height in Atlantic City are projected to increase as baseline sea level grows.



residents' perceptions of their broader community were more influential in the buyout decision than were their experiences of Sandy, or their personal or family characteristics," wrote Sherri Brokopp Binder, an expert on postdisaster relocation, and her colleagues in a 2015 study in the *American Journal of Community Psychology*. McGee realized that grassroots support from a few residents could make all the difference between a transformative buyout and a dud.

IT DIDN'T TAKE LONG after Sandy for Monique Coleman to decide that she wanted a buyout. Now she would have to convince her neighbors and the town to want the same. McGee remembers meeting Coleman in 2013, when she hosted a standing-room-only meeting in Woodbridge to tell the residents about Blue Acres. "People would listen to me but then look over at Monique for her to signal it was okay," McGee says. "We always have police at these meetings because people get heated, but Monique had this calming effect on her neighbors. It was astonishing."

Coleman, it turned out, had exposure to grassroots organizing dating to her childhood. Her grandmother took her to Black Liberation Movement meetings, and her father brought her door-to-door during his city council run. These days Coleman works as a teacher for blind children, so in a sense her profession is helping others adapt to unfamiliar challenges. When Coleman and a handful of buyout supporters began canvassing their own streets in late 2012, she expected resistance. "You can't present this idea once, and when you hear that 'no,' just say, 'Okay, I understand,'" she says. She set up a blog and a Facebook group and organized monthly meetings. It was going to take a lot of listening at a time when people were traumatized by Sandy and overwhelmed by the day-to-day choices of recovery.

Blue Acres has been touted as a model for how retreat might evolve. Roy Wright, former resilience lead at FEMA, called New Jersey's approach to buyouts "masterful." But in all McGee's meetings and maps and her talks with mayors and residents, she was not able to evoke the language or data of climate change. Until January 2018, under the administration of Governor Chris Christie, McGee "was not to use those terms," as she puts it.

So Coleman took it on herself to "learn the scientific side of things." When she started doing Web searches for the impacts of climate change in 2012, she couldn't find much that spoke to her area specifically—it simply didn't exist yet. But what she did find convinced her that the back-to-back floods she had experienced in Woodbridge weren't a spate of bad luck but signals of a new reality. Coleman wrote and distributed a leaflet of 12 reasons why life in the flood zone wasn't sustainable in a climate-changed future.

Eventually some of her neighbors stopped slamming their doors when she showed up to chat about buyouts and started asking her questions instead. Coleman was patient but persistent. "It is very hard for people to accept this is really happening," she says. She explained that no matter how she sliced it, she found no positive paths forward. Leaving for good was simply the least onerous. "Who knows when a flood will come again," she would tell her neighbors. "But it will be coming."

THE MODELS SCIENTISTS HAVE MADE to predict the influence of sea-level rise on those future floods have become highly sophisticated, combining global factors such as the thermal expansion of the seas with local variables such as land subsidence and variations in the gravitational pull of land on the ocean around it. But major uncertainties remain. For one thing, we don't know how quickly and severely societies will cut greenhouse gas emissions. For the next few decades certain effects will occur regardless of how much we mitigate climate change. Rutgers's Kopp, a leading climate scientist, says that New Jersey will likely experience between one and 1.8 feet by 2050. Even at the low end, numbers like that will reshape life along the coast. After 2050 the rise continues to accelerate, but the picture gets murky: NOAA estimates that New Jersey could see between three and 12 feet of sea-level rise by 2100. That range is overwhelming if you're a mayor who is trying to come up with an adaptation strategy. "Climate change is a study of probabilities, but the public wants yes or no answers," says Graham Worthy, director of the National Center for Integrated Coastal Research.

Besides the human element, however, the biggest wild card when it comes to the fate of coastal communities in New Jersey and beyond is the stability of the West Antarctic ice sheet. The rate at which the whole of Antarctica is shedding ice has tripled over the past decade, and West Antarctica, being especially sensitive to the forces of climate change, is one of the most rapidly changing places on the planet. The West Antarctic ice sheet is so voluminous that it will add more than 10 feet of sea-level rise alone if it catastrophically collapses. This scenario might only be avoided with extreme emissions cutbacks in the next decade, according to a June 2018 report in *Nature*.

NASA's satellites have been collecting data on this ice sheet and others for more than four decades. Satellites are unrivaled at capturing continuous observations over a wide area, but they can't pick up details that would make it possible to predict the ice sheet's fate with a higher degree of certainty. Some of those more granular clues include ice thickness, the grounding line where a glacier's base meets the sea and the slope of the ice sheet, which is a driving force that sends ice from the interior of the continent to the ocean, says Kenneth Jezek, a glaciologist and retired polar researcher. Because of its sheer size and remoteness, studying West Antarctica up close is a dangerous, logistical nightmare.

One survey project, a NASA airborne mission called Operation IceBridge, has been able to capture some of those details by flying above the region in a retrofitted jetliner. From an altitude of just 1,500 feet, scientists onboard this winged laboratory can see that the top of the ice sheet is textured with signs of movement, such as geometric crevasses, the milky cerulean of ancient ice exposed to sunlight and cracked-up plains that resemble lake beds in drought. These features, they know, are carved by katabatic winds from above and by invisible rivers from below. But it is the ridges of black bedrock that hint at dramatic topography underneath the ice—a hidden world that IceBridge has been mapping extensively over the past decade.

To understand what is happening under the frozen surface, pilots maintain a precise track over the sheet while radar streams data to an onboard computer screen, revealing evidence of entire mountain ranges and valleys that make up the shape of the continent. A gravimeter picks up the depth and size of glacial cavities filled with seawater, a marker of how floating ice shelves might be melting as they interact with the ocean. Along the glaciers' terminal edges, icebergs float against the inkiness of the Amundsen Sea, a scene photographed every second by two cam-

AS HOUSES come down, Thomas C. Flynn, Brooke Maslo and Jeremiah Bergstrom are restoring floodplains in Woodbridge Township, N.J.

eras affixed to the belly of the plane. IceBridge has flown some of these tracks year after year, capturing change in unprecedented detail. At a time when the necessity of earth science is being attacked by political leaders, "I can't emphasize enough that we do not collect this data because we find it scientifically interesting," says John Sonntag, IceBridge's mission scientist. "We collect it to try to warn and protect our communities from sea-level changes that are coming their way."

As raw data from IceBridge, satellites and similar projects have percolated through scientific papers and reports such as the 2017 National Climate Assessment, new tools have emerged. NOAA's Digital Coast and Climate Central's Surging Seas, for instance, allows town planners to begin envisioning how sea-level rise will affect flooding in their jurisdictions.

IceBridge data have turned out to be essential for filling in fundamental gaps in polar ice knowledge, "but we still have a way to go in Antarctica," says Eric Rignot of the University of California, Irvine, and NASA's Jet Propulsion Laboratory. Rignot was the lead author on a landmark 2014 paper in *Geophysical Research Letters* that used radar measurements of a large sector of West Antarctica and concluded that it "is undergoing a marine ice sheet instability that will significantly contribute to sea level rise in decades to centuries to come." That same week a *Science* paper suggested that, based on modeling, the collapse of the West Antarctic ice sheet had already begun, making extreme sea-level rise inevitable, possibly within two centuries. But Rignot thinks that time line might be too conservative. Real observations of ocean temperature—and how glaciers are responding to those warmer waters—are still "totally lacking" in parts of Antarctica, meaning that "it is a matter of fact that our projections tend to underestimate sea-level changes," he says.

Neither Rignot nor Jezek thinks that launching the next NASA ice-monitoring satellite, slated to happen next month, will be enough to narrow the uncertainties coming out of Antarctica. Rignot suggests that it will take more airborne research such as IceBridge, along with shipborne surveys by unmanned subs and multibeam sonars and new forms of intelligent technology—"an entire army of robotic devices"—dispatched to the remotest fringes of the continent.

This October science teams led by the U.S. and U.K. will travel by air and icebreaker to West Antarctica's marquee feature—the massive and infamously unstable Thwaites glacier—to do just that. More than 100 scientists from around the world will study the interaction between warming ocean water and the ice shelf to examine how Thwaites is thinning from below. Thwaites is like a tub stopper holding much of West Antarctica in place; if it's doomed, so is the ice shelf. The more these researchers and others learn about the shifting dynamics among ice, ocean water and atmosphere, the more factors they can plug into regionally specific sea-level predictions. The data they gather will inform whether coastal populations have centuries, or mere decades, to prepare for the onset of the deluge.

BY THE SUMMER OF 2014, when Coleman signed over the deed to her old house and moved into a new one, Woodbridge Township was on its way to becoming the site of Blue Acres' biggest

TIDALLY INFLUENCED wetlands abut the Watson-Crampton neighborhood in New Jersey. By 2050 it will likely be underwater.

ever buyout project. Today a total of 142 homeowners have accepted offers. And about 115 homes from the Watson-Crampton neighborhood alone have been removed, most of them clustered within a grid of streets covering about 30 acres. Millions of people globally will have to move inland to escape the coming floods, so these numbers can sound too tiny to be meaningful. But what happened in Woodbridge upends many of the assumptions traditionally tied to buyouts: that no residents want to leave, that politicians will never get onboard, that ecological health in suburbia will never win out over real estate growth and that no one is planning for a climate-changed future by making painful choices in the present. "What we're doing here is paving the way for conversations about how to manage retreat," says Thomas C. Flynn, the town's floodplain manager.

Officially the buyout process ends once the property has been demolished. Woodbridge, however, found itself with an abundance of lots and ambitions beyond mowing the grass. The town reached out to Rutgers ecologist Brooke Maslo, who works with the school's Cooperative Extension to assist New Jersey communities with science-based projects. The term "resilience" gets tossed around a lot, "but what does it actually translate to?" Maslo asks. She came to see the Watson-Crampton buyout project as a unique opportunity: she could create a floodplain restoration that buffered the remaining neighborhood from sea-level rise. She brought in Jeremiah Bergstrom, a landscape architect with experience managing stormwater in urban environments. "As far as I can tell, this is the first coastal land restoration in the context of residential retreat," Bergstrom says.

Using nature as infrastructure is a well-established concept—think mangroves and oyster beds as storm-surge absorption—but it is not commonly applied in places as densely developed as the greater New York City area. Liz Koslov, an assistant professor at the University of California, Los Angeles, who did ethnographic research on Staten Island's post-Sandy buyouts, says she has seen next to no discussion about what happens to the land itself after the houses come down. "Residents said they just want the land to go 'back to nature,' but when you get down to it, 'nature' can mean a lot of different things," she says. Karen O'Neill, a Rutgers sociologist who is cataloguing global instances of coastal retreat, says that "you hardly ever see a comprehensive ecological restoration. It just doesn't exist."

The Watson-Crampton neighborhood can't simply return to nature, because it was built on fill. "We have to re-create a new ecology, a new nature," Bergstrom says. Over the past year the restoration team has ripped out roads, assessed soil quality, and planted more than 950 saplings to increase flood storage capacity and encourage the growth of a biodiverse salt-marsh habitat. Without intervention, the land would become a monoculture of

invasive reeds that can break down and form dense mats, which might ultimately make flooding issues worse, Flynn explains. Maslo and her team are softening the hard curvature of the swale so that tidal surges entering from the river below the New Jersey Turnpike don't rush in at high velocity. They'll carve a channel that will allow for spillover, with the hope that the depressions will create permanent standing water for wildlife. Maslo wants to prove that a town can recoup its tax losses with new lures, such as parkland trails and a kayak launch. "This is not a wasteland," she says.

Maslo's vision helped to convince the Woodbridge mayor and city councillors to change the township's buyout regions—120 acres in all—from residential zoning and existing marshland to something they named the Open Space Conservation/Resiliency Zone. No development would be allowed. Nineteen households in the Watson-Crampton buyout area dug in their heels. The town warned these "holdouts" that if they ever wanted to sell, their houses would first need to meet new floodplain standards—which would likely mean elevating them higher. Land-use changes like this are controversial because they make what is supposed to be a voluntary process into one that is significantly less so. But without them, developers might be attracted to come in and build bigger and higher properties. Then new people—those who can afford higher flood insurance premiums and the building costs of living in a floodplain—are likely to move in, replacing those who can no longer afford to stay.

FOUR YEARS AFTER RELINQUISHING her home to the forces of nature, Coleman says she has no regrets about taking the buyout. For moving within the same county, she received an incentive grant of $10,000, which helped her afford another single-family home on higher ground. The process was financially and emotionally stressful, but the way Coleman describes her participation reframes a reaction to misfortune as a deliberate act. In an era of climate refugees who will be forcibly cast out of their homes by either too much water or not enough, Coleman sees herself as more of a retreat pioneer—someone who seized whatever agency she could as she faced an uncertain future. "There's nothing worse than sticking your head in the sand and resisting all this change going on around you," she says. "Because then you end up feeling pushed to make a decision that you are not prepared to make."

McGee, meanwhile, is playing the long game. In the spring of 2018, five and a half years after Sandy, Blue Acres was still submitting new buyout applications to the federal government. Woodbridge is on its third round of buyouts, which involves seven of the 19 holdouts that remain in the resiliency zone. "I don't close out a grant until we've done enough demolition so that the holdouts can digest how the character of their community is changing," McGee says. The tactic is working. She has spent $172 million of her total funding pot, which has grown as other recovery programs failed and FEMA directed the unused money her way. Blue Acres has facilitated nearly 1,000 buyout offers since Sandy, of which 713 have been accepted by homeowners. "You think it'd be 10,000 families for all the work we've done, but it's not, because it's so damn hard," McGee says.

Woodbridge's resiliency zone is not quite ready to be held up as a demonstration project. The work isn't done, and the marsh isn't yet beautified. Over the years, as the houses came down in stages, the scene sometimes looked like an eerie abandonment of the built environment, not a harbinger of progressive adaptation. But now that nearly all the structures are gone and the outlines of formerly paved roads are blurring into grass, "it looks less like a ghost town and more like it's just land," says Coleman, who visits every few months to see the transition in progress. "Now it's the houses that look like they don't belong."

No one disagrees that undeveloping certain areas of the coastline will be messy and expensive. But as the science of coastal resilience becomes more collaborative, the how-to of retreat may become less daunting. Retreat, after all, will not mean drawing a line some distance inland from Maine to Florida and removing everything to the east, explains Bryan Jones, a geographer who models climate-induced human migration. Modeling combined with artificial intelligence is now producing tools that allow planners to play out what-if scenarios in their towns. If, say, you buy out 40 houses from one location, restore groundwater storage and run the 100-year flood of the future, would that significantly reduce damage to adjacent houses? What are the social and economic trade-offs of undeveloping one neighborhood to protect another? Can land be designated as a safe relocation spot? These are the kinds of questions that Fugate, who led FEMA during Sandy, and others are working on now. "Just as the quantification of catastrophe risk drove a huge expansion in catastrophe insurance, it is about to drive a great industry of disaster risk reduction," wrote Robert Muir-Wood in his 2016 book *The Cure for Catastrophe*.

Retreat is so new that few planners are thinking about the next step: relocation. "Globally, there's substantial evidence that people end up right back in harm's way," Jones says. In a survey of Staten Island families who took buyouts after Superstorm Sandy, Binder, the sociologist, found that 20 percent moved to a home that is equally or more vulnerable to flood risk. As more people begin to flee slightly inland, they will encounter a wave of people still moving toward the coast. Just like backwash hitting the surf, the result could be turbulent.

As U.C.L.A.'s Koslov wrote in 2016 in *Public Culture,* "the complexity and ambivalence of retreat serves as a reminder that there are no easy solutions and that it is not possible to rebuild forever or to wall ourselves off from the problems we face." Retreat signals not just the physical movement of recalibrating to the tides but an existential reckoning with our ways of living along the water. The word itself is borrowed from the language of geologic processes, which humans have undeniably hastened. As glaciers and beaches retreat, so, too, will we. SA

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SPECIAL EDUCATION REPORT 2018

BRINGING DARWIN BACK

Research shows that 60 percent of American teachers avoid or skimp on teaching evolution. A growing movement is trying to change that

By Adam Piore

Illustrations by Gérard DuBois

PATTI HOWELL HAD THOUGHT LONG AND HARD ABOUT THIS MOMENT IN HER 10th-grade biology class. She had spent months subtly preparing her students for it, had agonized and worried about it, had even attended a training session to get ready for it.

Now, on a sun-dappled April morning, Howell stood before 26 15-year-olds at the Baconton Community Charter School in southwestern Georgia, scanning the slip of paper she had just plucked off a heavy wood table.

"All right, let's see what we got here," said Howell, a 40-something teacher, wearing horn-rimmed glasses and a loose floral print shirt.

"Biologists 'believe' in evolution. How many of you think that is fact?"

Hands shot up around the classroom, along with a chorus of "fact," spoken in adolescent murmurs.

"Majority are saying fact," Howell said.

She nodded sagely—she had set up perfectly the exercise she learned in her training session. Now it was time for the payoff.

"Science is not a belief system," she said. "Science is a collection of evidence, reporting and communicating what you get from that evidence. You do not 'believe' in evolution; you do not 'believe' in science."

Howell scanned her students' faces.

"Religion is our belief system," she continued. "I believe in God, I have faith in God, I do not need for God to burn a bush in front of me. But for science we need evidence."

It's day one of the evolution unit in Howell's class. And for a science teacher, the job doesn't get much more challenging than this. Baconton, population 850, is a devout farming community known for growing easy-to-crack pecans. A road sign at the entrance to town welcomes visitors to "the paper shell pecan capital of the world." Almost all Howell's students attend local Baptist congregations that follow a "strict literalist" interpretation of the Bible. Their pastors teach that God created Earth in six 24-hour days, including Adam and Eve, and that humans do not share a common ancestor with lower life-forms. Most of Howell's colleagues have strong beliefs on the topic, too. When the Spanish teacher in the classroom across the hall learned that evolution was on today's agenda, he asked Howell for the names of her 50 students. He wanted to pray for their souls.

Howell thinks what she is doing right now, as she begins the evolution unit, is key to everything that will follow. Somehow she must convince her students that they can consider what she has to say about evolution with an open mind and still retain the religious beliefs that lie at the center of their cultural identity—that, contrary to what many of their pastors tell them every Sunday, she is not attempting to force them to choose between God and science.

It's a tough sell. Which is why, for months, Howell has refused to discuss the subject with her students. Many had been asking her from the first day of school: Do you believe in evolution? Do you think we came from monkeys?

Now Howell looks out at the faces of her students and finally answers.

"I know that y'all think I'm a heathen," she says. "I understand that, but I am Christian. Do I believe in evolution? No, that's not a belief system. But I accept the theory of evolution."

AVOIDING THE SUBJECT

STRAIGHT TALK about evolution in classrooms is less common than one might think. According to the most comprehensive study of public school biology teachers, just 28 percent implement the major recommendations and conclusions of the National Research Council, which call for them to "unabashedly intro-

IN BRIEF

Only 28 percent of teachers craft lesson plans around evolutionary theory. **Many fear** a backlash from religious students and parents or because they feel underprepared. **Groups,** including the Human Origins Initiative and the Teacher Institute for Evolutionary Science, are working to boost teachers' knowledge of and confidence with the subject.

duce evidence that evolution has occurred and craft lesson plans so that evolution is a theme that unifies disparate topics in biology," according to a 2011 *Science* article by Pennsylvania State University political scientists Michael Berkman and Eric Plutzer.

Conversely, 13 percent of teachers (found in virtually every state in the Union and the District of Columbia) reported explicitly advocating creationism or intelligent design by spending at least an hour of class time presenting it in a positive light. Another 5 percent said they endorsed creationism in passing while answering student questions.

The majority—60 percent of teachers—either attempted to avoid the topic of evolution altogether, quickly blew past it, allowing students to debate evolution, or "watered down" their lessons, Plutzer says. Many said they feared the reaction of students, parents and religious members of their community. And although only 2 percent of teachers reported avoiding the topic entirely, 17 percent, or roughly one in six teachers, avoided discussing human evolution. Many others simply raced through it.

To confront these challenges, several organizations have launched new kinds of training sessions that are aimed at better preparing teachers for wh at they will face in the classroom. Moreover, a growing number of researchers have begun to examine the causes of these teaching failures and new ways to overcome them.

Among many educators, a new idea has begun to take root: perhaps it is time to rethink the way evolution teachers grapple with religion (or choose not to grapple with it) in the classroom. "There has been this war between creationism and what I think of as a cold teaching of evolution. Basically, 'Check your religious beliefs at the door, we don't talk about that in here, this is science. All you narrow-minded fundamentalist Christians, shut up and listen to us talk,'" says Lee Meadows, an associate professor of science education at the University of Alabama at Birmingham. Meadows also serves on the social impact committee of the Smithsonian Institution's Human Origins Initiative, a group helping to find ways to better promote acceptance of evolution education. "There's a growing number of us," he adds, "who are saying there's got to be a way to teach the science without throwing kids who come from religious backgrounds into turmoil."

A LEGACY OF ACRIMONY

FOR DECADES the most high-stakes, high-profile battles over evolution education were fought in the courts and state legislatures. The debate centered on, among other things, whether the subject itself could be banned or whether lawmakers could require that equal time be given to the biblical account of creation or the idea of "intelligent design." Now, with those questions largely resolved—courts have overwhelmingly sided with those pushing to keep evolution in the classroom and creationism out of it—the battle lines have moved into the schools themselves.

The most promising efforts nowadays are focused on laws advocating "academic freedom," which leave it up to individual teachers to say what they want about controversial science topics, including evolution, says Glenn Branch, deputy director of the National Center for Science Education, which monitors antiscience legislation.

Some 70-odd "academic freedom bills" have been introduced in state legislatures around the country since the first one appeared in Alabama in 2004, and three have passed: in Mississippi in 2006, in Louisiana in 2008 and in Tennessee in 2012.

IN ADDITION TO TACKLING MISCONCEPTIONS ABOUT EVOLUTION AT WORK IN THE WORLD TODAY, IT MAY BE EQUALLY EFFECTIVE TO ADDRESS THE ELEPHANT IN THE SCIENCE ROOM: RELIGION.

"If you can't ban the teaching of evolution, and you can't balance it with creationism in some form or other, what do you do?" Branch asks. "You belittle it, you say evolution is just a theory or you say it's controversial. Creationists have been saying this all along. The difference is that now they don't have anything better."

Today, many are now realizing, the far larger obstacle for the vast majority of ordinary science teachers is the legacy of acrimony left over from the decades of legal battles. In many communities, evolution education remains so charged with controversy that teachers either water down their lesson plans, devote as little time as possible to the subject or attempt to avoid it altogether.

Meanwhile teachers in deeply religious communities such as Baconton face an additional challenge. Often they lack tools and methods that allow them to teach evolution in a way that does not force those students to take sides—a choice that usually does not go well for the scientists perceived to be at war with their community.

Without such tools, even those teachers who do feel confident with the material often have trouble

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convincing students to listen to their lesson plans with an open mind—or to listen to them at all.

FROM THE COURTROOM TO THE CLASSROOM

THE WAR OVER EVOLUTION education has had three distinct phases leading up to the current era, according to NCSE's Branch.

The first wave of antievolution pressure in public schools started in the 1920s, when a number of states attempted to ban the teaching of evolution outright. After conspiring with a local businessman, a young substitute teacher in Tennessee named John T. Scopes deliberately defied the ban, taught evolution, and was arrested and charged with a misdemeanor. The intent was always to challenge his arrest in court. His trial, which began in July 1925, led to a spectacular showdown between defense attorney Clarence Darrow and prosecutor William Jennings Bryan, was broadcast on radio and transfixed the nation. Scopes was convicted, but the conviction was later overturned on a technicality, allowing proponents of the ban to avoid a ruling on its constitutionality that many had by then determined they were very likely to lose.

The ban was not actually overturned on constitutional grounds until 1968, when a similar Arkansas law was overturned by the U.S. Supreme Court in *Epperson v. Arkansas.* After that, antievolution forces moved to a second approach: advocating the teaching of creationism alongside evolution.

In the 1975 Tennessee case *Daniel v. Waters,* courts struck down an "equal time" law passed by the state legislature, requiring teachers to teach biblical creation whenever they taught evolution. Throughout the 1970s and 1980s, Branch notes, some 30 state legislatures considered bills advocating the teaching of "creation science," arguing that creation accounts of genesis, including the worldwide flood, were scientifically supportable.

A bill in Arkansas actually passed, leading to its defeat in the 1982 case *McLean v. Arkansas,* which fea-

tured evolutionary biologist Stephen Jay Gould and a whole host of celebrity scientists. Soon after, Louisiana passed a broader bill, which was struck down by the Supreme Court in 1987.

After those defeats, many moved on to advocating the teaching of intelligent design, which argues that "something, somehow, intervened in the history of life," according to Branch. That approach was struck down in 2005 by a federal district judge, after parents in Dover, Pa., challenged a policy put in place by a local school board that had been taken over by creationists (who were subsequently voted out).

In the minds of many, that put a stop to any credible legislative effort to bring creationism back to the classroom. Yet the issue hasn't gone away. No one knows that better than teachers on the front lines such as Patti Howell.

On the first day of the evolution unit, Howell set to work subtly chipping away at her students' resistance to the theory. As soon as her backpack-toting teenagers shuffled past her that morning, she handed each one a brief article on the evolutionary vulnerability of asexually reproducing toenail fungus. Then she instructed them to partner up and rotate through a series of stations set up around the room.

As she had done with her two other biology classes, at each station she had placed a slip of paper with a single statement on it: "Humans evolved from monkeys," read one. "Only Atheists accept the theory of evolution," read another. After reading each slip, the students placed beads on one of two sticks, each anchored by a small wood square labeled either "fact" or "fiction." Howell addressed the "misconceptions" one by one. Then she played brief video clips about dog fleas that have developed resistance to store-bought anti-itch creams and bacteria that have grown resistant to antibiotics.

Her goals on this first day were twofold: to provide examples of evolution that students might observe every day and to address common misconceptions.

Howell learned these two approaches at a recent teacher-training session sponsored by the Teacher Institute for Evolutionary Science (TIES), an organization launched in 2015 by Miami-Dade middle school teacher Bertha Vazquez, with funding from the Richard Dawkins Foundation for Reason and Science. During the past three years TIES has held 92 workshops in more than 30 states and trained upward of 1,500 teachers. Countless others have accessed the organization's Webinars remotely.

The idea, Vazquez says, is to take aim at perhaps the biggest obstacle to evolution education: the fact that many teachers feel unprepared to teach it. "If I mess up when I'm teaching weather to my students—say I don't know the difference between an occluded front and a stationary front—no one is calling the office and nobody's really going to question me," Vazquez explains. "If I mess up between natural selection and genetic drift or theory versus fact, then you're going to have parents on you full of misconceptions. If you don't feel confident teaching this, you're just not going to teach it."

In 2013 Vazquez participated in a discussion with Richard Dawkins and about a dozen science professors at the University of Miami about exactly this issue. They concluded the problem is that teachers are not comfortable with the material. Therefore, after the event, she set up a professional development course in evolution for some of her friends in area middle schools. When Vazquez met Dawkins a year later at another event and told him what she had done, Dawkins offered to come talk to her teachers. And a few months later Dawkins asked if Vazquez might be willing to take her project national. (Dawkins serves on *Scientific American*'s board of advisers.)

In 2016 the program added Webinars, available to teachers who cannot make it to the workshops in person. These resources supplement a growing body of teaching materials already on the Web—in 2004, for instance, the National Center for Science Education, in collaboration with the University of California Museum of Paleontology, developed a Web site entitled Understanding Evolution that offers science content, teaching resources and teaching strategies. "We're trying to get teachers to a point where they have confidence teaching it and can present it for what it is," Vazquez says, "a beautiful awe-inspiring way of seeing the world, you know, that's current and relevant."

Although Vazquez, who teaches in a Miami-Dade school, does not face nearly the level of resistance Howell is confronting, she estimates every year she has a handful of students for whom evolution is a problem, either Christians, Muslims or Jehovah's Witnesses. And when designing her training materials, she built in the approaches she has found to be effective and intuitive in engaging them.

"If you start with misconceptions, and modern, current relevance of evolution and how important it is in terms of agriculture and medicine, it brings their guard down a little bit," Vazquez says. "I think showing just a common little example, those kids can go home now and say, 'yeah, she talked about fleas.' The teacher's not really going to get in trouble, but the kids are going to get natural selection."

"When teachers ask us about how to deal with students' religious questions in TIES workshops, we recommend the teachers say, 'Since this is a science class, we will not address religion here. We advise you to ask your parents and faith leaders about the religious question,'" Vazquez adds. Howell herself chose to add in a mention of her own religious beliefs to drive home the idea that religion and science coexist.

The approaches that Vazquez and Howell have arrived at through intuition and experience, others are confirming or refining using the scientific method. Indeed, a growing number of researchers are beginning to argue that in addition to tackling misconceptions and showing evolution at work in the world today, it may actually be equally effective to explicitly

address the elephant in the science room: religion.

In one influential 2011 study published in the *Journal of Research in Science Teaching,* investigators at Southern Nazarene University, Purdue University and Florida State University examined the experiences of 15 biology majors at a Midwestern Christian university who were raised to believe in creationism but were forced to grapple with evolution. In the end, almost all of them came to accept evolution. The researchers wanted to know why. In fact, rather than glossing over religion, they found, their professors had acknowledged the religious beliefs of their students, talked openly about the issues raised and served as role models who could help the students reconcile the science with their beliefs.

In another 2012 study, a researcher at Towson University explored the difference between religious students who were unwilling to learn evolution and those who were able to learn and understand evolution, despite the fact that they did not believe in it. In that study, researchers suggested, among other things, that when teachers failed to mention religion it increased their feelings of alienation and made them less open to learning.

Inspired by this research, Arizona State University researchers Sara Brownell and Elizabeth Barnes set out to find out how often professors actually did approach evolution in the college classroom. Not only did they find that instructors rarely touch on the issue of religion, they found the likely reason. The vast majority of instructors teaching evolution were atheists, whereas the population of students who identify as religious in the class was sometimes as high as 80 percent. "When we asked the professors why, they often cited reasons that were related to their own religious cultural background," Barnes says. "Mainly that they didn't have experience talking about these issues, and so it was a little intimidating. They weren't aware of their students' religious beliefs and whether their students were struggling with evolution. And they had some negative stereotypes."

Yet to those who grew up in devoutly religious communities and have gone through the process of learning evolution, it is obvious that ignoring religion won't work. Amanda Glaze, who is a professor of middle grades and secondary education at Georgia Southern University, was inspired to study evolution education in part by her own experience. After growing up in a creationist family on an Alabama farm, she fell in love with science and eventually came to accept Darwin's theory of evolution. But it was not an easy journey.

"I cried, I was depressed, I was worried that I was going to Hell. I mean, years, years of literal torment back and forth," she recalls. "And yet we try to come into a classroom in a semester or a year and tell people, 'Oh, well, you know, your beliefs are wrong,' or 'They don't matter, this is what's true,' And people wonder why evolutionary acceptance in this country is abysmal." What many evolution education advocates do not realize, Glaze says, is that for many, religious beliefs and worldviews are "an identity construct." "If you're not a part of that, if you've never experienced that, it's very easy to say well, it doesn't matter, you're just being irrational," she says. "Students will just shut down."

To reconcile her new knowledge with her identity, Glaze says, required her to find a way to consciously segregate her religious beliefs from her scientific knowledge and let them each exist independently, an approach process some have termed "cognitive apartheid." "We have science, which is a physical explanation of events occurring in a physical world, then we have religious ways of knowing, philosophical ways of knowing that are not tied to physical evidence," Glaze says. "The standards and the burdens in those different ways of knowing are very, very starkly different, but so often we try to conflate the two."

"It's not a matter of supplanting or breaking down someone's existing worldview. What our actual goal should be is to add a scientific worldview to whatever worldviews people are bringing to the classroom. But to do that, you have to recognize what those worldviews are and the power that they hold with people."

David Wilcox, a professor emeritus of biology at Eastern University, a Baptist school located in Pennsylvania, spent more than 35 years teaching evolution to students who came in believing in creationism. And for him, "disentangling" the messages received about religion and science was essential. "What's happened is that evolution is taught in an awful lot of churches not as a matter of science but as a part of a worldview packaged with other ideas—including the idea that one does not believe in God and a worldview in which morality will disappear and in which civilization is not going to survive," he says. "Many of my students come in having been taught that if you believe in evolution, you have to believe all those other things are true, too. But that's not the case."

Wilcox was consistently successful with his students because the first thing he did was attempt to break apart these disparate ideas and convince his students that it is possible to deal with science and still have faith. He also emphasized that there are theologians who have interpretations of the Bible different from those of strict literalists (St. Augustine, for instance)—that, in fact, the theological interpretations that God created Earth in six "literal" days is not at all universal. At the very least, he shows them there is "another door" they can return to later that leads to acceptance of evolution that does not come with atheism.

FINDING RELIGION

PERHAPS THE MOST PROMISING and potentially impactful resource to address religion and evolution in the classroom is being developed by Briana Pobiner, a prehistoric archaeologist and museum educator at

the Smithsonian Institution's National Museum of Natural History, and her colleagues in close consultation with educational researchers and faith leaders who meet several times a year through the Smithsonian's Human Origins Initiative's social impact committee. Recently they unveiled a 75-page *Cultural and Religious Sensitivity (CRS) Teaching Strategies Resource* guide for teachers to use for discussing human evolution and for actively testing their techniques in the classroom.

"Ignoring the issue of religion doesn't work," Pobiner says. "But there is a way to engage students' faith perspective and help them not shut down completely. Increasingly we are finding that when you don't dismiss students' faith perspective, you get a much better outcome for helping them engage with the content of evolution."

Among other things, the document includes several classroom exercises that teachers can introduce either at the start of evolutionary instruction or "at the first signs of unexpected negativity"—"not to change personal or cultural religious beliefs or to resolve any conflicts between science and religion your students may feel, but to help your student understand the nature of science and that the theory of evolution is a scientific tool useful in addressing biological questions."

In the first exercise, students are given a homework assignment that asks them to summarize the theory of evolution, to summarize alternative explanations for the variety of life-forms that are important to people they know and to list reasons why some people might be concerned about the study of evolution. In class, the students then break up into groups to discuss their answers.

Over the course of the 2012–2013 school year, Pobiner and her colleagues field-tested the CRS materials with AP biology students in 10 schools in eight states. They used assessments of students' understanding of evolution before and after it was taught to test their effectiveness. In results published earlier this year in the journal *Evolution: Education and Outreach,* Pobiner and her colleagues found that students who had done the CRS exercise had a better understanding and acceptance of the theory of evolution.

The group is now testing this approach in a more challenging environment: 9th-grade biology classes across Alabama, the only state in the union where biology textbooks bear a sticker warning that evolution is "just a theory" and should not be taken as fact. (Alabama lawmakers also passed a resolution last year affirming teachers' rights to include creationism in their lesson plans.)

Birmingham's Meadows says the findings will be presented at the Alabama teachers association in November. "Alabama teachers are wanting permission to teach evolution, and they want to know they can do it without personal turmoil and student turmoil, and that's what I think we're going to show," Meadows notes. "It's going to be huge." No studies have yet been done on the TIES approach.

CHIPPING AWAY AT RESISTANCE

EVERY SUNDAY, Patti Howell sits in a pew of her church in the town of Americus and listens to her preacher preach: Those scientists are going to try and tell you this. Those scientists are going to try and tell you that.

She never broaches the topic of evolution with her friends, and on the few times she and her husband have discussed the matter, they have argued.

"In church, I just keep my mouth shut. I would never open my mouth. I don't discuss it with my friends and family," she says. "I just sit there and listen to it."

Howell doesn't have that option in her class—she has a job to do. And she knows the hardest part lies ahead.

Accepting the biological resistance of bacteria is one thing. She expects many of her students will even be interested in the adaptations Darwin discovered in the beak shapes of finches separated from their ancestors by geography. The problems, she expects, will begin when she gets to the similarities between humans and other species—commonalities in DNA, vestigial structures such as the tailbone and other evidence that humans share common ancestors with other species. This part of evolution, she knows, is hard to reconcile with the biblical accounts of creation, Adam and Eve, and the Garden of Eden. "They're going to have a hard time with that," she says.

Howell has had enough experience teaching evolution in other communities for 17 years to know the signs. The students will cross their arms; they will stare at the floor. The most defiant among them may even kick the chairs on the way out. Although she believes the tools she has learned through the TIES program will improve her chances of reaching some students, she knows she won't reach them all.

Howell isn't sure what kind of class she will have in coming years. She is hungry for more tools to help her navigate the cultural minefield in her classroom. It's a lonely battle but one she is willing to fight. "I've got these people's kids, and that's the most important thing in the whole world to anybody," she says. "I don't want to tell them something wrong or damage them. It's a huge responsibility." SA

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Evolution Education in the American South: Culture, Politics, and Resources in and around Alabama. Edited by Christopher D. Lynn, Amanda L. Glaze, William A. Evans and Laura K. Reed. Palgrave Macmillan, 2017.

Using Human Case Studies to Teach Evolution in High School A.P. Biology Classrooms. Briana Pobiner, Paul M. Beardsley, Constance M. Bertka and William A. Watson in *Evolution: Education and Outreach*, Vol. 11, No. 1, Article No. 3; December 2018.

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scientificamerican.com/magazine/sa

SURFER PLUMMETS down a colossal wave at Nazaré, Portugal.

MONSTER WAVES

FRANCISCO SECO AP Photo

OCEAN SCIENCE

Forecasting technology and surfer experience create record rides on the planet's biggest breakers

By Chris Dixon

SLEEP CAME FITFULLY to Rodrigo Koxa during the night of November 7, 2017. The seasoned, 38-year-old big-wave surfer from a tiny island near São Paulo, Brazil, was in the bungalow he had rented for the fall and winter at Nazaré, a fishing village on the central Portuguese coast. In the dark outside, titanic waves were crashing onshore, shaking the ground. "I was telling myself, 'You gotta go straight down on your wave,'" he recalls, haunted by a bad memory.

October through March is when the huge breakers come to Nazaré. Koxa fixated on his laptop computer, watching animated blobs of yellow, blue and deep purple in the wave forecasts produced by the European weather services, the National Oceanic and Atmospheric Administration and Surfline, a preeminent surf portal. It was evident that the next morning would be go time.

Some of the largest waves on earth had thundered down in plain sight of the village's residents for 1,000 years, yet they had escaped the surfing world's attention until November 1, 2011. That was when a Yamaha WaveRunner pilot towed champion surfer Garrett McNamara and his surfboard onto an avalanching wave that Guinness World Records judges declared to be a record 78 feet tall.

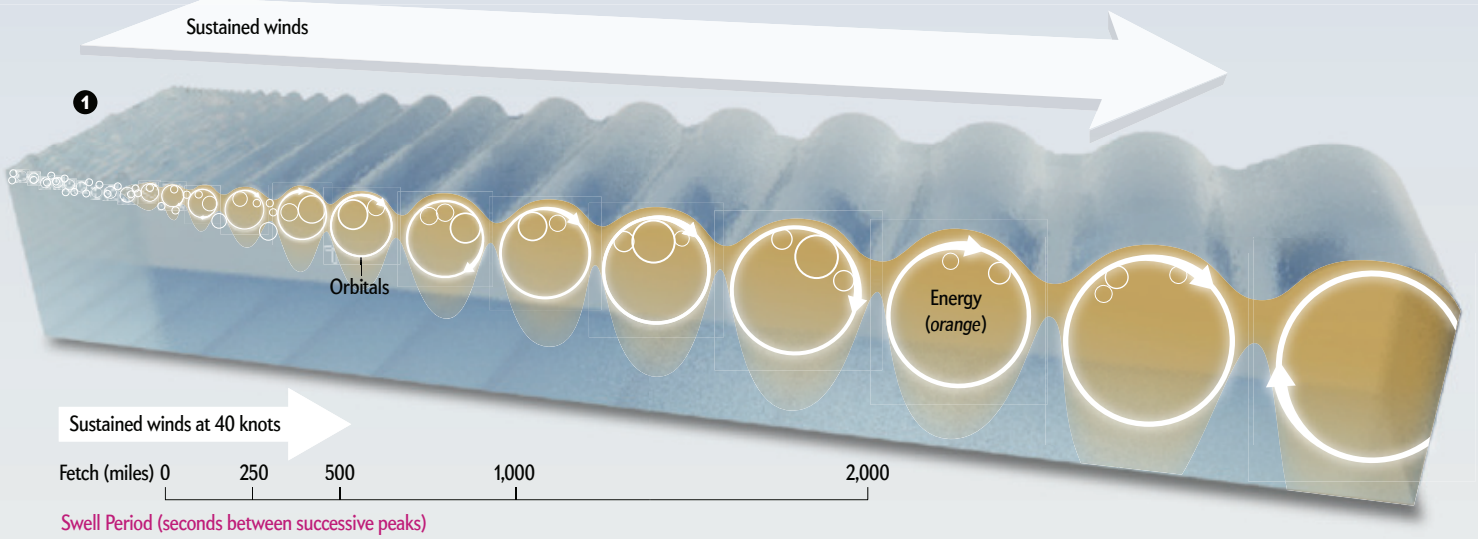
Koxa's first Nazaré attempt came in 2014, and it almost killed him. Immediately after starting a run

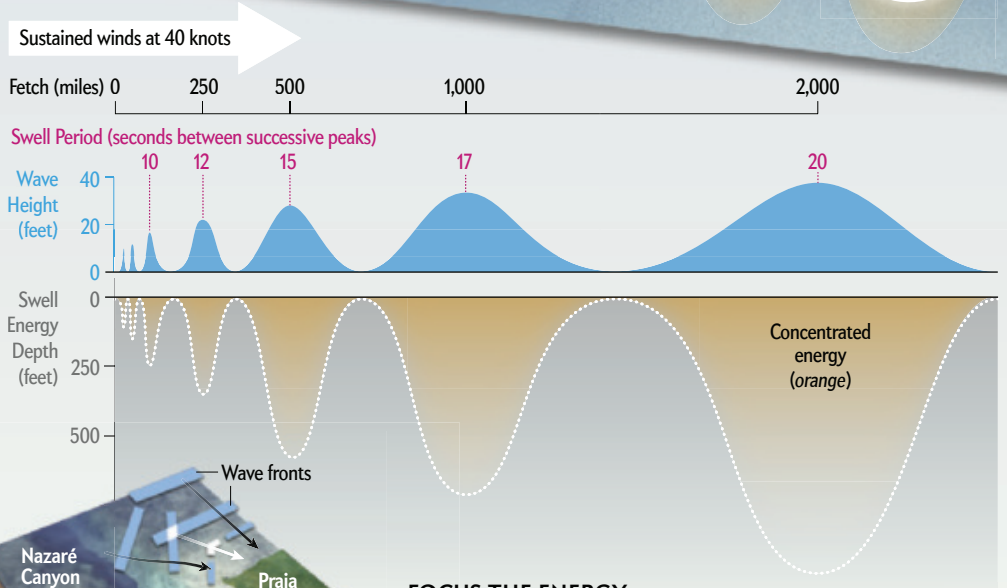
IN BRIEF

Giant waves up to 80 feet tall arise on only a few shorelines worldwide, such as at Nazaré, Portugal.
Scientists have combined real-time wind and water data with models of the seafloor to explain why. They also use the information to predict when and where the next record waves will break.
World-class surfers are flocking to these places for the terrifying thrill of riding the big one.

Making Waves

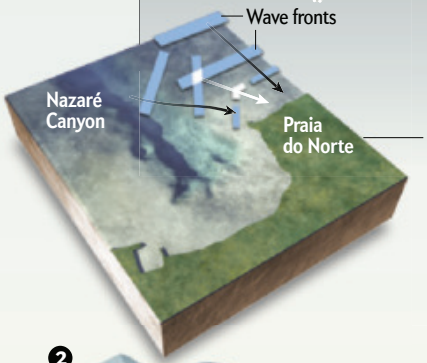
Truly titanic waves that erupt to 70 or 80 feet by the shore occur at only a few locations on earth (*map*). They begin as small waves that organize into cylindrical swells. When sustained winds can blow across many miles for a long time, they steadily enlarge the swells ❶, making them higher, longer and faster (*graph*). As a swell approaches land, a deep-sea canyon or seafloor that rises abruptly by the shore can concentrate the swell energy, like a lens focusing light, boosting the water skyward into a huge, breaking wave ❷. The bending canyon at Nazaré, Portugal, enhances the effect (*cutaway illustration*).





BUILD THE SWELL

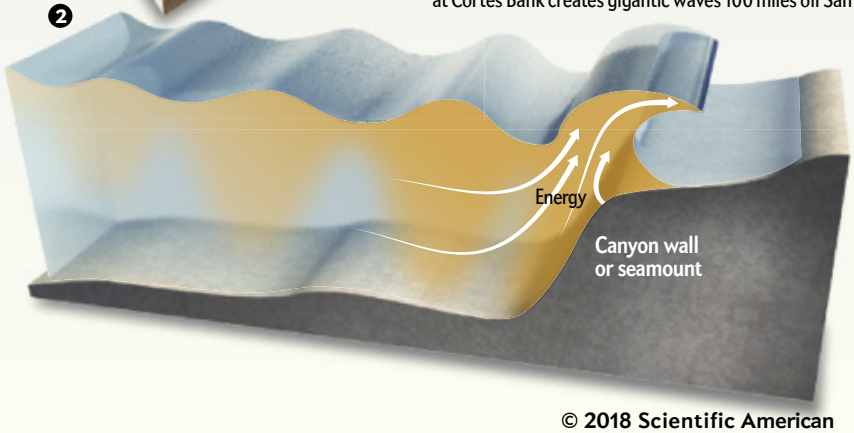
Strong, steady winds, often spawned by storms, cause water molecules to vibrate in a circular path, forming small orbitals that winds convert into swells—the tops of which we see as waves. Rotating eddies of air between the waves push them along. As winds continue to blow over long distances, known as fetch, the swells get higher and longer, and the period increases. Most of the energy is concentrated below the surface and can tail off hundreds of feet down. The swells continue to sweep forward, drafting off one another, at speeds sometimes exceeding 30 knots.



FOCUS THE ENERGY

At Nazaré, an abrupt canyon wall refracts a deep part of a swell back into the greater swell, creating constructive interference that drives the water upward into a tremendous, pyramid-shaped peak that finally breaks as a wave thundering down on the shore. A 15-foot swell might produce an 80-foot wave. Variations of the canyon effect occur at Jaws off Maui, Mavericks in northern California and Teahupoo on Tahiti. An abruptly rising seamount at Cortes Bank creates gigantic waves 100 miles off San Diego.

❷



BETTER FORECASTS

Experts are more accurately forecasting big waves by merging wave and weather models with artificial-intelligence programs that assess data streaming in from surf cameras, miniature buoys and even social media accounts about water conditions. Predictions will soon be custom-generated for a surfer holding a tablet computer on a particular shore.

SOURCE: SEAN COLLINS *Surfline (fetch diagram)*

Illustration by Don Foley

down a mountain of water, he was nearly crushed against Nazaré's cliffs. Staring at the forecast in 2017, he knew he would face another giant the next day.

Chris Dixon is a freelance writer and author of *Ghost Wave: The Discovery of Cortes Bank and the Biggest Wave on Earth* (Chronicle Books, 2011).

DEEP DATA

WAVES THAT BREAK at any seashore have a similar genesis. A breeze over the ocean builds small ripples into waves. If strong winds can blow for many miles, the waves become swells that grow and morph into horizontal water columns. Imagine a series of mostly submerged logs in the water rolling toward a coast. If the wave above the sea surface is 10 feet high, the rest of the log might reach hundreds of feet down.

Giant swells are spawned by powerful winds from big storms. The swells barreling toward Nazaré at 35 knots had roared to life during a gale that started four days earlier and 3,000 miles away, between Newfoundland and Greenland. Koxa was able to prepare for them because surf forecasting had advanced tremendously in just the past decade. Early generations of wave models had crunched vast amounts of real-time and recent data from satellite, ship and buoy-borne observations of winds and swells. Predictions about whether big waves would rise near shore came from modeling the interaction of all the data with maps of the seafloor.

In the past few years global wind and wave models have become increasingly precise, as ever more powerful supercomputers assimilate all manner of input data: anything from inch-high capillary waves measured by satellites to tidal currents and the drag that winds encounter over sea ice versus water.

Understanding how the seafloor near the shore influences breaking waves has also improved. At Nazaré, one of the world's most pronounced submarine canyons rises from 16,000 feet of water and more than 125 miles of continental shelf, then funnels right up to the headland onshore. The canyon focuses a wave like light through a lens. It compresses wave energy while the seafloor forces it upward, and the water's forward momentum creates a towering breaker. "You can have 15 feet of swell in deep water creating a breaking wave up to 80 feet," says Mark Willis, head of forecasting at Surfline. "The reason is the incredible, exaggerated canyon."

Despite improvements, the models still struggle with small geographical areas such as Nazaré, says Hendrik Tolman, former director of the Environmental Modeling Center at NOAA. Subtle differences in swell direction or even tidal phase can dramatically reduce or amplify wave heights. Enter machine learning. At its essence, machine learning weaves large quantities of past data with current observations to infer future waves. In a study of California's Monterey Bay last year, researchers at IBM compiled hourly NOAA weather and wave data from 2013 to 2017 into an enormous spreadsheet 11,078 rows deep and 741 columns wide. When combined with current observations, the artificial-intelligence system led to a 12,000 percent improvement in computational efficiency over models that rely solely on physics of wave and weather dynamics. Surfers, ship captains, wave-energy harvesters and fish farmers will soon be modeling waves at their exact locations—on their iPads.

To further enhance forecasts for specific spots, Willis and Ben Freeston, founder of the Magicseaweed surf portal and Surfline's director of data science, are using machine learning to essentially create a neural network of added observations from surf cameras and Surfline's paid reporters; it even includes updates from surfers on social media. Soon, Freeston says, surfers at Nazaré and other big-wave locations—such as Jaws off Maui and Cortes Bank off San Diego [*see box on opposite page*]—will be feeding data into AI programs. Tiny data buoys will be deployed outside of the wave zone, transmitting swell data to smartphones being scrutinized by surfers onshore. "Rather than $50,000 or $60,000 NOAA buoys, these can be deployed for 99 bucks," Freeston says. "Data will rise exponentially."

SURFING THE DREAM

TECHNOLOGY DOES NOT HELP a surfer once the person is out in the water, though. Experience is crucial for catching the world's biggest waves. On the morning after Koxa's restless night, the swells were approaching the Nazaré shore from the northwest, an ideal angle for the canyon to work its magic. Koxa and a crew of friends marveled as the canyon redirected swells into one another, forming massive, triangular peaks that erupted in front of the headland.

Koxa and his Sea-Doo pilot, Sergio Cosme, circled outside the waves for an hour and a half, but Koxa had yet to catch one. Finally, Cosme hollered, "Big set coming!" Koxa knew that the stiff offshore breeze would make the first wave extremely bumpy, so he held back. The surface of the second wave was cleaner. Then came the third wave. "It was smooth, glassy and beautiful," Koxa says. "It was so huge. I took one look, but I don't want to look again. Because if I do, maybe I don't want to go."

Cosme towed Koxa to the apex of a wave carrying perhaps a billion watts of power. When Koxa let go of the towrope, seven stories up, he reminded himself of his mantra: "You gotta go straight down." At that point, he says, "I'm just running for my life. So much energy. I've never gone so fast on a surfboard. Then suddenly, I'm in the shadow of the wave. I felt the blackness behind me. But I have enough speed, I think I'm gonna outrun it. And I do. Oh, my God, I just got the wave of my life."

That ride turned out to be a new world record—the wave was 80 feet from trough to crest, as determined by judges on-site using photographic analysis. At an awards ceremony several months later, Koxa said that the combination of forecasting technology, surfer experience and guts all came together: "It was a dream come true." SA

MORE TO EXPLORE

Magicseaweed surf reports and forecasting: www.magicseaweed.com
Surfline wave forecasting and portal: www.surfline.com

FROM OUR ARCHIVES

The Size of Ocean Waves. Editors; November 24, 1906.

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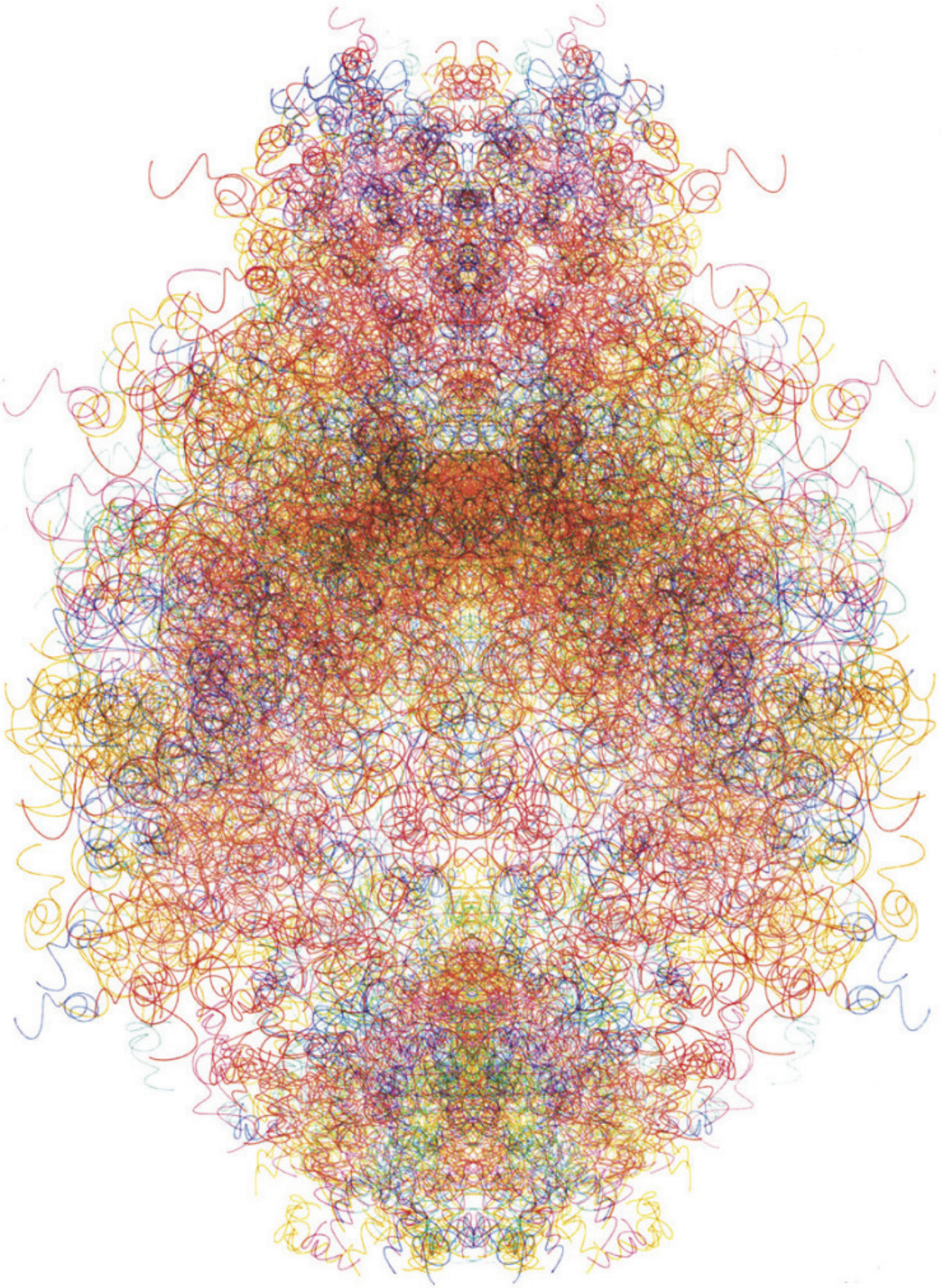


Stephen Ornes is author of the upcoming book *Math Art: Truth, Beauty, and Equations* (Sterling Publishing, 2019). He wrote "The Whole Universe Catalog" for *Scientific American*'s July 2015 issue.

Art by the Numbers

Images and sculptures inspired by mathematical principles show off the intense beauty of the discipline

By Stephen Ornes

Manchester Illuminated Universal Turing Machine, #23 (1998)

Roman Verostko

Verostko trained as an artist in the 1940s, became a priest, left the priesthood, got married, dissected computers and learned to code in BASIC. He is a pioneer in algorithmic art, which generates new visions using computer programs, and he uses algorithms to guide the drawing arm of a pen plotter.

He created this piece in 1998 after reading about the universal Turing machine (UTM) in Roger Penrose's 1989 book *The Emperor's New Mind.* The machine is named for computational pioneer Alan Turing, and the universal version is a machine that could emulate the functions of every specialized Turing machine, which means it could theoretically compute anything that could be computed. When Verostko learned about the UTM, he thought of it as a kind of foundational text of our time, a creation that would change culture forever. Through his religious studies, he had long been enamored of illuminated manuscripts—handwritten medieval texts embellished with elaborate illustrations in gold or silver—and decided the UTM was contemporary work that deserved illumination.

This UTM "text" (*above*) is binary code, a long string of 0s and 1s, the language of computers. As illuminations that evoke the work of medieval scribes, Verostko separately created abstract figures (*left*), produced with a plotter pen.

WE OFTEN REGARD MATHEMATICS WITH a cold reverence. The discipline is driven by rules and principles that are eternal and stoic. There will never be a countable number of primes, for instance, and the digits of pi will go on forever.

Beneath that certainty, however, lies a sublime attractiveness. A proof or equation can have an elegant, aesthetic effect. Mathematicians who study group theory, for example, analyze rules governing rotations or reflections. Visually, these transformations can appear as intensely beautiful symmetries, such as the radial patterns of snowflakes.

Some mathematicians and artists see a false choice between math and art. They choose not to choose. They ask questions using the language of numbers and group theory and find answers in metal, plastic, wood and computer screen. They weave, and they sketch, and they build. Many of them exchange ideas every year at the international Bridges conference on math and the arts or meet at the biennial Gathering 4 Gardner, named for Martin Gardner, who wrote the celebrated Mathematical Games column in this magazine for 25 years.

Now interest in math art appears to be blooming, shown by an uptick in exhibitions and even academic journals. Roots of the current wave go back to the end of the 20th century, but artists today call on a wider spectrum of mathematical muses and use more modern tools. Here are a few of the most striking works.

Borromean Rings Seifert Surface (2008)

Bathsheba Grossman

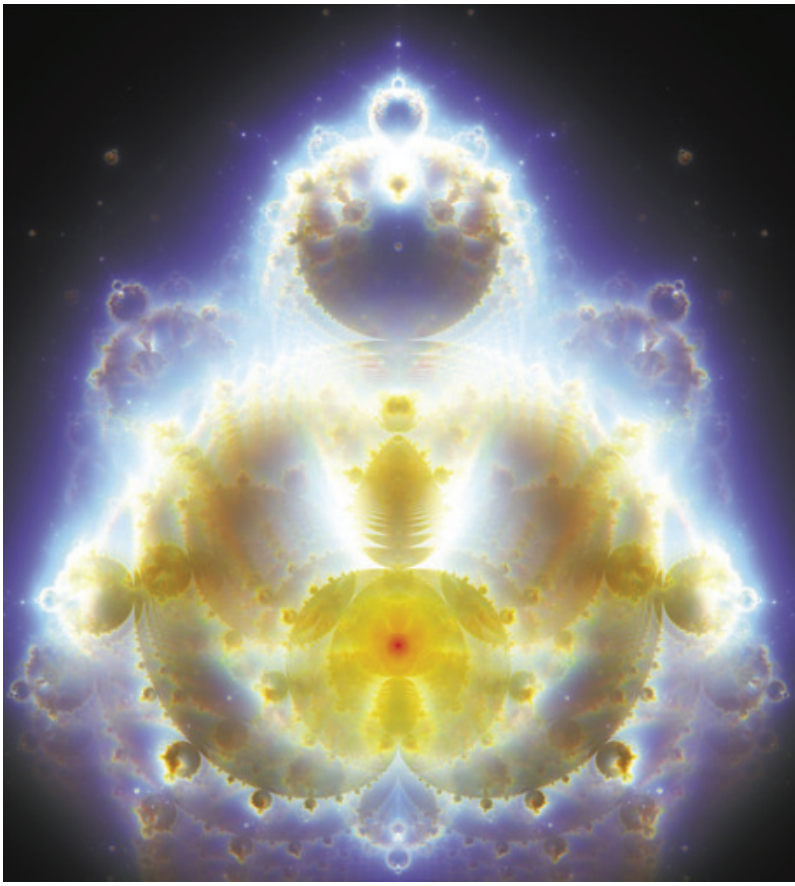
For more than a decade Grossman, who lives near Boston, has been using 3-D printing to forge mathematical sculptures out of metal. She delights in symmetries, impossibilities and the division of space. The three outer rings here do not touch one another but are still inextricably interlinked. If you remove one, the other two can separate. It is an ancient form called Borromean rings that is seen today in the logo of the International Mathematical Union.

The rings are members of a mathematical family of link forms, each member characterized by three closed curves with no two physically connected. Their interactions are of particular interest to mathematicians who work in knot theory. The surface bounded by the Borromean rings is called a Seifert surface.

Grossman's sculpture is part knot theory and part puzzle. To highlight the curious swoops of the surface, she used a perforated texture that both plays with light and draws attention to the curious topography.

Buddhabrot (1993)

Melinda Green



In the late 20th century a pattern called the Mandelbrot set took much of the math and art worlds by storm. It was a fractal set named for Benoit B. Mandelbrot, the late French-American mathematician who was the first to organize fractals into a field worthy of investigation. His 1982 book *The Fractal Geometry of Nature* remains a classic.

The set starts with a point on a complex plane, represented by a two-dimensional graph, and that point is used as the initial value for a particular equation. After making the appropriate calculations, take the new answer and plug it back into the equation. Repeat. If the answers do not get too large—increasing a bit, decreasing a bit—then the initial point is in the set.

Plots of such sets show telltale shapes that repeat as you zoom in or out. But until the 1990s the Mandelbrot set had a standard appearance that made it look like a big bug, with little bugs scattered around its edges and smaller bugs attached to those bugs.

Green, a computer programmer, did not like the "bug body" look. So she hammered out a program that showed more detail about the way certain points hopscotch around the plane. What appeared on her monitor was spooky. "I don't know if I literally pinched myself," she says. The image was a convincing facsimile of the Buddha, and Green revised the code to accentuate different colors. Many mathematicians compare the abstractions of mathematics to spiritual experiences, and Green's "Buddhabrot" invokes that bridge explicitly.

Aurora Australis (2010)

Carlo H. Séquin

In the math art world, Séquin, a computer scientist at the University of California, Berkeley, is known for making hundreds of pieces that give body to heady ideas about surfaces, twists and dimensions. He has produced a veritable zoo of pieces out of wood, metal and plastic.

This piece, he says, was inspired by the celestial light show that plays out in the skies of the Southern Hemisphere: the Aurora Australis, or Southern Lights. The twisting ribbon of the sculpture invokes the turning ribbons of light. In the sculpture, the ribbon changes from flat to curved to flat again and connects to itself. If you trace the sculpture's winding path with your finger, you will visit every part of it and wind up back where you started without lifting your finger. The inside surface is also the outside, which makes it a Möbius strip, the simplest known nonorientable surface, which means that you cannot use concepts such as "front" or "back" or "inside out" with it.

According to Séquin, such visuals are not just captivating; they also provide access to heavy mathematical ideas. "It's a way of getting people who hated math to refocus," he says. "It's a way to see math as much, much more than just rote learning."

Hyperbolic Plane/Pseudosphere (2005)

Daina Taimina

Taimina's adventures in geometric handicrafts began in the 1990s, when the now retired mathematician was teaching a class on hyperbolic geometry, a type of non-Euclidean geometry, at Cornell University. In Euclidean geometry, if you have a line and a point not on the line, there is only one other line that both passes through the point and is parallel to your first line. But in non-Euclidean geometries, there may be many lines that pass through the point and do not intersect the first line. This happens because a hyperbolic plane has constant negative curvature. (The surface of a sphere has constant positive curvature; negative curvature is more like what you would find on a saddle.) As a result, the angles of triangles on hyperbolic planes add up to less than 180 degrees. It is the kind of curvy weirdness that shows up as the frill on the edge of a kale leaf.

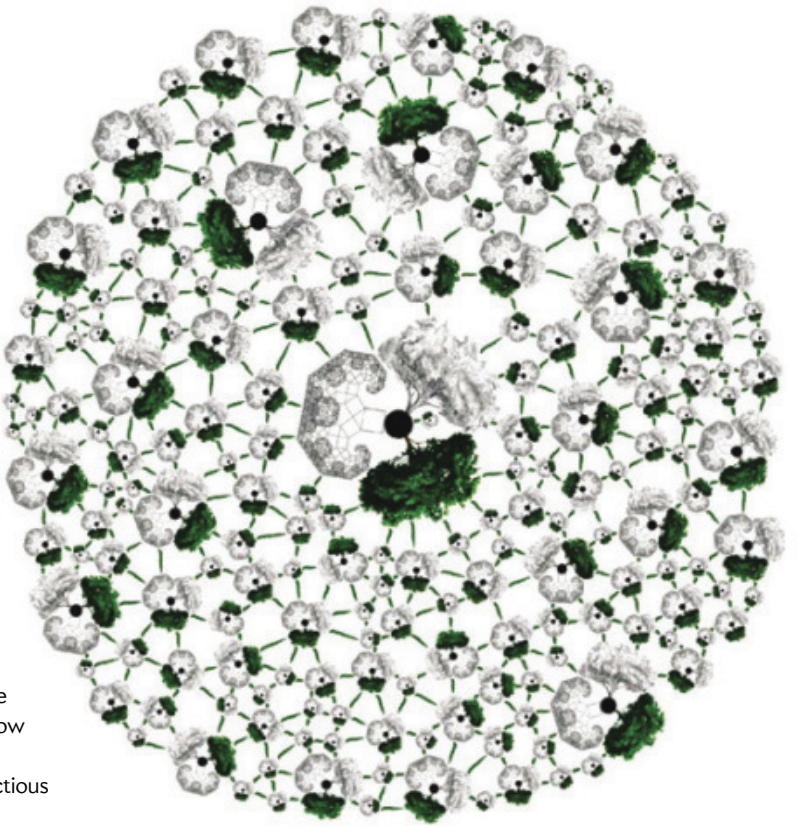
Taimina wanted to create tactile models so her students could feel the curvature. Crochet, which she has been practicing almost her entire life, seemed like a good fit. With a crochet hook and yarn, she created a hyperbolic surface using a simple recipe, increasing the number of stitches exponentially. The one shown here takes the form of a pseudosphere, which has negative curvature everywhere.

Since then, Taimina has made dozens of models in an array of colors—the largest weighs about 17 pounds—and can claim invention of "hyperbolic crochet." Her method for creating dazzling blobs has only one basic step. "It's very simple," she says. "Keep constant curvature."

THIS PAGE: DESIGNED, CROCHETED AND PHOTOGRAPHED BY DAINA TAIMINA; OPPOSITE PAGE (*bottom*): WITH INSPIRATION FROM A SKETCH BY M. C. ESCHER

Atomic Tree (2002)

John Sims



Mathematician-artist Sims lives in Sarasota, Fla., and draws inspiration from a range of mathematical ideas. The central image here depicts trees growing on a fractal, which is a pattern that is self-similar: it is the same at every scale, whether you zoom in or out.

Such patterns appear in nature in bushy broccoli crowns and jagged mountain ranges, and scientists have used them to study a range of phenomena, from the structure of the cosmos to the flight patterns of birds.

This figure combines images of a real tree, a drawn tree and a fractal in the shape of a tree. It "speaks to the intersection of math, art and nature," Sims says. In "Atomic Tree," the joined shapes serve as building blocks, repeated large and small and connected to form one big network.

Sims first showcased this piece at MathArt/ArtMath, a 2002 exhibition he co-curated at the Ringling College of Art and Design. He has also produced many works inspired by the sequence of digits of pi, including quilts and dresses. With fellow mathematician-artist Vi Hart, in 2015 he produced a "Pi Day Anthem," in which the duo recites the digits of pi over an infectious drum and bass groove.

Scarabs (2018)

Bjarne Jespersen

Jespersen calls himself a magic wood-carver. The Danish artist aspires to disbelief: he wants people to see, hold and move his wood creations and still not believe in them. "I'm more of a magician than I am a mathematician or an artist," he says.

If you hold this ball in your hands, you quickly realize that each of these beetles jiggles independently from the rest, and yet they are interlocked and unable to be removed from the whole without breaking something. The ball is carved from a single block of beech.

Jespersen has been inspired by Dutch artist M. C. Escher, much of whose art was mathematical in spirit. Escher popularized tessellations, which are geometric shapes that fit together in a repeated pattern that covers, or tiles, a plane. Mathematicians have long investigated the properties of tessellations—not only of a flat surface but also of higher dimensions. (Escher himself was inspired by the use of tessellations in Islamic art; in particular, the patterns used to decorate the walls of the Alhambra in southern Spain.) Jespersen's "Scarabs" uses the little bug as the basis for its tessellation.

MORE TO EXPLORE

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Interactions between termites and vegetation explain mysterious patterns throughout the world

By Lisa Margonelli

ECOLOGY

TERMITES AND FAIRY CIRCLES

AFTER I CAME BACK FROM AUSTRALIA, I WONDERED ABOUT A LARGE BAUXITE MINE THAT I'D HEARD of, where termites had rehabilitated the land. I wondered if there was more to the story than the fact that they fertilized the soil and recycled the grasses. There seemed to be a gap between bugs dropping a few extra nitrogen molecules in their poo and the creation of a whole forest. What were they doing down there? I started going through my files, looking for people working on landscapes.

This led me to the work of a mathematician named Corina Tarnita and an ecologist named Rob Pringle. When I contacted her, Corina had just moved to Princeton from Harvard and, with Rob, had set about using mathematical modeling to figure out what termites were doing in dry landscapes in Kenya. As it happened, I had interviewed Rob back in 2010, when he and a team published a paper on the role of termites in the African savanna ecosystems that are home to elephants and giraffes.

I took the train to Princeton to meet them in early 2014. By that time I'd been following termites for six years, and I'd pretty much given up on two ideas that motivated me early on: understanding the relation between local changes and global effects—that concept of global to local that dogs complexity theorists—and the development of technology that could potentially "save the world." But through mathematical models, Corina and Rob and their teams eventually delivered a version of those things. And it was purely a bonus that they might have even solved the mystery of the fairy circles.

FRANS LANTING

FAIRY CIRCLES at the NamibRand Nature Reserve in Namibia.

Lisa Margonelli is deputy editor at *Zócalo Public Square*, an Arizona State University magazine of ideas. Her previous book is *Oil on the Brain: Petroleum's Long, Strange Trip to Your Tank* (Random House, 2007).

Corina was teaching when I arrived at Princeton, which is a mixture of old buildings with weather-rounded bricks and cautiously futuristic buildings made of glass and new bricks, so I went to find Rob. Back when I talked with him on the phone, Rob had been using lizards to understand ecosystems. He would map off a section of land, cut it into a grid, and go in and count the lizards as an index species. If there were lizards there were bugs, and if there were bugs there were plants, and if there were plants there was some water. As it happened, places with enough plants to attract lots of lizards were also favorites of elephants. And elephants were, in a way, the point of these studies: everyone wants more elephants.

In the relatively dry savanna in Kenya, Rob had been finding between 300 and 1,100 geckos in his plots, but there were two places where his lizard counts went through the roof: in abandoned cattle corrals filled with dung and on termite mounds. The dung was obvious—it would fertilize lush plants that would attract insects—but the relation between geckos and termite mounds was not.

Fungus-growing *Odontotermes* termites in that part of Kenya build most of their mound underground, so they look less like the fingers of dirt you see elsewhere in Africa than like land with a case of chicken pox, with each bump of a mound situated 20 to 40 yards from other bumps on all sides. The closer he was to the center of the mound, the more geckos Rob found. So then he looked at the bunchgrass and the acacia trees. A similar pattern. It was as though the termites had organized the entire landscape from below into a large checkerboard of fertility. "The termites are unwittingly pulling the strings without coming out of the ground," he had said when I called him in 2010.

Some part of termites' influence had to do with nutrients: scientists Dan Doak, Kena Fox-Dobbs and others found that the soils in the mounds were much richer in nitrogen and phosphorus than those off the mounds, and as a result the trees and grasses not only were more abundant there but also had more nitrogen in their leaves, making them more nutritious—and possibly even more delicious—to everyone eating them. The termites also moved sand particles, so water behaved differently on the mounds. I asked Rob whether the termites were "farming" the land to get more grass to eat. He said that while it was clear they were caring for their belowground fungus, the mechanics of what was happening aboveground were unclear. It could be a series of feedback loops that resulted in more for everyone. Part of their impact was that the soil around the mounds held water differently, but how exactly that happened wasn't clear. "Termites are really important at regulating water flow. They're a black box."

When I first heard Rob talk about the black box, I understood it as a metaphor rather than an engineering concept. Now, as I looked over my old notes, I wondered what he had meant by it: Was he really looking to engineering to answer an ecological question? Or did he also mean it metaphorically?

What really bugged Rob about termites was the pattern they created on the land. It was as though the termites created a lattice that turned an otherwise monotonous plain into a series of hotspots. Something was going on with the way the space was organized that made the entire system more productive. And with the advent of remote imaging technologies such as lidar, which uses lasers to create images of the ground, these patterns were showing up all over. The amount he did not know had bothered Rob: "I can't not notice these patterns whenever I get in a small plane or look at Google Earth." I knew what he meant because I'd seen similar patterns. When he was at Harvard, he had shared his irritating problem with Corina.

I knew that Rob had a fine sense of the absurd because I'd run into a photo of him online wearing a black suit while wrestling with a tape measure near an electric fence. When I found him in his office, he was wearing jeans and cowboy boots amid Princeton's old brick.

Corina arrived from class in high boots and a striking dress, poised and glamorous in the unadorned junior faculty offices. She also has a profoundly cerebral air: she takes things in, refracts them through a mathematical prism and sees them in an entirely new way.

Corina grew up on a farm in Romania, was fascinated by math early on and won multiple prizes before heading off to get an undergraduate degree at Harvard. She started her master's program there working on something called high-dimensional geometry but switched midway to mathematical biology, where the questions were more real and messier.

She became interested in how cooperation works, and in 2010 she published the big paper reexamining a well-accepted theory for the evolution of social insects with biological mathematician Martin Nowak and entomologist E. O. Wilson. Corina had spent a year redoing the math behind the theory and found that the fact of being related alone wasn't what made cooperation successful. When a queen could produce daughter ants that would stay and raise her brood, more of her babies survived: cooperation produces more kin.

In 2013 she went with Rob to the Mpala Research Center in Kenya. There, instead of modeling competition and cooperation on her computer, she could actually play with termites from different nests to see how they fought when they were put together. At first all of the flat, grassy land they were studying looked the same, and she had a hard time picking out where the termite mounds were. But as she got used to finding that pattern, she started getting a funny feeling: "A million questions are triggered in the field. I could see that there were more patterns than just

IN BRIEF

Termites are key players in the fertility of the world's arid grasslands.
Their mounds support nutritious greenery and a wide variety of insects, geckos and even elephants.
Princeton University scientists Rob Pringle and Corina Tarnita are using mathematical ecology to model termites' impact.
Termites influence landscapes at a large scale, increase drought resilience and play a role in fairy circle patterns.

those of the mounds. I sensed a pattern, but I could never quite pick it up."

One afternoon, after they had been working on their National Science Foundation grant proposal for three weeks, they went for a walk. They went past a field that had been burned; the vegetation was just stumps of grass, not the waving tops. Corina thought she saw something and asked to stand on the roof of a Range Rover. And then she saw it, among the burned stumps: two separate patterns interacting with each other. First there was the polka-dotted pattern of the mounds, and then she thought she saw a leopard-spot pattern in the vegetation between the mounds.

Leopard spots beckon to biological mathematicians because they are a natural shape with a theory behind it. The leopard pattern resembles a Turing pattern, a theoretical construct that was first proposed by British mathematician Alan Turing in 1952 and was subsequently demonstrated in some natural systems. If you've seen leopards, zebra fish, zebras-who-are-not-fish, seashells and chameleons, you've seen these patterns, which are sometimes called reaction-diffusion or scale-dependent patterns. They are essential components of the world's organization, influencing everything from how slime molds form in sink drains to the way rabbit brains perceive smells.

In the early 20th century the eccentric termite observer Eugène Marais had said we would need a "new alphabet" to see termites as they really are. Perhaps this was that alphabet.

When Corina told Rob she saw leopard spots, he was skeptical and said it was just clumpy bunchgrass. But she insisted, and so he took some photos. Later they sent graduate students out to take more photos with a camera on a 33-foot pole. And when they examined these images, it was clear that another pattern was in operation on the ground. Rob quickly realized his error—he had simply known too much about the plants to really see past what he knew. "It's awesome to be in the field with Corina," he said. "It's not surprising, but she didn't have the same ideas about root competition that I did."

Corina, for her part, was in heaven. "Before Rob brought me to Africa, I was a theoretical biologist," she noted. "I now almost don't want to work on systems that I can't see or manipulate. That's a big change."

But that moment was only the beginning of the work her team had to do to build a model, verify a hypothesis and use it to predict how these interacting pattern mechanisms would look in nature. "What comes before the model is an intuition of what the rules for the patterns could be," she told me later. "I put that together into a skeleton, and then I add in a lot of detail about how the termites and the plants actually function. It's like detective work."

Working with Juan Bonachela, a theoretical biologist trained in statistical physics, and Efrat Sheffer, a Jerusalem-based biologist who studies the relation between individual plants and their ecosystems, Corina began to build a model, starting with a proxy for how termite mounds organize the landscape: a simple lattice of hexagons. Termites leave the mound to forage in an ever widening circle, but over many decades, as a landscape gets filled with termite mounds, the foraging zone of each mound bumps up against others. When all the mounds contain roughly the same number of termites, they end up spacing themselves across the landscape evenly. Where the radius of foraging termites from one mound hits the radius from the next, they form an edge. It's not a perfect border, and it's not visible aboveground. But it's there anyway, perhaps caused by the ferocious fighting their postdoc Jessica Castillo-Vardaro saw when she put termites from two mounds together or maybe caused by termites avoiding other termites who don't smell like their kin. If the mounds are distributed evenly across the landscape, most mounds will have six neighbors. In the end, the mounds look like a patchwork of hexagons, maximizing the distance between every mound. This made sense: many other creatures have self-organized hexagonal territories, including wolves, Alaskan sandpipers and even some kinds of fish.

Next the team built a model for the pattern in the grass. The basic concept of Turing models is that there are two different feedback mechanisms. Within a short distance, growth is encouraged (activated), and over a long distance, it is discouraged (inhibited). For example, plants that are close to one another may help one another by more efficiently absorbing water from rainfall, creating a little tuft, but over distances the tufts begin to compete for water, suppressing growth and leaving bare dirt. In a model, if you give the activator and the inhibitor each four different parameters (how fast they diffuse, how strong they are, and so on) and build a model where they interact, over time they will form a characteristic set of patterns. Those with a strong activator, say, will form large spots, whereas those with a strong inhibitor will form small polka dots. Play with the parameters for diffusion at the same time, though, and you'll get patterns that look more like a tortoise shell, a bunch of doughnuts, gaps or stripes, or a labyrinth. These patterns look very much like things in real life, including mussel beds, coral reefs and fungi. So biologists have speculated that the activators for such scale-dependent feedback could be as diverse as water, hormones or organisms helping one another; the inhibitors could be drought, hormones or predators.

Using a mixture of activators and inhibitors appropriate for the grasses in Kenya, Corina and Juan built a mathematical model that created scale-dependent feedback patterns. Playing with the parameters on the grasses alone, they could limit the water and turn the tufts from big tufts to a labyrinth and finally to desert, which looked a lot like the photos. "We said, 'Okay, there's plenty of reaction diffusion,'" she said of the grass patterns. "'Can we couple that with the termite patterns?' " She combined the self-organized termite mounds and the scale-dependent feedback model for the grass. Now, instead of an even pattern of polka-dot-

ted mounds in the middle of hexagons or a leopard pattern of grasses, the leopard pattern arranged itself over the hexagons: lush over the resource-rich mound in the middle and sparse at the edges of the mound. Corina printed out images of the two models interacting, with different amounts of rainfall, and showed them to Rob. In very general terms, the images looked like African patterned cloth: regularly spaced large dots surrounded by halos with a kind of calico background pattern. The dots were the mounds, and the calico was the leopard pattern in the grass. When Corina and Rob compared the models with satellite images of termite landscapes in Africa, they found that they looked very similar. They could even zoom in on the calico in the model to see the shapes of the bunchgrass, and they found it resembled the shapes in the photos they had taken. These patterns had previously been hidden in plain sight. "It was the convergence of the model predictions and the data that made me believe," Rob said.

For Corina, the thrill was finding that the two different patterns, at multiple scales, were interacting and influencing each other. The local was connecting to the global, and it was even showing up on the satellite maps. "I'm happiest when models can be tested and we find so much agreement," she said, with obvious delight.

For me, the math of Corina's team explained the unsettling feeling I had looking out of planes in Namibia and Australia. That sensation that I could almost see the pattern of a Persian rug in the landscape had been correct. And now that I could finally really see the design in her modeled images, I thought about how Corina's intuition had combined with the powerful math of the models to reveal something new. In the early 20th century the eccentric termite observer Eugène Marais had said we would need a "new alphabet" to see termites as they really are. Perhaps this was that alphabet.

But running the two models had provided another insight, with much bigger implications. In fiddling with the rainfall on the mounds, Corina discovered that when grass was associated with a termite mound, it could survive on very little water, much less than expected. In the simplest terms, termite mounds made the landscape much more drought-resistant.

This observation had a practical benefit. Biologists had used patterns of labyrinths and spots to predict that some dry landscapes grew patchy just before catastrophically shifting to become deserts, which is a great fear in both Africa and Australia. Those theoretical models, from the mid-2000s, predicted that when these dryland systems crashed, they would not gradually dry up but would instead progress from a labyrinth pattern of grass to spots and then basically fall off a cliff (called a critical transition) to become desert. Recovery would be very difficult, if not impossible.

But when Corina adjusted the rainfall in the model to produce the labyrinth of plants that might precede a crash, she found that when a landscape had termite mounds, the crash occurred very slowly—it was not a cliff but a staircase. What this meant was that places that had termite mounds were much less likely to become desert, and if they did, they were likely to recover when rains reappeared. As long as the termites remained, grasses would sprout first on the mound and then in distinctive patterns. Termites, then, appeared to increase the robustness of the whole place, in addition to providing homes for the geckos and food for the elephants. And with dry lands making up about 40 percent of the world and climate change redistributing rainfall, termites might actually be saving the planet. For real. For once.

SOLDIER TERMITE (*Odontotermes montanus*) on a piece of white fungus comb, cultivated for food, is excavated from its mound.

ROBERT M. PRINGLE *Princeton University*

The model was nice, but models are a pseudo world. The team's next step was to further test the model's predictions with experiments in the Kenyan fields. By giving some mounds and their surroundings extra water while preventing others from getting rain, Rob and Corina and their team hoped to see whether the grass patterns would change as their model predicted. To do that, they needed to figure out how to block rain on some plots while increasing it on others. Fellow Princeton researchers Kelly Caylor and Adam Wolf were doing something similar in the Pine Barrens, a large forested area in otherwise suburban New Jersey, and they said I could tag along when they went to see their structures.

It was a cold day in November, and the Pine Barrens lived up to their name: miles of tall dark pines, scraggly in late fall with relatively clear ground under them. In the woods, the researchers had built careful little shelters out of two-by-fours, using Home Depot hardware, to prevent rain from falling on some plots, while sprinkling others with extra water. Under the pines it was dark and even chillier. I had worn only a fleece, and I tried to conserve heat by hunching.

Rob thought that the elephants were not going to like the little houses guarding an oasis of scrumptious-looking grass in a dry savanna. "I think elephants are a generalized stochastic hazard, but they're going to be very attracted to the water." He doubted that they could build something strong enough to keep them out. The elephants were wily, too. Even electric fencing would have drawbacks. "If we put fence that's two meters high, the elephants will play with it and mess around, but the giraffes will run right into it because they're not paying attention." It was funny to stand shivering under these dark pines in New Jersey, talking about the fields of inattentive giraffes.

On the way back to Princeton they mentioned they had had informal conversations with colleagues who questioned whether the patterning was the result of termites. Rob felt that some of the skepticism came from scientists unfamiliar with self-organizing systems, who might think that such large-scale pattern organization implied a "mastermind." And some ecologists assume that if competition among termite colonies is strong enough to drive this elaborate patterning, then it is likely to push the resource base toward collapse. The idea that termites could be competing so strongly that they create patterns while making the ecosystem less likely to collapse? "It's a hard hump to get over," Rob remarked.

Back in her office, Corina explained that her next plan was to work with the team to build a far more detailed model of both termites and grass with which to go to the Olympics of the patterning debate: fairy circles. Fairy circles are mysterious, roundish areas of dirt found in northern Namibia as well as in Australia, generally surrounded by grass. In aerial photos they look like regularly spaced pinkish elephant footprints of dry dirt, ranging in size from about nine to 98 feet across. They have been the subject of fierce debate between scientists who say they are made by termites and others who say they are made by grass patterning. Although these patterns have been the subject of scholarship since the 1970s, interest in them spiked between 2012 and 2016, when a small spate of papers attributing the circles to one thing or the other appeared in journals. Corina felt that with a more complete model she could show that the fairy circles were the result of the termites' self-organization and the grasses' scale-dependent feedback combined.

Building the model was difficult, however. "The model forces you to have a rule for everything. You can't have any blank spaces," she said when we spoke early in 2015. "It forces you to consider what you might not consider otherwise." The termites were toiling away in their black box underground, unknown. She was deep in termite literature and communicating daily with Juan in Scotland as the team built the computational aspects of the model. Corina said it was the most complex model she had ever worked on, and she was facing inconsistencies in the thinking about scale-dependent feedback: the idea that plants benefited from being close to one another made sense, but did competition really suppress growth on a large scale? Another question was how termites concentrated nutrients in the space—of course, they brought grass back to the mound—but they also processed some in their guts, such as bioavailable nitrogen. It was a big puzzle.

"For me it's not the fairy circles," Corina said. What she wanted was to understand how multiple pattern mechanisms could interact at multiple scales. "I think it's fascinating that these little organisms, which are part of messy and complex ecosystems, can produce regular patterns."=

In 2017 the team, which also included researchers Jennifer Guyton, Tyler Coverdale and Ryan Long, published a paper that modeled how burrowing animals such as termites, ants and rodents might interact with grasses to create vast patterns and structures around the planet. Adding the termite lands of Africa, Asia and Australia to similar earthmound-field landforms such as Brazil's murundus, the mima mounds of the Pacific Northwest and the heuweltjies of South Africa suggested that many tens of thousands of square miles may have been reordered from below. No mastermind could have possibly pulled this off: only trillions of mini minds could possibly have taken on a task this big.

Now that I could see this relation between the tiny diggers and the great scope of land from the air, I felt sympathy for the early explorers who looked into termite mounds and saw only metaphors for human society and proof of the rights of kings. By looking inward, they had missed seeing the earthly equivalent of the celestial spheres.

In the mound, it is possible to see the entire order of the terrestrial sphere or, in more modern language, the progress from local to global. First there is the teeming world of the termite's gut, processing grass; then the world of the termites, digging and grooming in their great social pile; then the world of the termites and their fungus, communicating in the mound through waves of chemistry and water vapor; and then the world of the plants and geckos on the surface. Way up in the air, a giraffe obliviously munches on a tasty leaf. And from the air, a regularly ordered carpet of fertility and superfertility becomes evident. And finally, a planet with an atmosphere.

Like the giraffes, we humans are ignorant of the vast churnings of smaller and larger worlds that we cannot see. We anthropomorphize or abstract these relations into puny concepts we can understand: aristocratic insects, altruism, competition, cousins, bad guys and good guys. But these collaborative behaviors, along with the sensing and signaling capabilities they require, may be the building blocks of complexity.

For a little while I had recriminating thoughts about the failure of humans to see beyond ourselves into the vast universe: we have so little ambition! But then I read a speech on the problem of scale in ecology, given by Princeton ecologist Simon Levin. And when I read it, I realized that we are subjects in this experiment ourselves, and our fitful awareness is part of what makes us human. Levin said that the world needs to be studied on multiple scales of size, time and organization—there is no one "correct" scale. In fact, the scale at which we see the world is a product of how we have evolved and how we will continue to evolve. "The observer imposes a perceptual bias, a filter through which the system is viewed. This has fundamental evolutionary significance because every organism is an 'observer' of the environment, and life history adaptations such as dispersal and dormancy alter the perceptual scales of the species and the observed variability." For humans as well as termites, these limits in how we perceive the world are the very core of who we are. SA

MORE TO EXPLORE

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A Theoretical Foundation for Multi-Scale Regular Vegetation Patterns. Corina E. Tarnita et al. in *Nature,* Vol. 541, pages 398–401; January 19, 2017.

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scientificamerican.com/magazine/sa

RECOMMENDED

By Andrea Gawrylewski

Buzz:
The Nature and Necessity of Bees

by Thor Hanson. Basic Books, 2018 ($27)

WESTERN HONEYBEE comes in for a landing.

Bees have been in the spotlight since the emergence about a decade ago of a mysterious bee ailment dubbed "colony collapse disorder," now responsible for the loss of millions of U.S. hives. The crisis brought attention to the benefits bees bring to humans, but long before they received such notice, the insects were vital to our own species. Through his engaging first-person narrative, biologist Hanson tells the full story of bees: They evolved from carnivorous wasps during the time of dinosaurs, opting for the protein-rich pollen of flowers with which they coevolved. Bees developed fuzz to better trap and transport pollen from flower to flower, and the structure of many flowers evolved to suit specific pollinators. The insects' honey has been an essential food source since the dawn of humankind and has been adapted to everything from alcohol to medicine.

Through Two Doors at Once:
The Elegant Experiment That Captures the Enigma of Our Quantum Reality

by Anil Ananthaswamy. Dutton, 2018 ($27)

"A simpler and more elegant experiment would be hard to find" is how journalist Ananthaswamy describes the double-slit experiment, one of the most important trials in the history of physics. By shooting particles at a wall with two slits cut into it, physicists revealed the dual nature of electrons, photons and other tiny bits of the cosmos as both particles and waves. Although the experiment itself is simple, with versions of it dating back to 1801, its results confound even the most brilliant scientists. It exposes the gaps in our understanding of quantum mechanics—such as why measuring what happens at the slits causes electrons to act like particles but leaving the slits alone results in wavelike behavior. This book is also a fascinating tour through the cutting-edge physics the experiment keeps on spawning. —*Clara Moskowitz*

The Tangled Tree:
A Radical New History of Life

by David Quammen. Simon & Schuster, 2018 ($30)

When Charles Darwin devised his theory of natural selection, he envisaged an orderly progression of new species evolving one after another, like limbs branching out on a tree. But it turns out the tree of life is more of a tangled mess. Science writer Quammen gives a lively account of how new genetic research is upending the fundamental history of life. Genes, for example, can flit between the cells of vastly different species. The genes of eukaryotes (life-forms with cells that have an enclosed nucleus), which include humans, also contain "living ghosts" of captured bacteria. Recent work suggests eukaryotes originally descended from archaea, only recognized as a different domain of life in the 1970s, not separately from them. These discoveries blur the lines of what defines a species and raise the question of just what it means to be human. —*Andrea Thompson*

Third Thoughts

by Steven Weinberg. Harvard University Press, 2018 ($25.95)

We are at a "watershed" moment in physics, Weinberg, co-winner of the 1979 Nobel Prize in Physics, said nearly 10 years ago, soon after the opening of CERN's Large Hadron Collider. (He also serves on our board of advisers.) Ten years on, that sentiment remains and is woven throughout this collection of essays, including some previously unpublished. He covers the ground nearest and dearest to him—cosmology and physics—in a 2011 review of Stephen Hawking's book *The Grand Design,* in which he analyzes Hawking's speculations on the nature of a multiverse. Weinberg also ventures into art theory, comparing the constraints of both art and theoretical physics (there are indeed commonalities, he argues). This collection is an easily digestible glimpse into the mind of a thoughtful scientific communicator and shows the truly all-encompassing nature of theoretical physics.

GETTY IMAGES

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

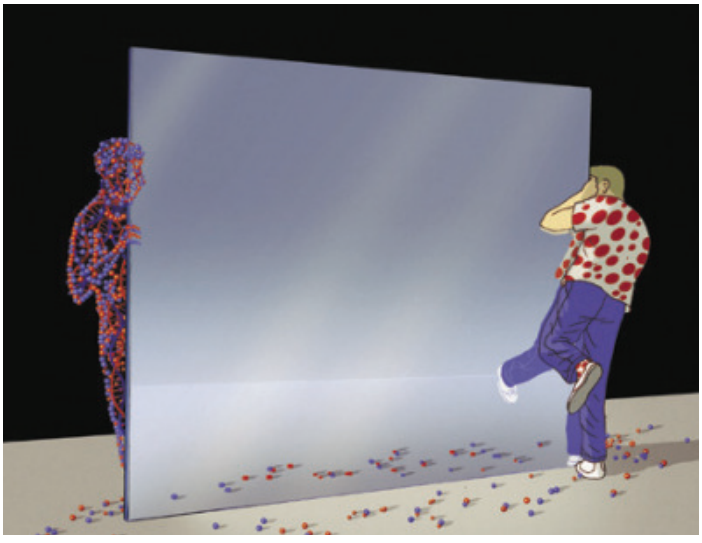
23 and We

The limitations of personal genome service testing

By Michael Shermer

Like a lot of baby boomers, I find myself gravitating to newspaper obits, cross-checking ages and causes of death with my current health parameters, most notably heart disease (which felled my father and grandfather) and cancer (which slew my mother). And then there is Alzheimer's disease, which a 2015 report by the Alzheimer's Association projects will destroy the brains of more than 28 million baby boomers. Given the importance of family history and genetics for longevity, I plunked down $199 for a 23andMe Health + Ancestry Service kit, spit into the little plastic vial, opted in for every test available for disease gene variants and anxiously awaited my reports. How'd they do?

First, the company captured my ancestry well at 99.7 percent European, primarily French/German (29.9 percent), British/Irish (21.6 percent), Balkan/Greece (16.4 percent) and Scandinavian/Swedish (5.5 percent). My maternal grandmother is German and grandfather Greek; my fraternal great-grandparents were from Sweden and Denmark.



Second, the traits report correctly predicted that I can smell asparagus in my urine, taste bitter and have hazel eyes, ring fingers longer than index fingers, little freckling and straight, light hair.

Third, for the disease reports, my eye lit on the phrase "variants not detected" for Parkinson's disease, cystic fibrosis, muscular dystrophy, sickle cell anemia, Tay-Sachs and, most concernedly, Alzheimer's. "Oh joy, oh rapture unforeseen!" (Thank you, Gilbert and Sullivan.)

But wait, 23andMe also says I have no bald spot, no cheek dimples, little upper back hair, a slight unibrow, no widow's peak and a longer big toe—all wrong. If a genetic test for such comparatively simple physical features can be mistaken, what does that say about its accuracy for more complex diseases? "Our reports do not include all possible genetic variants that could affect these conditions," 23andMe disclaims. "Other factors can also affect your risk of developing these conditions, including lifestyle, environment, and family history." Oh, that.

For toe length, for example, 56 percent of research participants with results like mine (15 genetic markers for a longer big toe, 13 for a longer second toe) have a longer big toe, but I'm in the 44 percent. A prediction barely better than 50–50 isn't terribly expedient. For Alzheimer's, carrying the e4 variant of the *APOE* (*apolipoprotein E*) gene increases one's risk of developing Alzheimer's to 1 percent by age 65, 4 to 7 percent by age 75, and 20 to 23 percent by age 85 in men (to the same figure of less than 1 percent, to 5 to 7 percent, and to 27 to 30 percent in women). Having two copies of the gene (one from each parent) moves the needle up to 4 percent (by age 65), 28 percent (age 75) and 51 percent (age 85) in men (2, 28 and 60 percent in women). But the test "does not include all possible variants or genes associated with late-onset Alzheimer's disease," so, for example, though lacking both e4 variants, I still have a 1 to 2 percent risk of Alzheimer's by age 75 and a 5 to 8 percent chance by age 85.

For further clarity on this tangle of interactive effects, I contacted Rudy Tanzi, a Harvard Medical School neurologist and head of the Alzheimer's Genome Project, who co-discovered many of the genes for Alzheimer's. He admitted that "no one can say with certainty [if] a calculation of the variance of [Alzheimer's is] due to genetics versus lifestyle," adding that the e4 variant of the *APOE* gene "is present in 20 percent of the population and in 50 percent of late-onset cases but does not guarantee disease."

Moreover, "until we identify all (or most) of the actual disease-causing mutations in these 40 genes, any attempts at putting an actual number at genetic variance is futile. In the meantime…, all we can say responsibly is that no more than 5 percent of gene mutations causing [Alzheimer's] are guaranteed to do so. This means that in the remaining cases, most if not all almost certainly involve genetic influences (risk-conferring and protective), but in these cases (95 percent), it is an interplay of gene and environment/lifestyle that determines lifelong risk."

What should we baby boomers do to shield ourselves against Alzheimer's? "SHIELD" is Tanzi's acronym for Sleep (uninterrupted seven to eight hours), Handle Stress, Interact (be sociable), Exercise (cardiovascular), Learn ("the more synapses you make, the more you can lose before you lose it," Tanzi says), and Diet (Mediterranean: high in fruits, vegetables, olive oil, whole grains).

As for personal genome service testing, actionable results with measurable outcome differences are still limited. But that is true for most medical knowledge, and yet we absorb everything we can for what ails us, so why not add genetics? SA

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Illustration by Izhar Cohen

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

That's Life

Recent research looks at basic bodily functions

By Steve Mirsky

As Cleveland Cavaliers guard J. R. Smith has probably heard a few times at this point, you have to be solid in the fundamentals. For a basketball player, some of the fundamentals are dribbling, shooting and, as Smith learned the hard way, knowing the correct score with seconds to play in the first game of the NBA Finals. For the rest of us (who blissfully do dumb things without attracting worldwide attention), the major fundamentals include sleeping, eating, sex and eliminating. Fortunately, new scientific research has made key discoveries all these areas.

Let's start with what would have been great news for Macbeth, who admits in the play that he has concerns about getting a decent night's sleep. He's all "Sleep no more!" and "Macbeth does murder sleep." Sounds a lot like modern life, doesn't it? Sure, he's racked with guilt over taking the crown, whereas we're up late binge-watching *The Crown*. But either way, a new study finds that lost sleep may once again be found.

Insufficient sleep is a big deal. People die early from it. One of the latest reports, "Sleep Duration and Mortality—Does Weekend Sleep Matter?" (published May 22 online in the *Journal of Sleep Research*), found that weekend bonus slumber wards off the deadly effects of weekday sleep deprivation. Of course, Macbeth never got a chance to catch up on his sleep tomorrow and tomorrow and tomorrow.

Over in the eating realm, a study calls into question the meaning of the famous marshmallow delayed-gratification test. The oft-cited analysis found a strong correlation between a kid's ability to hold off eating a marshmallow (with the promise of a second marshmallow for doing so) with that kid's later achievements and behavior.

The new study, "Revisiting the Marshmallow Test: A Conceptual Replication Investigating Links between Early Delay of Gratification and Later Outcomes," released May 25 online in *Psychological Science,* tested 10 times as many youngsters as did the original research. And it found a much smaller association between delaying gratification and how the children turned out. The work also discovered a connection between higher family income and short-term self-control. Perhaps the rich kids showed up for the test stuffed.

In news that won't surprise Westworld viewers, here's a *Washington Post* headline: "New Report Finds No Evidence That Having Sex with Robots Is Healthy." The paper, "I, Sex Robot: The Health Implications of the Sex Robot Industry," appeared online June 4 in *BMJ Sexual & Reproductive Health*. The authors note, "We found no reports of primary data relating to health aspects of the use of sex robots." Thus, any health claims made by manufacturers of sexbots—such as safer sex, therapeutic potential or sex offender treatment—are just wishful thinking.

The write-up also states: "The UK General Medical Council and medical defence organisations have not issued any guidance, but doctors might be advised to avoid using sexbots themselves, given police interest, prosecutions, and the potential negative impact on public trust." Or as Austin Powers, no stranger to sexbots, said, "Oh, behave."

Bringing up the rear, *Clostridium difficile* bacterial infections range from exhausting—numerous daily bouts of diarrhea—to life-threatening. (A possible complication is the one with the supervillain name "toxic megacolon.") In recent years so-called fecal transplants have proved to be an effective therapy against stubborn *C. diff* infections. As I wrote in this space five years ago, "the procedure involves the insertion of a small, diluted sample of stool from a donor into the colon of a recipient.... The swap imports a healthy community of bacteria."

A letter published online on June 2 in the *New England Journal of Medicine* entitled "Fecal Microbiota Transplantation for Primary *Clostridium difficile* Infection" describes the latest trial to once again find that another person's poop can get patients out of this pickle. It would thus seem that the frequently given advice to not take any crap from anyone has an important medical exception. SA

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Illustration by Matt Collins

1968 Breathing Water

"If by some special arrangement man could be made to breathe water instead of air, serious obstacles to attempts to penetrate deeper into the ocean and to travel in outer space might be overcome. Suppose we prepare an isotonic solution that is like blood plasma in salt composition and charge this solution with oxygen under greater than normal pressure. Can a mammal breathe such a solution? I performed the first experiments, with mice as the experimental animals, at the University of Leiden in 1961. After their initial agitation, the mice quieted down and did not seem to be in any particular distress. They made slow, rhythmic movements of respiration, apparently inhaling and exhaling the liquid. It became evident that the decisive factor limiting the mice's survival was not lack of oxygen but the difficulty of eliminating carbon dioxide at the required rate. —Johannes A. Kylstra"

1918 Wartime Edema

"Dr. F. S. Parks, of Toronto, has been a prisoner in a German camp at Minden, where he practiced for 18 months among his thousands of comrades. Many of these men suffered from war edema or dropsy, the most prevalent malady in that camp. The German rations, along with hard work, exposure and depressing environment, were responsible for this dropsy, which prevailed most in the spring and early summer of 1917, when those rations were most insufficient. That diet was very low in protein (tissue building food), and was practically fat-free. It consisted almost entirely of soup; so that much fluid had to be taken to obtain a small amount of nourishment. This extra load of fluid was too great to be eliminated by the feeble heart and the overworked kidneys; hence, the dropsy, the anasarca."

The Fighting Walnut

"More American walnut is needed for airplane propellers and gunstocks. During the four years' test in the present war this wood has proved to be the best material for the manufacture of the foregoing articles. The Government needs all the walnut that can be secured. 'Fight with your walnut trees' is the new slogan of the Hardwood Section, Bureau of Aircraft Production, and the Small Arms Section, Ordnance Department. Every tree counts."

1868 Early Bicycle Craze

"Within a few months the vehicle known as the velocipede has received an unusual degree of attention, especially in Paris, it having become in that city a very fashionable and favorite means of locomotion. To be sure the rider 'works his passage,' but the labor is less than that of walking, while the exercise of the muscles is as healthful and invigorating. A few years ago, these vehicles were used merely as playthings for children, and it is only lately that their capabilities have been understood and acknowledged. The engraving represents one used by the well-known Hanlon Brothers [an acrobatic troupe] in their public exhibitions."

1868: Bicycles become the height of fashion—albeit briefly.

1968

1918

1868

A Theory of Rabies

"It is customary to regard the mid summer as tending to increase the prevalence of hydrophobia, and extra care is taken to prevent danger by confining and muzzling dogs, if they are not otherwise summarily disposed of. The practice of killing dogs upon the arrival of summer heat is of ancient date, and has the sanction of custom to recommend it. Some have, however, expressed the opinion that dogs are no more liable to attacks of rabies at this season than at any other. If, as has been stated, this terrible disease originates from excitement consequent upon the ungratified sexual instinct of the male dog, it is hard to see how the excessive heat of July and August could fail to aggravate such excitement."

Bronze Age

"Mr. Thomas W. Kingsmill, Secretary of the North China Branch of the Royal Asiatic Society, states that the use of bronze for cutting instruments still obtains in China and Japan. He says, 'It is a fact that in those two countries, to the present day, in the midst of an Iron Age, bronze is in constant use for cutting instruments, either alone or in combination with steel. In the Canton province, every school boy may be seen with a clasp knife made of a sort of bronze, case, spring and blade being all made of this material. To form the cutting edge of these clasp knives, a thin piece of steel is let into the bronze blade; but knives made entirely of bronze, and occasionally ornamented and riveted with copper, are not uncommon.'"

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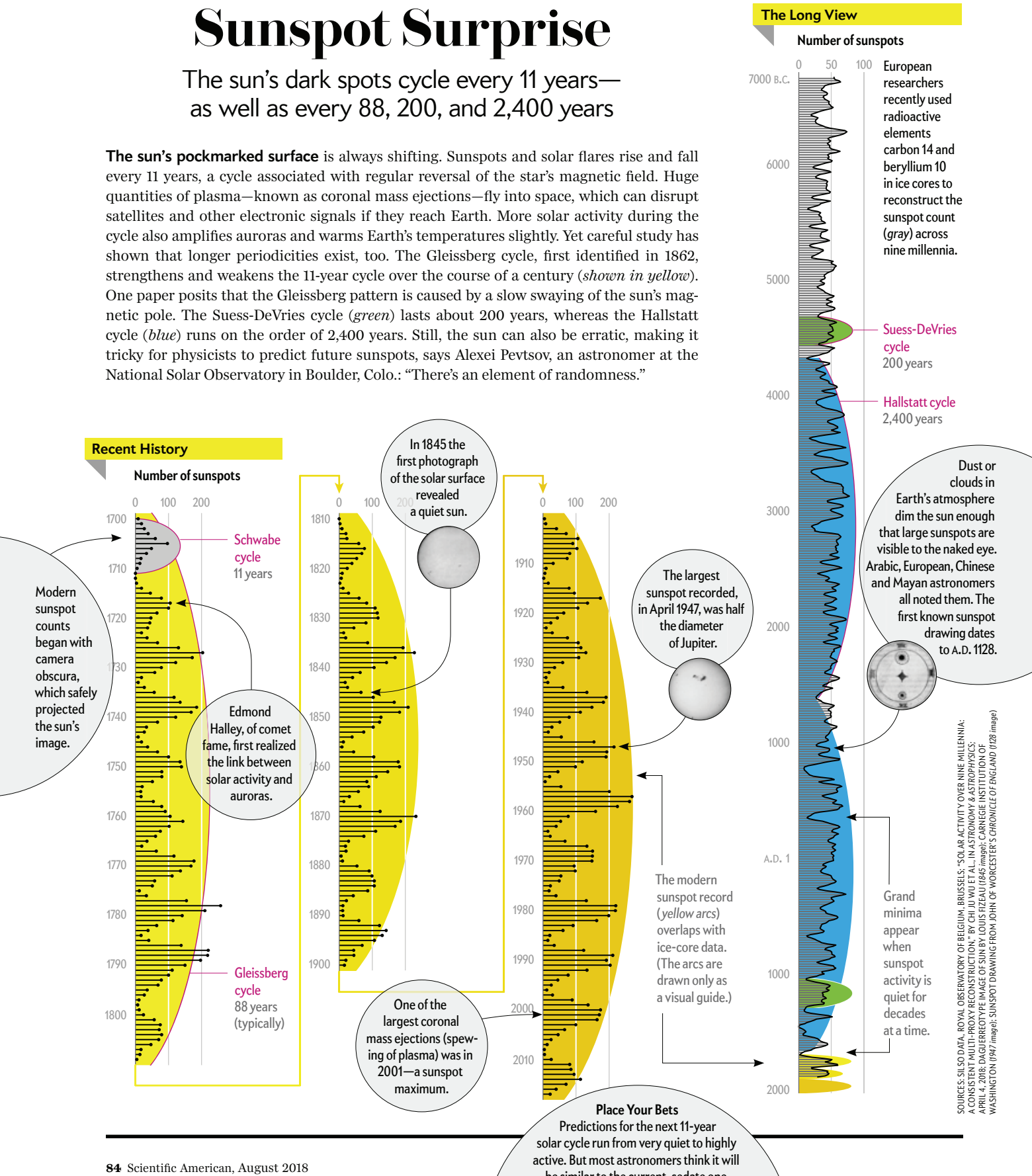
Text and Graphic by Katie Peek

Sunspot Surprise

The sun's dark spots cycle every 11 years—as well as every 88, 200, and 2,400 years

The sun's pockmarked surface is always shifting. Sunspots and solar flares rise and fall every 11 years, a cycle associated with regular reversal of the star's magnetic field. Huge quantities of plasma—known as coronal mass ejections—fly into space, which can disrupt satellites and other electronic signals if they reach Earth. More solar activity during the cycle also amplifies auroras and warms Earth's temperatures slightly. Yet careful study has shown that longer periodicities exist, too. The Gleissberg cycle, first identified in 1862, strengthens and weakens the 11-year cycle over the course of a century (*shown in yellow*). One paper posits that the Gleissberg pattern is caused by a slow swaying of the sun's magnetic pole. The Suess-DeVries cycle (*green*) lasts about 200 years, whereas the Hallstatt cycle (*blue*) runs on the order of 2,400 years. Still, the sun can also be erratic, making it tricky for physicists to predict future sunspots, says Alexei Pevtsov, an astronomer at the National Solar Observatory in Boulder, Colo.: "There's an element of randomness."



SOURCES: SILSO DATA, ROYAL OBSERVATORY OF BELGIUM, BRUSSELS; "SOLAR ACTIVITY OVER NINE MILLENNIA: A CONSISTENT MULTI-PROXY RECONSTRUCTION," BY CHI JU WU ET AL., IN *ASTRONOMY & ASTROPHYSICS*; APRIL 4, 2018; DAGUERREOTYPE IMAGE OF SUN BY LOUIS FIZEAU (*1845 image*); CARNEGIE INSTITUTION OF WASHINGTON (*1947 image*); SUNSPOT DRAWING FROM JOHN OF WORCESTER'S *CHRONICLE OF ENGLAND* (*1128 image*)

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