JULY 2022

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Trauma in the Family Tree

Climate Education Undermined

New Momentum in Computing

VOYAGERS' FINAL FRONTIER

Two record-breaking spacecraft reach interstellar space

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SCIENTIFIC AMERICAN

NASA/ESA/HST Frontier Fields team (STScI)

ON THE COVER
The Voyager spacecraft are the longest-running, farthest-traveling space missions of all time. After touring the giant planets of the solar system, they exited the heliosphere—the domain of the sun's influence—and entered interstellar space. Now, after 45 years, some of their instruments will be turned off, beginning the end of a spectacular voyage. **Illustration by NASA/JPL-Caltech.**

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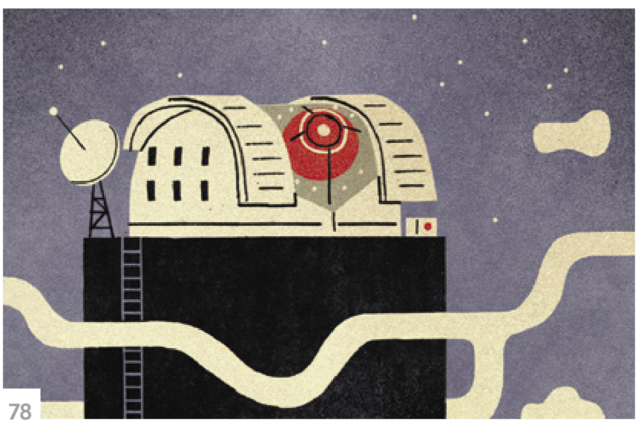

78

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Necessary Science

When science teacher John Scopes was prosecuted for teaching evolution, in 1925, evolution was already recognized by science as the explanation for all of life on Earth. That knowledge was kept from students, however, by laws, misinformation, antiscience bias and fear. A survey of high school biology teachers conducted in 1939–1940 found that only half taught evolution. A similar survey, conducted in 2007, decades after state laws banning evolution in schools had been overturned and almost 150 years after *On the Origin of Species,* found the same proportion. The people and institutions who felt threatened by evolution were really good at casting doubt on one of the surest things humans have ever discovered.

There has been some progress. Scientists, parents, teachers, civil rights lawyers and other advocates for reality-based education have spoken to school boards, supported lawsuits, and educated the media and public about the importance of teaching evolution. The National Center for Science Education, which advocates for the teaching of actual science in science class, conducted another survey of high school biology teachers in 2019 and found that the proportion who teach evolution had grown to two thirds.

Yet now we're in another creationism vs. evolution moment, as the powers that feel threatened by the science of climate change are trying to keep students from learning about one of the other surest things humans have ever discovered. A gripping story by reporter Katie Worth on page 42 shows how oil and gas interests are distorting how science is taught in Texas and by extension in much of the U.S.

Keeping science (or accurate history or health education) from kids just seems so selfish. Sure, some of it is disturbing. But it's also fascinating, empowering and necessary. During the world's worst mass extinction (which is disturbing!), bacteria and algae devastated freshwater life, according to new work presented by Chris Mays, Vivi Vajda and Stephen McLoughlin on page 56. The implications of this research are just the sort of thing students need to know if they're going to make good decisions about the future.

The Voyager spacecraft have reached interstellar space, and their journey has been glorious. They gave us close-up views of Saturn, Uranus, Jupiter and Neptune, and as writer Tim Folger shares in our cover story on page 26, they're still sending us information about the edge of our solar system after 45 years in space.

There's still so much about the universe we don't understand, and one of the big questions is how fast it's expanding. Astronomers using different methods to calculate that rate, as well as other fundamental properties of matter, are coming up with different answers. As author Anil Ananthaswamy explains on page 64, if the conflict is real, it could have interesting implications for our understanding of the cosmos.

Traumatic experiences can echo through future generations, psychologically and biologically. On page 50, trauma expert Rachel Yehuda narrates how she uncovered distinct and lasting physiological changes in people whose parents were traumatized. And she discusses what we know so far about how epigenetic effects can be transmitted through eggs and sperm.

Computers encode information in on/off bits, which can be thought of as the position of a particle. Now, as journalist Philip Ball describes on page 70, physicists are exploring a type of computing that encodes not just the position but also the velocity of a particle. Momentum computing could escape computers' heat limit, and it's also just a lot of fun to contemplate. SA

Illustration by Nick Higgins

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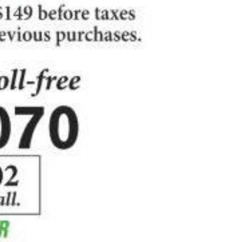

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March 2022

"The word 'truth' is elemental, and its misuse promotes division."

RAY JEANNOTTE *LANGLEY, BRITISH COLUMBIA*

TRUTH VS. FACT

In the past year *Scientific American* has published several articles examining the rise of misinformation and disinformation in media and general communication and what we can do to resolve this growing dilemma. "Conspiracy Theories Made It Harder for Scientists to Seek the Truth," by Stephan Lewandowsky, Peter Jacobs and Stuart Neil, discusses this topic in the context of the virus that causes COVID, as well as earlier pathogens.

I would like to focus on one aspect of these articles: the misuse of the word "truth" and the confusion over its fundamental meaning. In your examinations, the term has been used repeatedly to suggest that given information is genuine and factual. Without a doubt, truth and fact are sometimes the same. But it is important to recognize that they are often different.

For example, it's springtime where I live near Vancouver, and I have two friends visiting me. One is from Inuvik, Northwest Territories, near the Arctic Circle, and the other from Ecuador, which straddles the equator. While sitting together, one friend complains about how hot it is in my home and asks if we should open a window; the other expresses how cold it is. Now, is it hot or cold? Which friend is lying, and which is telling the truth?

A realization that truth does not equal fact might seem a matter of trivial semantics, but the social consequences of misusing the former term can be substantial and dire. The word "truth" is elemental, and its misuse (unintentional or intentional) promotes division. Such social polarization is not limited to individuals or to small groups alone. It spreads with communication and is therefore able to permeate entire societies.

On the other hand, the word "fact" promotes consensus and agreement because it focuses on a point of common certainty (say, that the temperature is 72 degrees Fahrenheit) that is objective and impersonal. Without using facts to mediate, would it be possible to reconcile the two groups' opposing truths?

The whole misinformation and disinformation issue is admittedly bigger than a one-word fix. But communicating facts instead of truth is a good place to start.

RAY JEANNOTTE
Langley, British Columbia

While reading the article by Lewandowsky, Jacobs and Neil, I wondered what advantage might follow from believing that humans were somehow directly responsible for the virus that causes COVID. It occurred to me that if humans created it in a lab, then the unspoken reasoning might be that humans could uncreate it. That is, if the pandemic isn't a "random act of nature," this might assuage anxiety from uncertainty, and some people might need such comfort more than others.

ANN G. FORCIER *via e-mail*

THE EDITORS REPLY: Jeannotte makes an apt point that facts are not always synonymous with truth. Jen Schwartz and Dan Schlenoff highlighted this distinction in "Reckoning with Our Mistakes" [September 2020]. Schwartz and Schlenoff noted, "If it were that simple to establish and convey a shared reality ... wearing masks and cutting greenhouse gases would not be political issues." In 1856 Scientific American*'s editors wrote, "What is science but well-arranged facts derived from study and observation? It is not merely speculation—hypothesis—it is positive truth."*

TO INFINITY AND BEYOND

In describing Amazon founder Jeff Bezos's July 20, 2021, trip on a rocket made by his company Blue Origin in "Billionaire Space Tourists Became Insufferable," Clara Moskowitz opined, "The sight of the richest man in the world joyriding in space hit a nerve." Perhaps it hit a nerve with some—but not everyone. I thought it was cool. My wife, who is a self-described "space nut," and my nephew, who is an aerospace engineer, were both excited by the news of private space travel, even if of a rudimentary and exclusive sort.

Moskowitz also noted billionaire Richard Branson's trip to space on a rocket made by his company in the same month and criticized him and Bezos for hogging the spotlight from the many who worked so hard to make their flights a reality. In leveling this charge, I think she forgot that if the two had not shelled out enormous sums of their own wealth to create the workforce and infrastructure necessary for their respective rockets, the various workers would never have had the chance to create them. Rather than masking the reality of private spaceflight, their financial support would appear to be contributing to that very reality.

MEL TREMPER *Berwyn Heights, Md.*

DISASTER PREPAREDNESS

In "Get Ready for the Next One" [Science Agenda], the editors emphasize that an important point of focus in preparing for future pandemics is "building new systems" and "strengthening ... institutions already in place." Indeed, the World Health Organization, the Centers for Disease Control and Prevention, and other health agencies need to put in place organizations that are prepared to coordinate responses to a biological threat such as COVID.

The editorial doesn't mention that when President Barack Obama was in office, he grew the National Security Council (NSC) to include the Directorate for Global Health Security and Biodefense, whose staff was dedicated to pandemic response and related medical threats. This organization would have been well prepared to guide the U.S. through the early days of the COVID pandemic.

But in 2018 the Trump administration decided to eliminate this office as part of a reorganization of the NSC. The team was not fired outright, but many of the staff were effectively elbowed out. And the net result was, at best, muddled management, with a lack of focus and coordination. One must believe that the COVID pandemic would have played out much differently if the response structure that Obama shaped had been left in place.

Daniel Hicks *Rochester, Minn.*

POLAR PIONEER

"Women on Ice," by Naomi Oreskes [Observatory; December 2021], highlights several women's accomplishments in polar research. I would like to add another: Gisela Dreschhoff of the University of Kansas. Over 10 summers in Antarctica between 1976 and 1986, she used gamma-ray spectrometers to search for uranium and measure radiation from space. She has spent at least 20 field seasons and expeditions in the polar regions. Dreschhoff even has an Antarctic summit named in her honor!

Craig Paul *Kaneohe, Hawaii*

WANTED: YOUR INFORMATION

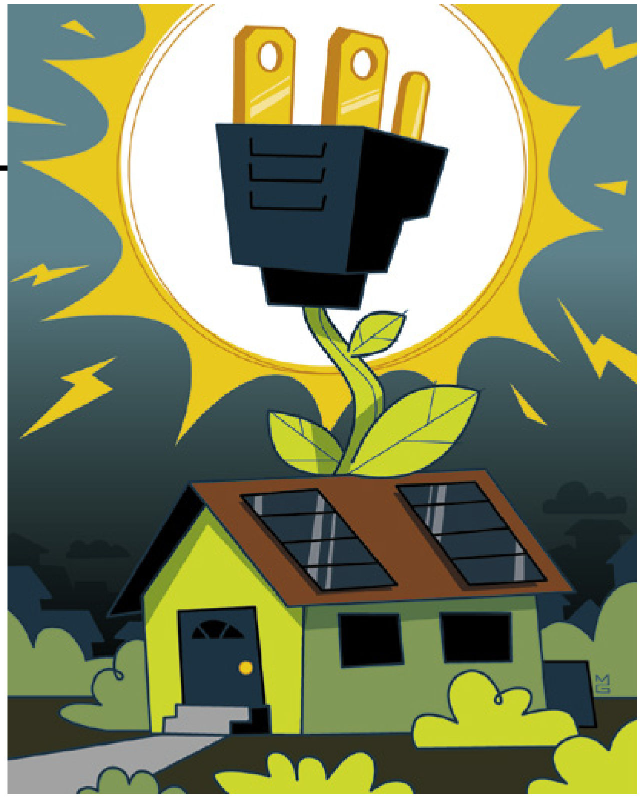
I am very disturbed by "Spying on Your Emotions," by John McQuaid [December 2021]. Although I realize that some functions of AI data collection are used for product improvement, that does not justify, in my mind, the activity of companies to covertly gather information on individuals, even if it is purportedly "anonymized." We say that privacy is very important, but we are apparently charging headlong into an era stripped of it.

Robert Walty *Stephens City, Va.*

ERRATA

"Healthy Skepticism," by Naomi Oreskes [Observatory], should have indicated that male fertility, not male infertility, declines with age.

"Conspiracy Theories Made It Harder for Scientists to Seek the Truth," by Stephan Lewandowsky, Peter Jacobs and Stuart Neil, should not have described U.S. Right to Know as an anti-GMO organization.



Electrifying Everything

Incentives and remodeling need to be more straightforward and equitable

By the Editors

Converting a home to run on renewable energy has never looked more appealing. Oil and gas prices have surged while material costs for solar panels and other clean technologies continue to fall. Billions of dollars have been proposed for decarbonizing efforts in the Biden administration's Build Back Better plan. And, of course, the climate crisis is urgent.

In the U.S., an estimated 13 percent of total carbon emissions come from fuel used for heating and cooking in residential and commercial buildings. Only about 25 percent of homes run solely on electricity. Although residential energy infrastructure differs by region, one thing is becoming increasingly clear: For a shift to clean power, we need to get as many homes as possible off fossil fuels and electrify whatever we can. That way, as the grid carries more and more energy from photovoltaic, wind, hydroelectric, tidal and nuclear sources, our appliances, cars and HVAC systems will be poised to operate on net-zero-emissions technologies.

We've been told that individual actions won't make a dent in the climate crisis without structural change, but people are hungry to participate directly in solutions. Lobbying efforts that push back against renewables and incentives make the goal of net-zero homes out of reach for most in the U.S. Our policy makers at every level of government must make it easier for all to take part and to benefit.

For new construction, clean-energy mandates have been enacted in places such as New York City, where developers will be prohibited from installing gas hookups starting in 2024. But many of the existing households in the U.S. will require retrofits. If you've looked into this process yourself, you know it can be a labyrinth.

The biggest barriers to residential energy conversion are political and psychological. Our love of gas cooking, for example, comes from industry's success in convincing us that real cooks prefer gas. Yet recent studies have shown that stoves running on natural gas and other fossil fuels create indoor air pollution and elevate risk levels for asthma and other health issues, especially in children. Meanwhile improved induction stovetop technologies (which use an electromagnetic field to heat pans directly) are widely available. They offer more temperature precision than flames and don't heat up the kitchen while you're cooking. But they still account for less than 2 percent of the U.S. market and are more expensive than their fossil-fuel-burning counterparts. Installing them often requires electrical work upgrades, which, for many people, make the cost and hassle not worth it.

Policy makers are trying to make upgrades cheaper, but they are going about it in a nonequitable way. Incentives for rooftop solar panels are often given through tax rebates, for example. This puts them out of reach for many people because of the upfront costs. And tax credits for renewable energy have gone down over time, meaning later adopters benefit less.

Smaller, community-based utilities that are trying to set up clean energy and are dependent on tax credits are vulnerable to politics. Because utilities need investors, banks are often the beneficiaries of the tax incentives, rather than the fledgling company or the customers it serves. That is why supporters of the congressional Green New Deal, for instance, suggest more publicly owned power companies that give agency to consumers, especially as more people are *contributing* to the electricity grid with rooftop solar panels.

Promising legislation to address the equity issue is the High-Efficiency Electric Home Rebates Act. It would provide rebates to make the cost of an electric-powered appliance such as an induction stove (or heat pump) competitive with its fossil-fuel counterparts. And the rebate would occur at the point of sale, meaning it's an immediate discount. The nonprofit Rewiring America also supports rebates to subsidize installation and conversion costs, which would especially benefit low- and moderate-income households. Zero- or low-interest "climate loans" for consumers are also an increasingly popular idea; they are already available in places such as Australia and New Zealand.

To "electrify everything," the grid will need to be updated to improve resiliency; material resources need to be secured for supply chain consistency; and the economic and health benefits that come from converting to clean energy must be accessible to all, particularly the communities that have suffered the most from fossil-fuel pollution and environmental racism. The U.S. has set ambitious targets for decarbonizing its energy use over the next few decades, and if we are to get there, end users cannot be an afterthought. SA

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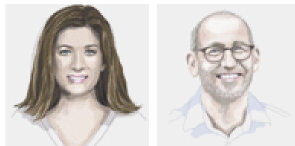
Illustration by Martin Gee



Nora Kenworthy is an associate professor of nursing and health studies at the University of Washington Bothell (@NJKenworthy). **Mark Igra** is a doctoral student in sociology at the University of Washington Seattle (@markigra).

Crowdfunding in a Crisis

Despite growing popularity, the fundraising strategy will never be a social safety net

By Nora Kenworthy *and* Mark Igra

Many of us are familiar with crowdfunding: donating money to people and their projects using one of many platforms on the Internet. During the pandemic, people have sought help through crowdfunding in record numbers, making the activity seem like part of the American safety net.

Some of these campaigns are truly transformative. Brandon Stanton—of the popular Humans of New York project—started a GoFundMe campaign for Kasson, a young man who had been blinded in an attack. Kasson's campaign has raised more than $675,000 from nearly 23,000 donors since late 2021. Contrast that with the story of Jim (whose name has been changed to protect his privacy), who didn't have the benefit of such exposure. A single father of a disabled son, Jim wrote that after his own medical crisis, he needed help "to not lose our home." Jim was asking for $2,000 to avoid eviction. He did not get a single donation.

Although stories like Kasson's are more well known, our research into this new form of charity has revealed, distressingly, that many campaigns end up like Jim's. GoFundMe and similar platforms have been largely unsuccessful in solving financial problems for most of the people who use them. Technological fixes are unlikely to change these dynamics because they're unlikely to counteract the entrenched effects of income inequalities, social network disparities and social media dynamics.

We have found that nine out of 10 campaigns do not reach their financial goals, and the median campaign raises only a few thousand dollars. In 2020 one third of medical campaigns received no donations at all. Meanwhile top campaigns of many types on the site can raise millions of dollars from thousands of donors.

And crowdfunding seems to work best for people with very large social media followings. Kasson's story, for example, appealed on its own merits, but his campaign benefited enormously from Stanton's extensive social media networks.

We've also learned that before a worthy crowdfunding campaign can receive a donation, it must first get a donor's *attention,* typically via a post on a social media platform such as Facebook, Instagram or Twitter. People simply don't have the capability to prioritize the enormous volume of content available, so these platforms choose for us, highlighting via their algorithms a limited selection of online content based on factors such as popularity, when the content was created, geographic or social proximity, what advertisers pay for, or alignment with our interests.

In this so-called attention economy, we can feel overwhelmed by the amount of content we see while often failing to recognize that what we do see is but a tiny, highly curated fraction of the information on a platform. What this means is that only a few crowdfunding campaigns ever reach large audiences and that audiences are far more likely to see already successful campaigns.

Crowdfunding can work moderately well for those who have high-income friend networks. People tend to have social ties to those who are similar to them in economic, educational and cultural terms; social scientists call this "homophily." We recently found that U.S. campaigns started in counties where the median income was in the top 20 percent earned more than twice as much as those started in counties in the bottom 20 percent. When it comes to crowdfunding, social networks amplify income inequalities.

These effects are the result not of differences in generosity but of differences in income and resources. In fact, research routinely finds that Americans with the lowest incomes are the most generous. A recent survey found that nearly 40 percent of those donating to campaigns had household incomes of less than $60,000; more than a third were without work when they donated. But without significant income to draw on, these donations are often small and spread out among a larger number of people needing help.

GoFundMe itself understands that it cannot provide an adequate fix to the unmet basic needs that fill its site. In February 2021 its CEO, Tim Cadogan, implored Congress to pass further pandemic aid, arguing that "we can't do your job for you." Yet COVID support programs have largely ended, even as many people in the U.S. continue to face financial hardships. Unless legislators decide to extend and expand essential support programs akin to the highly successful Child Tax Credit, people will keep seeking help online, where successes are few and inequalities are more often amplified than ameliorated.

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Illustration by Aad Goudappel

ADVANCES

As they travel a city's streets, increasingly Internet-connected cars can measure urban heat islands.

Ezra Bailey/Getty Images

TECH

Heat Map

Cars can chart the contours of dangerous city temperatures

Early one May morning in 1927 researcher Wilhelm Schmidt attached a mercury thermometer to his car door and drove around Vienna for three hours, recording temperatures. His resulting thermal maps showed hotter areas that coincided with "tightly built parts of the inner city" and cooler contours tracing wooded patches, grassy parks and waterways. Schmidt's efforts were the first to map a city's "islands" of heat in a "sea" of lower-temperature surroundings.

During Europe's 2003 heat wave, such islands were linked to approximately 50 percent of heat-related deaths in parts of England and to increased deaths among the elderly in Paris. The Environmental Protection Agency cites these zones as a prominent contributor to the 702 heat-related deaths reported in the U.S. on average each year from 2004 to 2018. More than half of the world's population now lives in cities, which exacerbate the local effects of rising global temperatures—and the suffering is getting worse.

University of Toulouse meteorology researcher Eva Marques and her colleagues are now updating Schmidt's car technique with modern methodology to chart dangerous heat zones. Their approach uses thermometers in Internet-connected personal cars to map how temperatures can vary over just a few city blocks; such data could help urban planners develop heat-mitigation policies in places without access to sophisticated instrumentation.

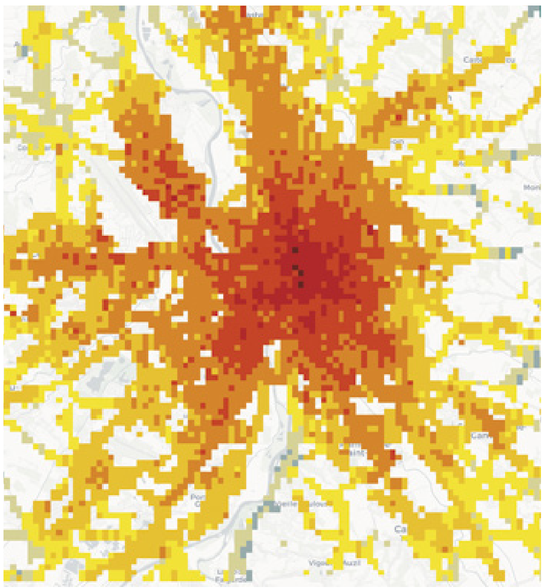
Urban heat islands occur when natural land cover is replaced with asphalt, concrete, steel, or other materials that absorb and retain more heat than their surroundings. This keeps these areas warmer, especially at night. Heat islands also affect a city's air quality by influencing humidity and how pollutants get distributed in the atmosphere. "With the increase of extreme events like heat waves, city planners need to rethink how urban spaces are designed," Marques says.

Many cities lack weather station networks that can monitor heat islands comprehensively, so Marques and her colleagues took advantage of Internet-connected sensors that are increasingly becoming standard equipment in cars. First the researchers collected measurements from car temperature sensors in the French city of Toulouse, which has high-resolution weather stations for comparison, and examined how factors such as airflow affected the accuracy of the car-mounted thermometers. Next the scientists created temperature maps in several western European cities using a database comprising millions of car sensor measurements that manufacturers had collected for insurance purposes from 2016 to 2018.

The researchers found they could reliably estimate temperature variations for spaces as small as 200 by 200 meters with fine-grained data collected at 10-second intervals. This method let them assess heat at the street level, where temperatures vary locally based on human activity, 3-D urban geometry and airflows. Their work was detailed in the *Bulletin of the American Meteorological Society*.

"Connected vehicle observations related to weather are an underused source of microscale observations," says Amanda Siems-Anderson, a research scientist at the U.S. National Center for Atmospheric Research (NCAR), who was not involved in the study. "This work demonstrates a novel use for these data." Iain Stewart, a researcher in urban climatology at the University of Toronto, who was also not involved in the study, adds that the work "is provocative and points to future possibilities for data retrieval in cities."

Factory-installed sensors in vehicles can provide a wealth of weather- and climate-related data, Siems-Anderson says. The challenge is ensuring data consistency and quality, as well as building a robust infrastructure to pull those data from enough vehicles. For example, NCAR already collects vehicle data to supplement weather forecasts using a system that updates every five minutes. But such projects "often use 10 to several hundred [dedicated] vehicles, which do not provide adequate coverage unless they're in a very confined area," Siems-Anderson says. Moving beyond pilot studies would require a dramatic scale-up. Additionally, quality control is crucial for opportunistic data sets gathered by cars that just happen to be in an area.



The urban heat island surrounding Toulouse, France, is shown in aggregated car thermometer data from 2018 summer nights. Warmer colors indicate hotter air.

University of Toulouse, Météo-France/CNRS, France

Authorities are working toward those capabilities. Local, state and national initiatives in the U.S. aim to install and operate infrastructure that can collect and process connected vehicle data and to improve the accuracy of community-driven urban climate research. The U.S. Department of Transportation, for instance, has deployed pilot programs in locations such as New York and Wyoming that monitor traffic and weather. Such data could eventually fill gaps between fixed weather stations for applications that include mapping and monitoring urban heat islands.

"Our maps could help researchers improve their understanding of how greenbelts, new buildings and bodies of water impact local thermal variations," Marques says. Her goal is to make urban climate data available for policymaking processes. For example, her team collaborates with Toulouse municipal officials on making schoolyards greener and prioritizing neighborhoods for upgrades to cool buildings more efficiently—although they are not yet using her car-collected maps. And some small French cities that lack sophisticated weather station networks nonetheless want to use heat maps to assess urban conditions, Marques says. "Crowdsourcing data is a new hope to produce and share maps with these municipalities in the years to come," she adds.

According to Stewart, it is difficult to create temperature maps of sufficient quality for city planning, and crowdsourcing the necessary data is in early stages. Maps would ideally also incorporate off-road places where people congregate. But eventually, Stewart says, "hot, crowded cities in lower-income regions of the world stand to benefit most" from crowdsourced thermal maps. Lower-income cities in tropical regions are historically understudied in urban climatology, and many still do not have access to the instruments that benefit other parts of the world—yet they are among the most vulnerable to urban heating.

More detailed maps of these cities could help planners design climate mitigation and adaptation strategies to address problematic spots within individual heat islands. "The advantage of developing this approach is that cars are everywhere," Stewart says. "So you have the whole world at your fingertips." —*Rachel Berkowitz*

HEALTH

Marker Magic

Felt tips make good medical samplers

Simple swabs and vials play crucial roles in transporting blood, saliva and other fluids during medical lab tests. Samples on cotton swabs dry out rapidly, however, and vials can require an additional transfer step before analysis. Now researchers have found that a felt marker's fibrous tip—without ink, of course—can double as an effective, long-lasting sampler.

Physicist Igor Popov and his team at the Moscow Institute of Physics and Technology bought replacement tips, designed to hold inks for long periods without drying, that are used in a popular commercial marker. After soaking these highly porous tips in blood or saliva spiked with the painkiller acetaminophen, the researchers successfully tested their MacGyvered samplers to identify the drug and determine its concentration—even after seven days of room temperature storage. Popov says such samplers would work best for tests to detect drugs and hormones that do not break down quickly. "This technology could be utilized for medical investigations in difficult conditions, such as facilities far away from large cities," he adds. The tool's use is detailed in *Acta Astronautica* and in *Molecules*.

Another potential implementation: space travel. Popov says samplers used to test astronauts on the job must be compact, lightweight and usable without intensive training. Samples must also be easily storable for return to Earth; space station astronauts currently use vials that take up valuable freezer space.

The marker idea "is a new application I've never seen for this purpose before," says University of South Carolina chemist Susan Richardson, who was not involved in the study. She adds that future research should test how long compounds of interest remain viable in bodily fluids such as saliva, which might host microorganisms that degrade them.

Next the researchers will compare various marker types to see which qualities contribute to better sample storage—testing nibs of every composition, shape and size. —*Maddie Bender*

Illustrations by Thomas Fuchs

SPACEFLIGHT

Hyper View

A new satellite picks out extreme detail of Earth's surface materials

A new tool will soon let researchers analyze Earth's surface in mesmerizing detail, from the state of the planet's soil to the plants that bloom on its surface to the makeup of urban sprawl. This spring a SpaceX Falcon 9 rocket lifted off from Florida to deliver Germany's €300-million Environmental Mapping and Analysis Program (EnMAP) satellite into orbit. Starting in the fall, remote sensing researchers around the world can apply to set the spacecraft's sights on specific targets as it orbits the globe from pole to pole. "We are superexcited," says Sabine Chabrillat, EnMAP's principal investigator, who is an Earth scientist at the German Research Center for Geosciences in Potsdam and Leibniz University Hannover. "We are really pretty confident that we will have high-quality data."

EnMAP is among the next generation of so-called hyperspectral missions that promise to fill a big gap in remote sensing. Compared with ordinary cameras and multispectral imagers, hyperspectral sensors record a much broader portion of the electromagnetic spectrum more precisely, capturing the distinctive reflected wavelengths of various materials. Although other satellites track urban sprawl from space, these spectral fingerprints could reveal just how much expansion is attributable, for instance, to housing versus asphalt. And where other satellites spot toxic algal blooms, hyperspectral data can pinpoint the phytoplankton species responsible. "It's going to hugely improve our understanding of biodiversity around the world," says Susan Ustin, director of the Center for Spatial Technologies and Remote Sensing at the University of California, Davis, who is not involved in the mission.

Chabrillat is looking forward to analyzing Earth's soil, which faces increasing damage from industrial agriculture and climate change. Dirt grows food and stores carbon, but monitoring its global health is challenging. "We are really missing an assessment of the current status of our soils," she says. "Are they degraded? How much are they degraded? Where are the hotspots of degradation?" EnMAP will help answer these questions at a glance.

Scientists have recognized the potential of spaceborne hyperspectral imaging since the 1980s, but new missions were scarce. "NASA managers were skeptical about the funding potential of a satellite mission that could address many ecological applications and science questions, saying that a mission that acted like a Swiss Army knife wouldn't fly," explains Elizabeth Middleton, who was a mission scientist with NASA's EO-1, an extended hyperspectral demonstration mission that operated from 2000 to 2017. That thinking has evolved. "With more concern about climate change, and the resilience to climate change, there's more demand for having more precise information for the environment," Ustin says.

EnMAP's freely available data will complement observations from other missions, such as Italy's PRISMA demo spacecraft, which launched in 2019. And both NASA and the European Space Agency aim to fly major hyperspectral missions by the end of the decade to further broaden our views of the planet's surface. *—Megan I. Gannon*

ANIMAL BEHAVIOR

Krill Cam

Tiny swimmers' swarms examined

Antarctic krill form the biggest biomass swarms on Earth. "You can even see them from space," says Alicia Burns, a behavioral biologist at Taronga Conservation Society Australia. Krill swarms play a vital role in the food chain and in cycling atmospheric carbon into the depths of the Southern Ocean. How these tiny, shrimplike creatures form and maintain massive clusters is poorly understood. But Burns and her colleagues describe in the *Proceedings of the Royal Society B* that unique and mathematically predictable social rules govern the seemingly chaotic crustacean crowds.

To observe swarming behavior, the researchers teamed up with the Australian Antarctic Division's aquarium in Tasmania—one of only two facilities worldwide capable of raising krill. There the researchers filmed krill from different angles to track individuals in 3-D and then statistically determined the patterns of each animal's movements in relation to its neighbors. "Matching the mathematics with the biology is the new part," Burns says.

Geraint Tarling, a biological oceanographer at the British Antarctic Survey, who was not involved in the study, agrees: "This is the first leap that we've had from a theoretical expectation—what we expect [krill] to do—to an absolute observed identification of what the behavioral rule is."

Swarming can help animals evade predators, find mates and food, and travel more efficiently. The new study revealed that in forming these clusters, the krill (like many swarming species) adjusted their speed based on that of their neighbors in front—similar to a driver in traffic. But unlike other species, krill most often changed direction based on neighbors in the vertical plane, swimming toward peers ahead and below but away from those ahead and above. Ryan Lukeman, a St. Francis Xavier University mathematician who studies swarming but was not involved in the study, says this is fundamentally different from what has been seen in fish and birds: for them, "there tends to be little information transfer vertically."

An Antarctic krill

The researchers are still picking apart why this might be. Krill eyes point upward, and the animals' undersides flash with bioluminescence when startled, Tarling says; these characteristics may help explain their vertical focus while swarming. Many of their predators attack vertically, and krill might be watching one another for signs of incoming danger. They might also be avoiding vortices produced by neighbors' paddling, which—unlike a fish's swim method—pushes water downward and behind.

Burns says the next goal is confirming that the newly found swarming rules apply in the wild, using a "krill cam" slung from a buoy. Lukeman says scientists could one day use the rules to simulate how changing ocean temperatures and currents might affect these crucial crustaceans' ability to stick together. *—Andrew Chapman*

Stocktrek Images, Inc./Alamy Stock Photo

Ankylosaur tracks

PALEONTOLOGY

Follow the Food

Dinosaur diets offer a clue to an evolutionary puzzle

If you traveled across what is now North America around 75 million years ago, you would see vastly different dinosaur species everywhere you went. The dramatic variation in this period's fossils, found throughout the western half of the continent, has long puzzled paleontologists. Some have proposed that mountains or rivers might have isolated evolving dinosaur populations, leading to greater diversity. But a new study suggests a different possibility. Part of the answer, researchers report in the journal *Palaeontology*, rests in what herbivorous dinosaurs were munching on.

Paleontologists can investigate dinosaur diets by looking at geochemical isotopes—versions of elements with different numbers of neutrons—found in fossilized bones. As herbivorous dinosaurs digested ferns and conifers, for example, isotopes of oxygen, carbon and strontium from those plants accumulated in different proportions. Researchers have identified the distinct ratios associated with each plant type and the locations where it grew; measuring the isotopes in dinosaur bones can tell experts not only what these animals ate but where they ventured for food.

In the new study, Carleton University paleontologist Thomas Cullen and his colleagues looked at the horned ceratopsids, armored ankylosaurs and duck-billed hadrosaurs of southern Alberta's Oldman Formation. Horned and armored dinosaurs walked on all fours with their heads near the ground, and isotope ratios show these dinosaurs ate low-growing plants in a relatively limited geographic area. But the duck-billed dinosaurs, Cullen and coauthors found, could reach higher foliage in the trees and fed on a broader range of plants—and these animals ranged as far as 100 kilometers in search of sustenance. "I was initially surprised at just how different the hadrosaurs are from the ankylosaurs and ceratopsids" in their eating and travel habits, Cullen says.

If horned and armored dinosaurs foraged only in relatively constrained areas, such dietary restrictions might have helped drive the evolution of their many new species in each habitat—whereas duck-billed species, whose individuals had broader geographic ranges, show far less variation. "This study is an example of how the use of geochemical and high-precision analytical techniques continues to allow paleontologists to make significant interpretations of ecology and biology of ancient ecosystems," says University of Arkansas geologist Celina Suarez, who was not involved in the research.

Such work could offer new insights into dinosaur species' distribution 75 million years ago, says Andrew Farke, a curator at the Raymond M. Alf Museum of Paleontology in Claremont, Calif., who also was not involved. "I would bet the diet of hadrosaurs probably relates to the broad distribution of their species," he adds. —*Riley Black*

Alexandre Morin-Laprise/Getty Images

BIOMECHANICS

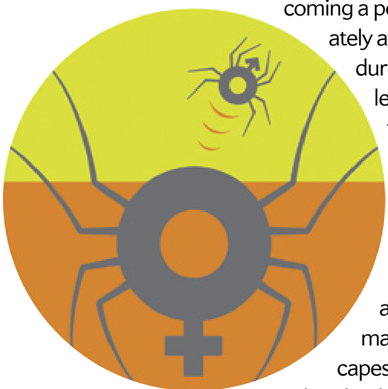
Spider Launch

Male orb weavers spring away to survive mating

For some spiders, love is all-consuming. In a grisly practice known as sexual cannibalism, females of many species devour their mates after procreation, either for sustenance or to keep their reproductive options open.

Female spiders are usually much larger than their male counterparts and thus have a strong physical advantage. But new research published in *Current Biology* shows how some males protect themselves. Using energy stored in their front leg joints, the males of an orb-weaving spider species called *Philoponella prominens* can fling themselves off of a ravenous mate in a split second. "When I first observed this catapulting behavior in the field, I knew I had found something special, based on my 13 years of studying the sexual behaviors of spiders," says the study's lead author, Shichang Zhang, a behavioral ecologist at China's Hubei University.

These orb weavers live together in complexes, formed from many interconnected webs, that can house more than 200 individuals. With so many leggy bachelors roaming around, females can afford to devour a few—so to avoid becoming a postcoital snack, male spiders must flee immediately after procreation. The researchers discovered that during the deed itself, male spiders fold their front legs against the female. Immediately after mating, they straighten their legs, using the hydraulic pressure built up along their tibia-metatarsus joints to launch themselves as if on a spring.



The spiders fly off their mates so fast that ordinary cameras cannot capture the behavior. So the researchers used a Beijing advertising agency's special high-speed camera to film the mating creatures. Breaking down the dramatic escapes at 1,500 frames per second, the scientists found that the three-millimeter-long spiders launched themselves at speeds approaching 88 centimeters per second. "Imagine a man with a height of 1.8 meters catapulting himself 530 meters in one second," Zhang says. "That's what these male spiders do." As the acrobatic arachnids soar, they also spin like an eight-legged top, rotating nearly 175 times per second on average.

Among the 155 pairs of orb-weaving spiders initially recorded, 152 males successfully catapulted and survived. The remaining three didn't leap and were promptly eaten. Spiders that researchers blocked so they couldn't jump away were consumed as well.

The males that escape are surprisingly devoted: During mating, they fasten a silk "safety line" to their partner. And after they catapult, they crawl back along the line to mate with her again. They can repeat this cycle up to six times to increase the likelihood of successful insemination.

Although sexual cannibalism seems gruesome from a human perspective, the behavior makes evolutionary sense, according to Matthias Foellmer, a biologist at Adelphi University who studies this behavior in spiders. In most spider species, males contribute nothing to the next generation beyond their sperm, and females have nothing to lose by eating them. "If you think about it that way, it's surprising it's actually not more prominent," says Foellmer, who was not involved with the study.

Foellmer says this study illustrates how cannibalism can spark an evolutionary arms race between the sexes. The high escape rate seems to favor males for now, he adds, but "there could be a mutation arising that makes females a little quicker or better at grasping the males." *—Jack Tamisiea*

CELL BIOLOGY

Salivary Secrets

Frog skin cell type aids mammal mouths

Looking deep within mammalian spit-producing glands, scientists were recently surprised to find an ancient cell type long thought to exist primarily in the slimy skin of frogs and fish. Such discoveries are rare in modern science—and researchers say these tiny cells could fill many more roles than previously thought.

The scientists were trying to determine which cell produces a certain protein involved in salivary gland growth and repair. Using a technique called single-cell RNA sequencing, they isolated candidate cells from mouse glands and then examined their genetic function. They found the gene for the salivary gland growth protein—and discovered that the cells producing it were ionocytes, a specialized cell type that pumps charged particles across membranes. "It is a very, very interesting cell," says Helen Makarenkova, a molecular medicine researcher at the Scripps Research Institute and co-author of a *Cell Reports* study on the finding.

Historically, Makarenkova says, "people didn't really pay much attention to the ionocyte." The cells were well documented in frog and fish skins, where they help to maintain a healthy salt balance in aquatic environments. In 2018 researchers learned that a version exists in humans, too: Harvard University scientists unexpectedly found ionocytes in human lungs' lining. In retrospect, it made sense for the cells to be useful in this kind of moist, permeable tissue, says systems biologist Allon M. Klein, who was on that team and was not involved in the new research. "Frog skin looks very much like the [human] airway," Klein says.

The researchers suggest salivary gland ionocytes probably regulate saliva pH and viscosity and secrete the growth factor that is crucial for salivary gland repair. Although the cells have not yet been directly observed in human salivary glands, the growth factor they produce has been isolated in human saliva.

But how did scientists overlook mammalian ionocytes for so long? For one thing, single-cell RNA sequencing has been available only for about a decade, and it remains relatively expensive. Plus, ionocytes are physically small—about a quarter of the size of most mammalian cells—and few in number. "As compared with the major constituents of the tissue," Klein says, "they are rare." Still, he speculates that they might lurk in other mammalian tissues, such as intestinal lining.

Makarenkova's next steps are to confirm ionocytes' existence in human salivary glands and to investigate their potential to treat conditions such as dry mouth, in cases where the cells are insufficient or dysfunctional. And she would like to search for ionocytes in other tissues and investigate their function: "This might be quite a general mechanism." *—Joanna Thompson*

IN THE NEWS

Quick Hits

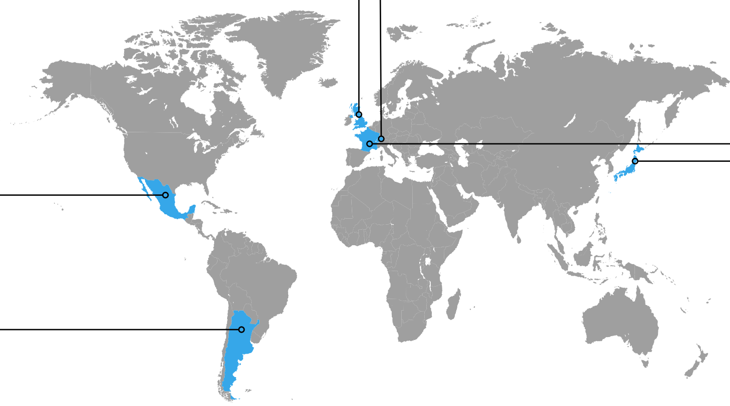
By Joanna Thompson

U.K.
Researchers searched for traces of parasite infection in more than 450 human pelvic remains dating from prehistoric times to the Victorian era. Petrified roundworm and whipworm eggs suggest that Roman-era and late medieval Brits were most likely to be plagued with these pests.

SWITZERLAND
A four-inch fossilized tooth, found nearly 9,500 feet above sea level in the Swiss Alps, may have come from the largest-known marine reptile. Paleontologists say the tooth belonged to an ichthyosaur up to 50 feet long that swam the ancient seas.

FRANCE
A pipistrelle bat set a new record for the longest-known bat migration. The tiny mammal covered about 1,545 miles—from Borok, Russia, to the French village of Lully—in 63 days. Its journey came to a tragic end when it drowned in a water tank.

MEXICO
Scientists discovered six new species of micro frog, including one that now holds the record for Mexico's smallest frog. When fully grown, these forest amphibians are smaller than a human thumbnail.



JAPAN
Scientists working with food and pharmaceutical company Kirin developed an electrical chopstick accessory that makes food taste 50 percent saltier—without adding salt. The device runs a minuscule current through the utensils, drawing extra ions from the food across a user's tastebuds.

ARGENTINA
Genetic analysis showed that the Patagonian sheepdog, a breed found in Argentina and Chile, is the closest living relative to the ancestor of all U.K. herding dog breeds. European colonizers likely introduced this line nearly 200 years ago.

ANTARCTICA
Investigations detail how the activity of an underwater volcano, the Orca Seamount, triggered a recent series of 85,000 earthquakes along the Antarctic continental plate. The quakes shifted the position of nearby King George Island by roughly four inches.

For more details, visit www.ScientificAmerican.com/jul2022/advances

MEDICINE

Snail Insulin

Deadly mollusk venom could inspire lifesaving treatment

Grabbing a live cone snail while collecting seashells could get you jabbed with a fanglike dart full of potentially fatal—and incredibly fast-acting—venom. But studying how this substance hijacks key bodily systems so efficiently may inspire lifesaving medications: cone snail venom includes insulin, a hormone that helps cells metabolize blood glucose and that many people with diabetes need to routinely inject.

And there is something special about cone snail insulin, which quickly drops their prey animals' blood sugar. Human insulin works much more slowly. It tends to form clumps, which stabilize the substance for easier storage in the body—but it cannot act until these clumps dissolve. The cone snail could offer insight into creating nonclumping insulin for faster diabetes treatment.

For a study in *Nature Chemical Biology*, University of Copenhagen biologist Helena Safavi-Hemami and her colleagues probed the peculiar anatomy of the Kinoshita's

Kinoshita's cone snail

Jon G. Fuller/VWPics/Alamy Stock Photo

cone snail's insulin. The researchers incorporated unique regions of the molecule into human insulin, creating a hybrid that lacks the human version's clumping region.

The researchers had performed a similar feat in 2020 using insulin from the geographer cone snail. They then checked other species and found the Kinoshita's cone snail produced insulin that acts in a never-before-seen manner. The human insulin molecule's clumping region is also crucial for binding to cells' receptors, and this region is truncated in the geographer cone snail's insulin. Conveniently, Kinoshita's cone snail insulin lacks this part altogether. Instead it has a unique elongated region that binds to receptors but does not produce clumps.

When Safavi-Hemami showed the new snail insulin to her collaborator Danny Hung-Chieh Chou of Stanford University, "he said, 'It's been done,'" Safavi-Hemami recalls, "but when we looked, the biology was so different." They used cutting-edge imaging technology to clearly visualize how the new hybrid attaches to a cell's insulin receptor and changes its shape—a detail that was unknown about the previous hybrid. These findings can help better illuminate how insulins work in general, says Mike Strauss, a biochemist at McGill University, who was not involved in the study. "This opens up possibilities for synthetic insulins," Strauss adds.

Now the team is further investigating the hybrid's safety and stability—challenges for nonclumping insulin designs that this strangely shaped molecule might overcome. Still, it has many tests to pass. "That's why it's good to have a repertoire," Safavi-Hemami says. Different cone snail species have distinct venom cocktails, likely including unique insulin types and other valuable molecules. With venom made of thousands of substances, cone snails have plenty to offer if we just keep looking—carefully. —*Anna Rogers*

PHYSICS

Science in Images

By Joanna Thompson

Sheltered underneath nearly a mile of rock in Abruzzo, Italy, scientists are hard at work unraveling the secrets of the universe's smallest bits of matter. When a radioactive process called beta decay occurs, it typically emits two particles: a negatively charged electron and a version of a tiny, neutrally charged neutrino. The Large Enriched Germanium Experiment for Neutrinoless Double Beta Decay (LEGEND-200) at the Gran Sasso National Laboratory is designed to figure out whether this process can occur without resulting in a neutrino at the end. The answer could shape our understanding of how matter came to be.

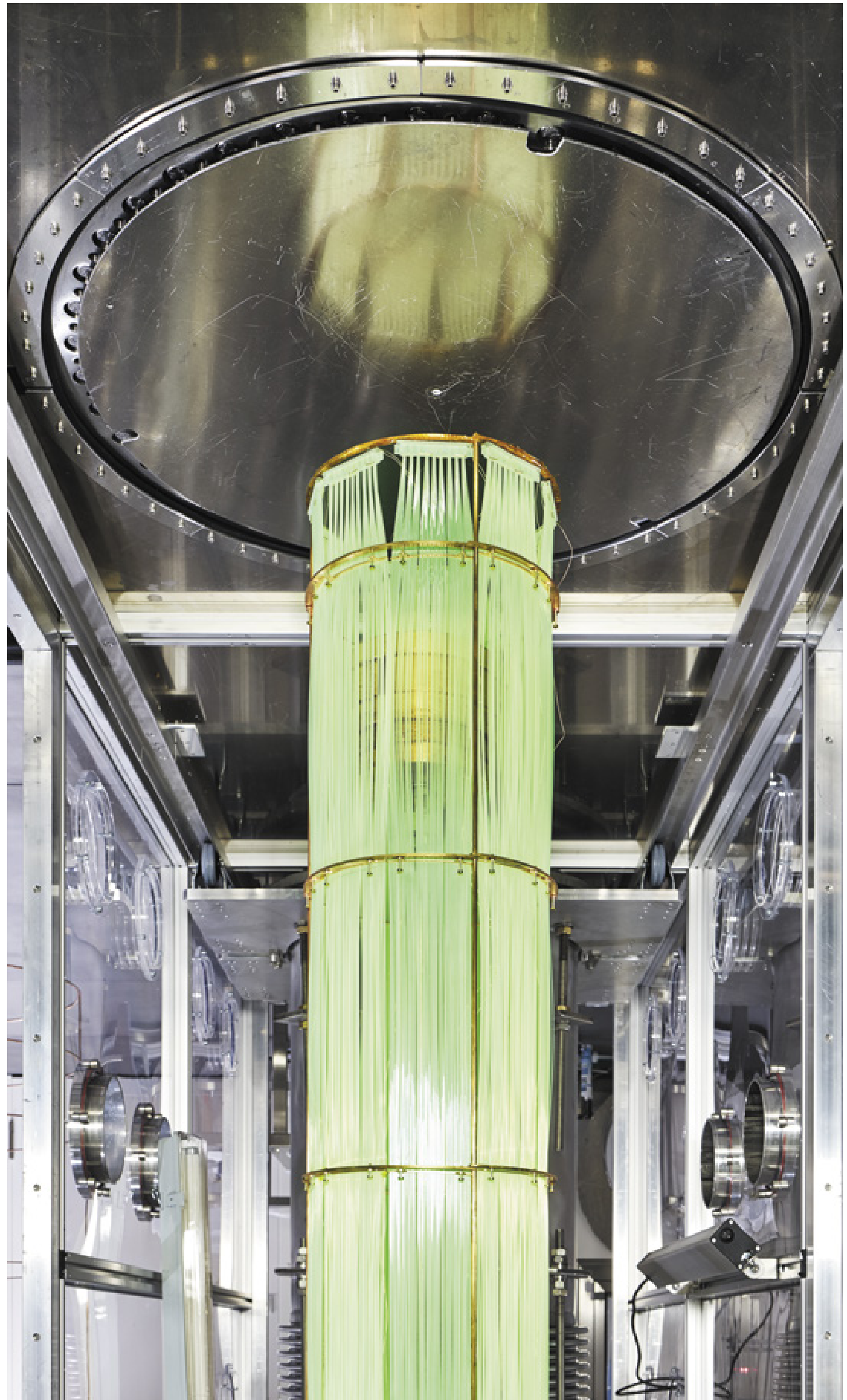
The process of "neutrinoless double beta decay," if it does occur, happens very rarely. Noticing when decay results in electrons but not neutrinos can be difficult, especially because neutrinos are plentiful everywhere—billions pass through your body every second—and are often produced when background radiation reacts with machine components.

That's why scientists focus on "choosing really low-radioactivity materials to start with and then also coming up with lots of clever ways to reject background [particles]," says Drexel University particle physicist Michelle Dolinski, who is not involved in the project.

LEGEND-200 is equipped with slightly radioactive germanium crystals, which act as both a source of beta decay and a neutrino detector. To screen out ambient particles, the entire setup is immersed in a cryogenic tank shielded by water and liquid argon. That core is surrounded with green optical fibers and a reflective film that bounces away stray particles (*right*).

If LEGEND-200 observes neutrinoless double beta decay, it will mean that unlike protons, electrons and other elementary particles—which each have an "antiparticle" that destroys them on contact—neutrinos are their own antiparticles and can destroy one another. If this is the case, then when double beta decay occurs, two neutrinos would be produced and immediately annihilated, leaving none behind. "This is an important ingredient in trying to understand why matter dominated over antimatter in the early universe and why the universe exists as it does today," Dolinski says.

LEGEND collaborator Laura Baudis, who is an experimental physicist at the University of Zurich, is excited to see what this experiment uncovers when it begins collecting data later this year. "There are so many things we don't know about neutrinos," she says. "They're really still full of surprises."



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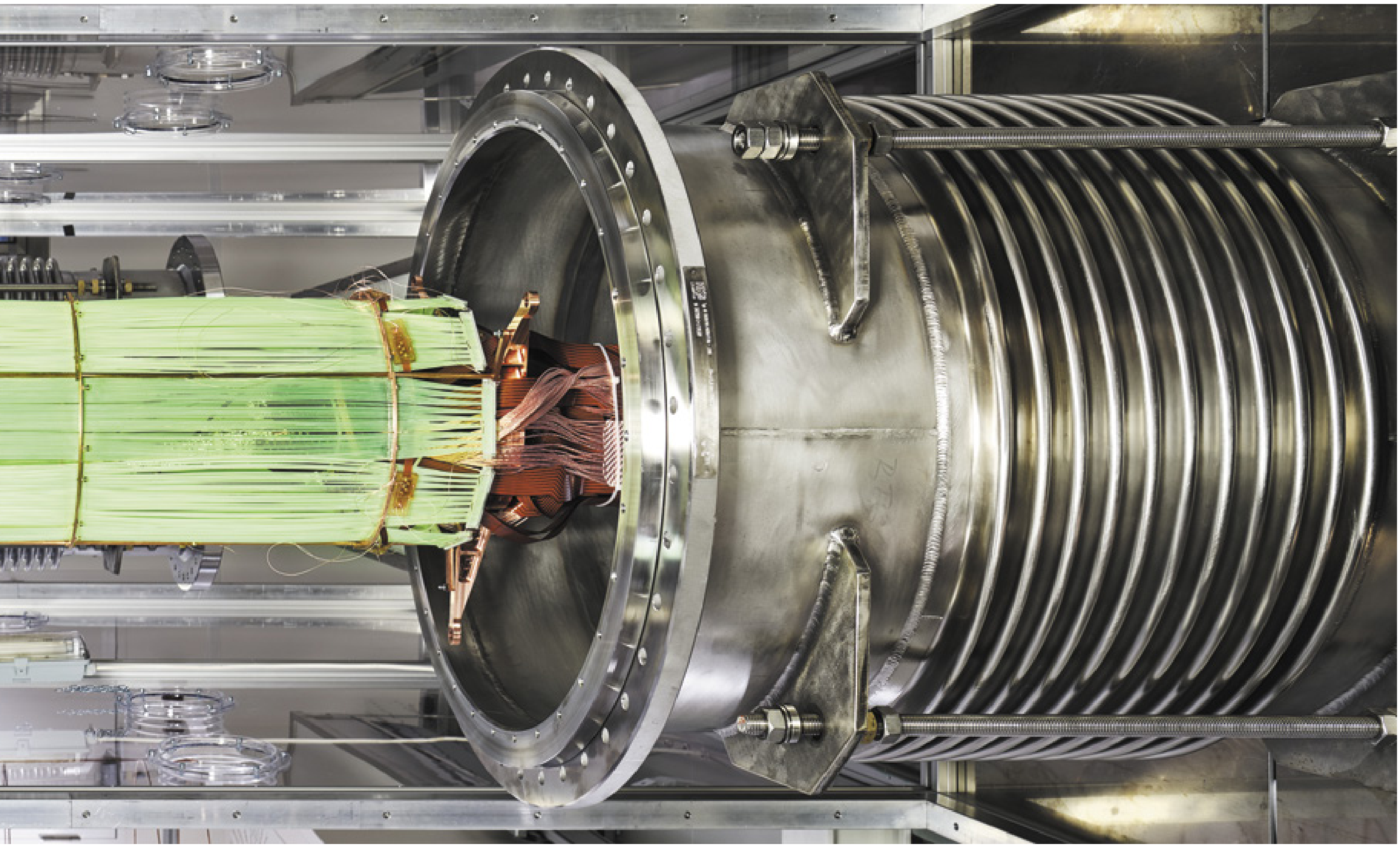
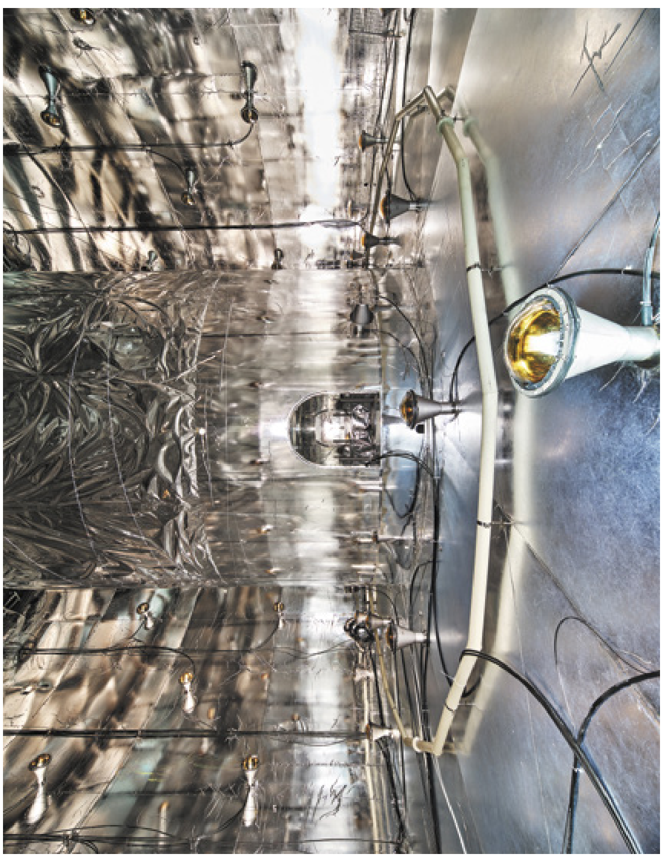
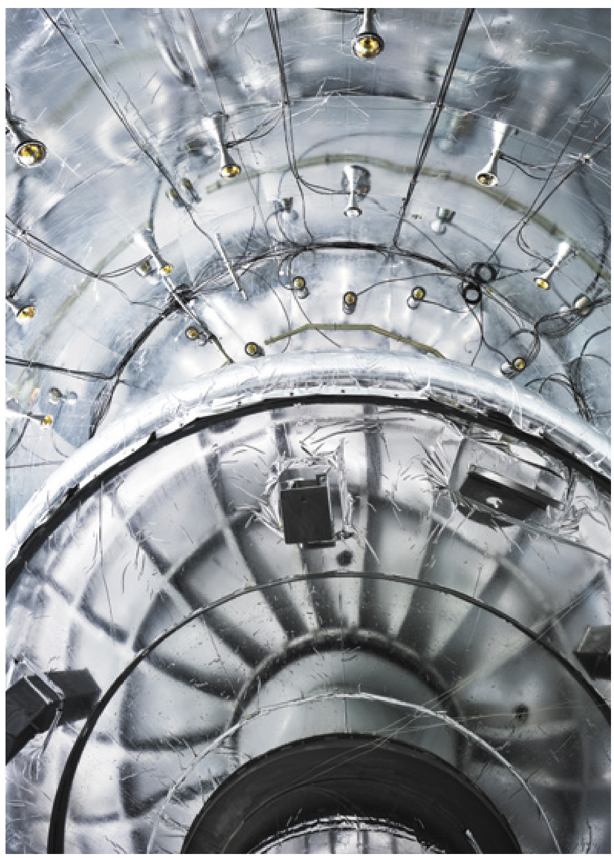




Inside the water tank, mirror film surrounds the liquid-argon cryostat.



Top-down view of the water tank, studded with photosensors.

Enrico Sacchetti

ATMOSPHERIC SCIENCE

Thirsty Air

Western skies are craving more water, stoking drought and wildfire

Drought is typically thought of as a simple lack of rain and snow. But evaporative demand—a term describing the atmosphere's capacity to pull moisture from the ground—is also a major factor. And the atmosphere over much of the U.S. has grown a lot thirstier over the past 40 years, a new study in the *Journal of Hydrometeorology* found.

Evaporative demand can be thought of as a "laundry-drying quotient," says Nevada state climatologist Stephanie McAfee, who was not involved in the study. When hanging laundry outside, she explains, "we know that it's going to dry best and fastest if it's warm, sunny, windy and dry." This quotient does not simply creep upward alongside climate warming; it increases exponentially, says study lead author Christine Albano, an ecohydrologist at the Desert Research Institute in Reno. "With a one- to two-degree rise in temperature, we're getting much larger increases in evaporative demand."


Arizona's Monument Valley

To measure how atmospheric thirst has been changing, Albano and her colleagues examined five data sets covering 1980 to 2020 that included temperature, wind speed, solar radiation and humidity—all of which contribute to evaporative demand. They found the biggest U.S. increases occurring over Southwestern states, whereas rising humidity offset higher temperatures in the East. In the Rio Grande region, the atmosphere craved 135 to 235 millimeters more water annually in 2020 than it did in 1980, an 8 to 15 percent increase. That water vaporized instead of quenching crops and filling aquifers. (A 10 percent increase means the same crops under the same management need 10 percent more water to be as productive as 40 years ago.)

Along with higher temperatures and lower humidity, the study also noted rising wind speeds and increasing solar radiation. In arid regions, humidity declines as temperatures warm. Albano says she is not yet sure why the sunlight and wind are changing.

Rising evaporative demand adds to the strain as the West continues to endure megadrought conditions that have not been seen for 1,200 years. The increase contributed to low spring runoff from the Sierra Nevada in 2021, when much less stream water came from snow than predicted, Albano says. A thirstier atmosphere also dried out Western forests, leading to larger wildfires.

The study shows that resource managers "really have to think a lot about how we make sure that we're controlling the amount of water that we're all using," says Caroline Juang, a Columbia University Earth scientist who was not involved in the study.

"Three inches of rain doesn't go as far as it used to," McAfee says. "The atmosphere wants a bigger sip." —*Ula Chrobak*

James O'Neil/Getty Images


Boa constrictor

BIOLOGY

Constriction Site

How snakes breathe while squeezing prey to death

When boa constrictors and other strangling snakes wrap their prey in a deadly embrace, they don't just exert pressure on their victim; they put the squeeze on their own lungs as well. Now new research shows how these remarkable reptiles use a sophisticated breathing technique to avoid suffocating themselves.

Instead of using a diaphragm muscle to inflate their lungs as mammals do, snakes activate a series of muscles around their extremely long rib cage. But crushing a struggling animal restricts these muscles, and scientists have long puzzled over how the snakes survive this constriction contradiction.

A team of researchers, led by John Capano of Brown University, reports in the *Journal of Experimental Biology* that boa constrictors can selectively move individual rib muscles in whatever parts of their chest are unblocked at a given moment. This lets small areas of the lungs function like a pump, sucking air through the constricted zones to absorb as much oxygen as possible. "Oftentimes, when they're not ventilating with that [squeezed region of the lung], it'll be more or less entirely collapsed," Capano says.

To discover this process, the researchers wrapped boa constrictors with blood pressure cuffs to prevent certain parts of their chests from expanding. Then they measured respiratory flow using small masks strapped to the reptiles' snouts. Unfortunately, the snakes proved to be mask skeptics. "One of the big challenges was really just getting the animals to perform in the lab setting," Capano says.

But the researchers eventually saw how the snakes used selective breathing to take in adequate air despite the cuffs. Recordings of electrical activity and x-ray images confirmed that nerve impulses strategically activated specific muscles in free areas. The snakes did not even attempt to breathe with the restricted parts of their rib cage—instead they exclusively used muscles on ribs that could still move. The researchers suggest this ability developed early in the snakes' evolutionary history because it would have let them swallow ever larger prey.

"The authors made really clever biomechanics experiments," says Eletra de Souza, a snake researcher at the University of São Paulo, who was not involved in the study. "The bony and morphological adaptations of snakes always surprise me. It's amazing to see how these animals cope so well in the absence of limbs."

—*Lars Fischer and Joanna Thompson*

Paul Starosta/Getty Images

Canadian poet **Donna Kane** divides her time between British Columbia and Nova Scotia. *Orrery,* the most recent of her three published volumes of poetry, includes nine poems about the Pioneer 10 spacecraft.

On Visible Light

Knowledge is the fruiting body of light,
and light the fruiting body of photons
at the end of traveling through our nights

to reach the velvet chair, the common snipe,
where we see that in an object's reflection,
knowledge is the fruiting body of light.

Just a slice of electromagnetic
wavelength and sight is ours, a blindness gone
at the end of traveling through our nights.

All this way and yet something's not right.
This blue color we see is the chair's rejection.
Knowledge is the fruiting body of light

whose shadows dog us. Might this be the heart
of why we fail to reach satisfaction
at the end of traveling through our nights.

Always wanting what is beyond our sight,
always drawn toward the parts still hidden.
Knowledge is the fruiting body of light
at the end of traveling through our nights.

"On Visible Light" is a villanelle, defined by the Academy of American Poets as a highly structured poem made up of five tercets followed by a quatrain, with two repeating rhymes and two refrains.

Masha Raymers/Getty Images

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*.

Mental Illness and Dementia

Why do psychiatric conditions multiply the risk of cognitive decline?

By Claudia Wallis

Age is the single biggest risk factor for dementia, with the odds doubling about every five years after age 65. But many things influence those odds for a given individual. Genetic vulnerability is a contributor, as are so-called modifiable risk factors such as smoking, cardiovascular disease, social isolation, and impaired hearing and vision. Certain mental conditions, particularly depression and schizophrenia, have also been linked to dementia. But because depression can itself be a sign of cognitive decline, the causality has been a bit muddy. Earlier this year an analysis of data from New Zealand provided the most convincing evidence to date linking many kinds of mental illness with dementia. That study raises important questions about the reasons for this increased risk and what could be done to reduce it.

The study looked at the health records of 1.7 million New Zealanders born between 1928 and 1967 covering a 30-year period ending in mid-2018. It found that those with a diagnosed mental disorder—such as anxiety disorders, depression or bipolar disorder—had four times the rate of ultimately developing dementia compared with people without such a diagnosis. For those with a psychosis such as schizophrenia, it was six times the rate. Among people who developed dementia, those with a psychiatric disorder were affected 5.6 years earlier, on average.

The study did not examine biological, social or other reasons for the increased risk, but research on dementia points to several possible explanations. "There might be shared genetic risk factors," suggests psychologist Leah Richmond-Rakerd of the University of Michigan, lead author of the study. Recent studies have found some overlap in genetic markers associated with Alzheimer's disease and those linked to bipolar disorder and to major depression. Long-term use of psychiatric medications could also be playing a role in dementia, but Richmond-Rakerd and her coauthors do not think it is a major contributor.

They suspect that a more significant risk factor is the chronic stress associated with having a psychiatric disorder, which may degrade brain health over time. Studies in animals as well as human autopsy studies have linked chronic stress to a loss of neural connections in the hippocampus, the brain's memory center, which is where Alzheimer's takes a heavy toll. Evidence suggests that stress drives inflammation and immune dysregulation in the body and brain, impacting brain connectivity, says Harvard University neurologist and dementia researcher Steven Arnold. "If you have fewer connections and synapses to begin with because of stress, then you can't afford to lose as many with aging before it starts to show up as what we might call dementia." In other words, people with mental illnesses may have less "cognitive reserve"—brainpower that is sufficiently robust to withstand normal aging without obvious losses of function.

Vulnerability in this population may also be linked to their finding it more difficult to lead healthy lives, physically and socially, Richmond-Rakerd says. "They might exercise less, or drink alcohol excessively, or have trouble staying socially connected"—all of which increase the risk for dementia. People with certain psychiatric conditions tend to have higher-than-average rates of smoking and fewer years of education, which are also risk factors.

Could a more holistic approach to treating mental illness mitigate the risk for dementia? Researchers tend to think so. In 2020 the British-based *Lancet* Commission on dementia prevention estimated that four in 10 cases could be prevented or delayed if society did a better job of addressing 12 modifiable risk factors, including such psychosocial contributors as depression, poor social support and low education level. Progress on some of these factors may explain why dementia rates have already fallen 15 percent per decade for the past 30 years in high-income countries. "We think there are two main reasons: better cardiovascular risk factor control and a big increase in education level," says Kenneth Langa of the University of Michigan, associate director of the Health and Retirement Study, one of the major efforts tracking these trends.

In an ideal world, Langa and other researchers say, efforts to prevent dementia would begin in childhood with strong investments in education and the inculcation of healthy habits. Such efforts would be incorporated into the treatment of depression and other mental illnesses that often emerge in the teen and early adult years. Sadly, we do not live in that ideal world; mental illness continues to be stigmatized and undertreated. But given the high costs to society and the personal tolls exacted by both mental illness and dementia, it's hard to imagine a wiser investment.

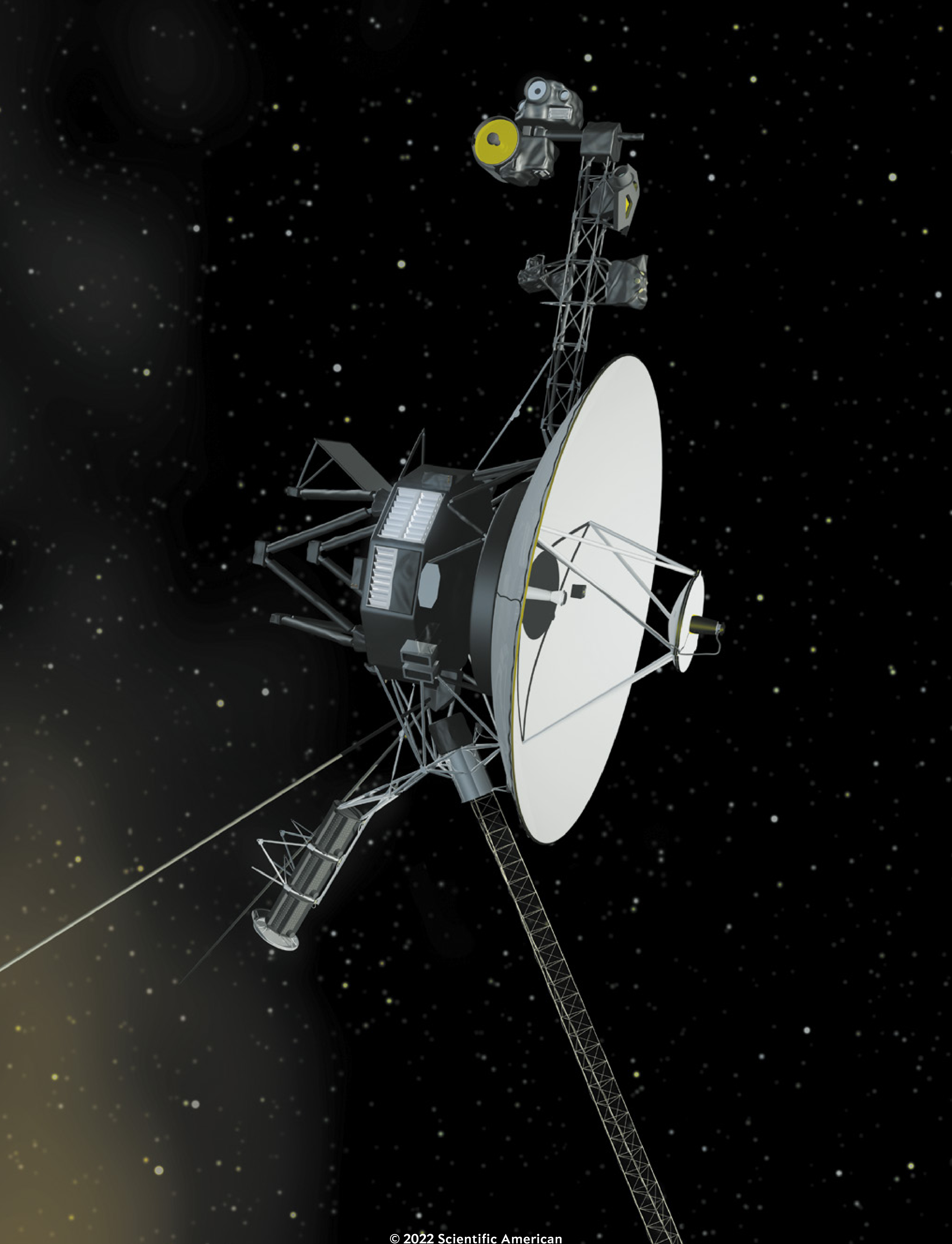
Illustration by Fatinha Ramos

SPACE EXPLORATION

Voyagers to the Stars

The farthest-flung spacecraft in history are entering a new realm—interstellar space

By Tim Folger



NASA/JPL-Caltech (*preceding pages and this page*)

IF THE STARS HADN'T ALIGNED, TWO OF the most remarkable spacecraft ever launched never would have gotten off the ground. In this case, the stars were actually planets—the four largest in the solar system. Some 60 years ago they were slowly wheeling into an array that had last occurred during the presidency of Thomas Jefferson in the early years of the 19th century. For a while the rare planetary set piece unfolded largely unnoticed. The first person to call attention to it was an aeronautics doctoral student at the California Institute of Technology named Gary Flandro.

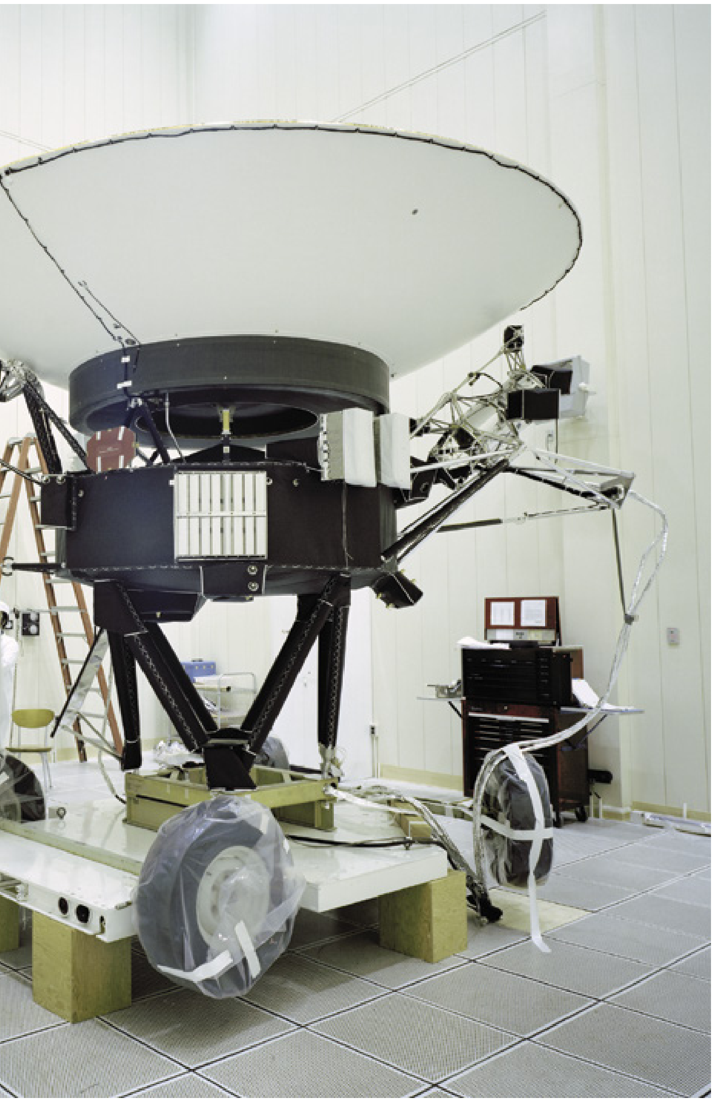
Tim Folger is a freelance journalist who writes for *National Geographic, Discover,* and other national publications.

It was 1965, and the era of space exploration was barely underway—the Soviet Union had launched Sputnik 1, the first artificial satellite, only eight years earlier. Flandro, who was working part-time at NASA's Jet Propulsion Laboratory in Pasadena, Calif., had been tasked with finding the most efficient way to send a space probe to Jupiter or perhaps even out to Saturn, Uranus or Neptune. Using a favorite precision tool of 20th-century engineers—a pencil—he charted the orbital paths of those giant planets and discovered something intriguing: in the late 1970s and early 1980s, all four would be strung like pearls on a celestial necklace in a long arc with Earth.

This coincidence meant that a space vehicle could get a speed boost from the gravitational pull of each giant planet it passed, as if being tugged along by an invisible cord that snapped at the last second, flinging the probe on its way. Flandro calculated that the repeated gravity assists, as they are called, would cut the flight time between Earth and Neptune from 30 years to 12. There was just one catch: the alignment happened only once every 176 years. To reach the planets while the lineup lasted, a spacecraft would have to be launched by the mid-1970s.

As it turned out, NASA would build *two* space vehicles to take advantage of that once-in-more-than-a-lifetime opportunity. Voyager 1 and Voyager 2, identical in every detail, were launched within 15 days of each other in the summer of 1977. After nearly 45 years in space, they are still functioning, sending data back to Earth every day from beyond the solar system's most distant known planets. They have traveled farther and lasted longer than any other spacecraft in history. And they have crossed into interstellar space, according to our best understanding of the boundary between the sun's sphere of influence and the rest of the galaxy. They are the first human-made objects to do so, a distinction they will hold for at least another few decades. Not a bad record, all in all, considering that the Voyager missions were originally planned to last just four years.

Early in their travels, four decades ago, the Voyagers gave astonished researchers the first close-up views of the moons of Jupiter and Saturn, revealing the existence of active volcanoes and fissured ice fields on worlds astronomers had thought would be as inert and crater-pocked as our own moon. In 1986 Voyager 2 became the first spacecraft to fly past Uranus; three years later it passed Neptune. So far it is the only spacecraft to have made such journeys. Now, as pioneering interstellar

probes more than 12 billion miles from Earth, they're simultaneously delighting and confounding theorists with a series of unexpected discoveries about that uncharted region.

Their remarkable odyssey is finally winding down, however. This year NASA plans to begin turning off some of the Voyagers' systems, eking out the spacecrafts' remaining energy stores to extend their unprecedented journeys to about 2030. For the Voyagers' scientists, many of whom have worked on the mission since its inception, it is a bittersweet time. They are now confronting the end of a project that far exceeded all their expectations.

"We're at 44 and a half years," says Ralph McNutt, a physicist at the Johns Hopkins University Applied Physics Laboratory (APL), who has devoted much of his career to the Voyagers. "So we've done 10 times the warranty on the darn things."

THE STARS MAY have been cooperating, but at first, Congress wasn't. After Flandro's report, NASA drew up plans for a so-called Grand Tour that would send as many as five probes to the four giant planets and Pluto. It was ambitious. It was expensive. Congress turned it down. "There was this really grand vision," says Linda Spilker, a JPL planetary scientist who started working on the Voyager missions in 1977, a few months before their launch. "Because of cost, it was whittled back."

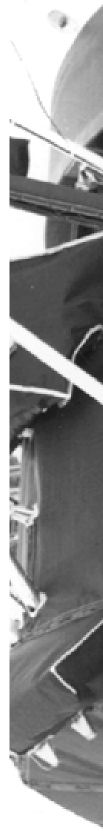
Congress eventually approved a scaled-down version of the Grand Tour, initially called Mariner Jupiter-Saturn 1977, or MJS 77. Two spacecraft were to be sent to just two planets. Nevertheless, NASA's engineers went about designing, somewhat surreptitiously, vehicles capable of withstanding the rigors of a much longer mission. They hoped that once the twin probes proved themselves, their itinerary would be extended to Uranus, Neptune, and beyond.

"Four years—that was the prime mission," says Suzanne Dodd, who, after a 20-year hiatus from the Voyager team, returned in 2010 as the project manager. "But if an engineer had a choice to put in a part that was 10 percent more expensive but wasn't something that was needed for a four-year mission, they just went ahead and did that. And they wouldn't necessarily tell management." The fact that the scientists were able to build two spacecraft, and that both are still working, is even more remarkable, she adds.

In terms of both engineering and deep-space naviga-

READY FOR LAUNCH: Voyager 2 undergoes testing at NASA's Jet Propulsion Laboratory before its flight (*left*). The spacecraft lifted off on August 20, 1977.

NASA/JPL-Caltech



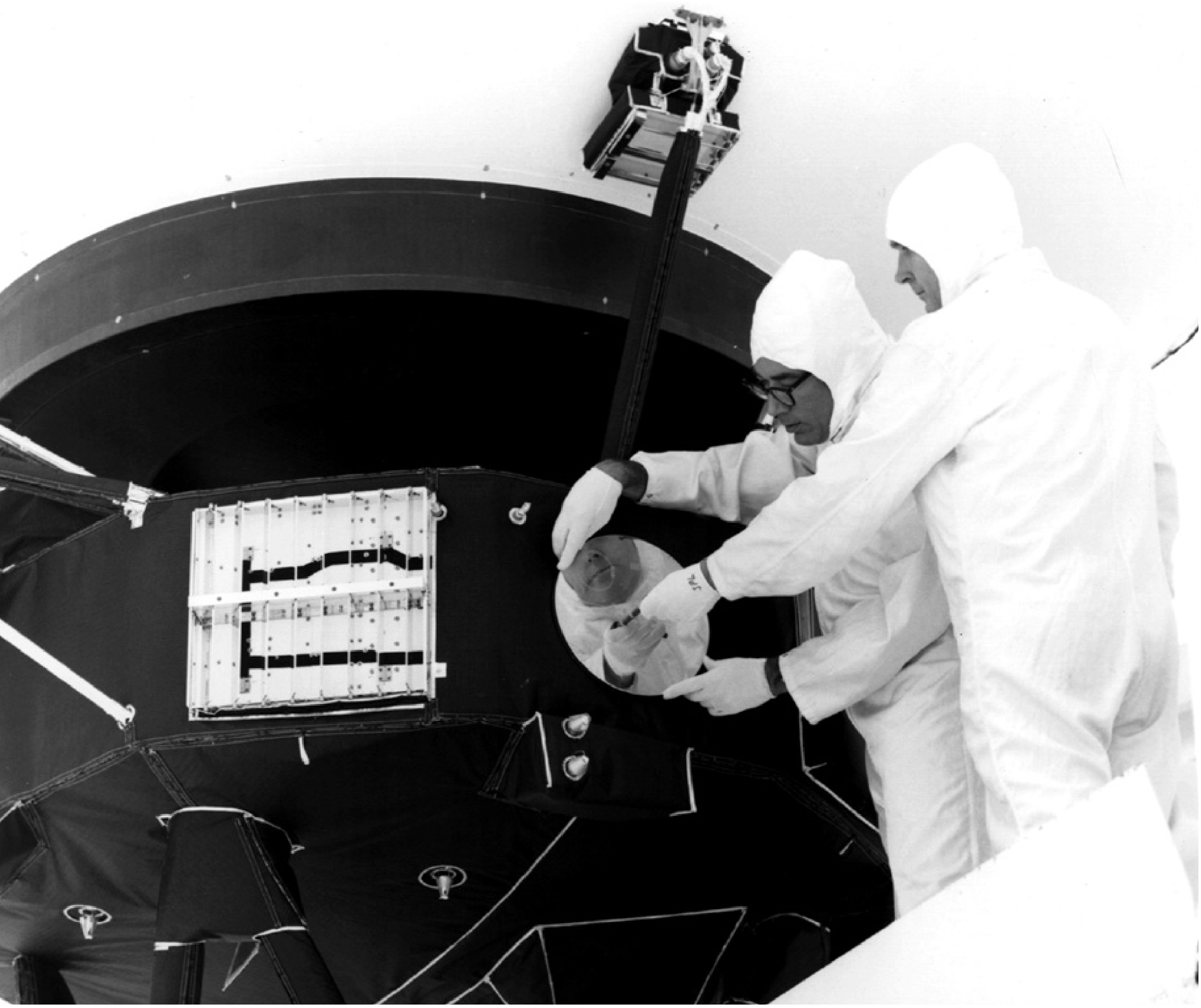
tion, this was new territory. The motto “Failure is not an option” hadn’t yet been coined, and at that time it would not have been apt. In the early 1960s NASA had attempted to send a series of spacecraft to the moon to survey future landing sites for crewed missions. After 12 failures, one such effort finally succeeded.

“In those days we always launched two spacecraft” because the failure rate was so high, said Donald Gurnett, only partly in jest. Gurnett, a physicist at the University of Iowa and one of the original scientists on the Voyager team, was a veteran of 40 other space missions. He spoke with me a few weeks before his death in January. (In an obituary, his daughter Christina said his only regret was that “he would not be around to see the next 10 years of data returning from Voyager.”)

When the Voyagers were being built, only one spacecraft had used a gravity assist to reach another planet—the Mariner 10 probe got one from Venus while en route to Mercury. But the Voyagers would be attempting multiple assists with margins of error measured in tens of minutes. Jupiter, their first stop, was about 10 times farther from Earth than Mercury. Moreover, the Voyagers would have to travel through the asteroid belt along the way. Before Voyager there had been a big debate about whether spacecraft could get through the asteroid belt “without being torn to pieces,” McNutt says. But in the early 1970s Pioneer 10 and 11 flew through it unscathed—the belt turned out to be mostly empty space—paving the way for Voyager, he says.

To handle all these challenges, the Voyagers, each about the size of an old Volkswagen Beetle, needed some onboard intelligence. So NASA’s engineers equipped the vehicles’ computers with 69 kilobytes of memory, less than a hundred thousandth the capacity of a typical smartphone. In fact, the smartphone comparison is not quite right. “The Voyager computers have less memory

NASA/JPL-Caltech



than the key fob that opens your car door," Spilker says. All the data collected by the spacecraft instruments would be stored on eight-track tape recorders and then sent back to Earth by a 23-watt transmitter—about the power level of a refrigerator light bulb. To compensate for the weak transmitter, both Voyagers carry 12-foot-wide dish antennas to send and receive signals.

"It felt then like we were right on top of the technology," says Alan Cummings, a physicist at Caltech and another Voyager OG. "I'll tell you, what was amazing is how quickly that whole thing happened." Within four years the MJS 77 team had built three spacecraft, including one full-scale functioning test model. The spacecraft were rechristened Voyager 1 and 2 a few months before launch.

Although many scientists have worked on the Voyagers over the decades, Cummings can make a unique claim. "I was the last person to touch the spacecraft before they launched," he says. Cummings was responsible for two detectors designed to measure the flux of electrons and other charged particles when the Voyagers encountered the giant planets. Particles would pass through a small "window" in each detector that consisted of aluminum foil just three microns thick. Cummings worried that technicians working on the spacecraft might have accidentally dented or poked holes in the windows. "So they needed to be inspected right before launch," he says. "Indeed, I found that one of them was a little bit loose."

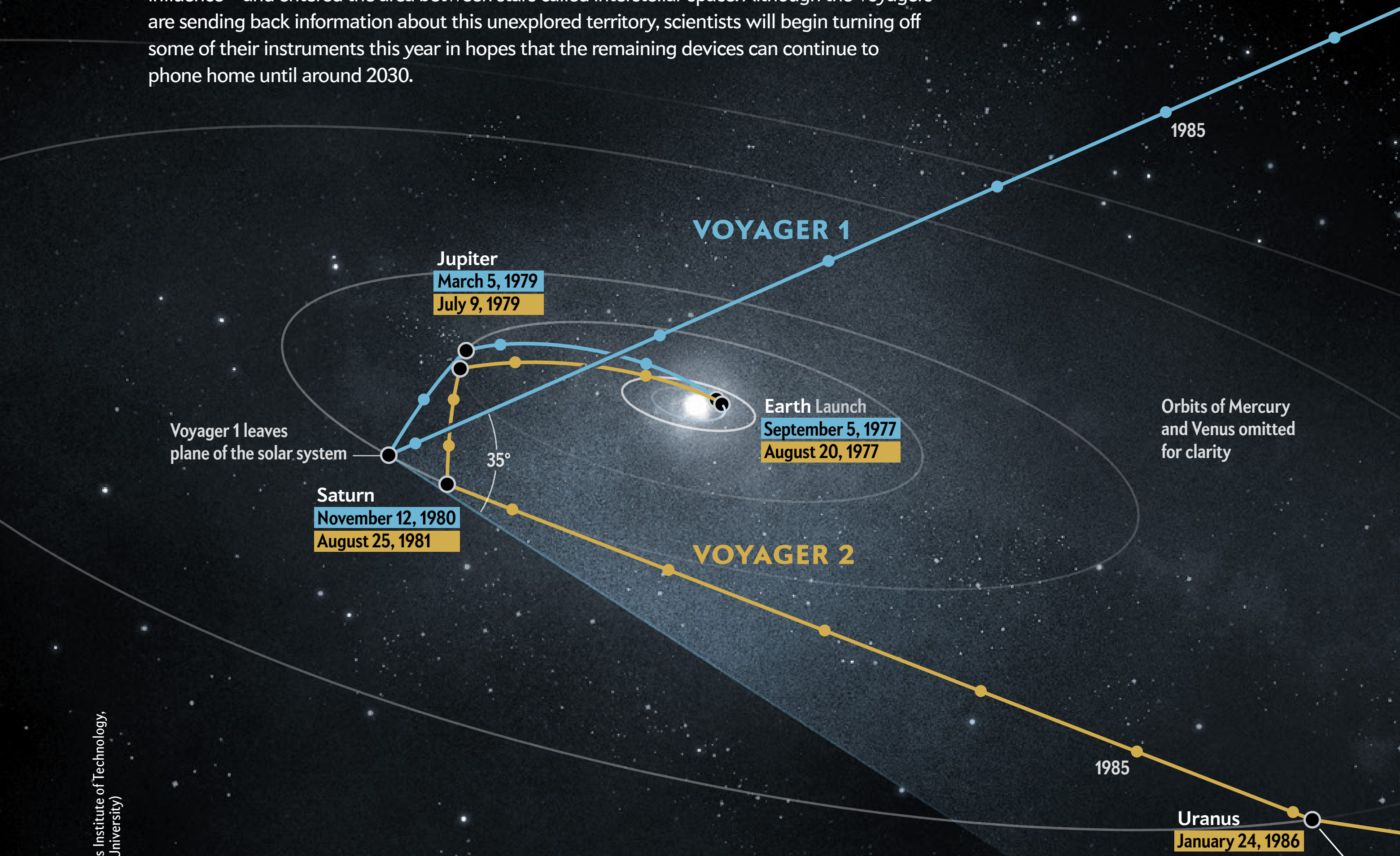
VOYAGER 1 REACHED JUPITER in March 1979, 546 days after its launch. Voyager 2, following a different trajectory, arrived in July of that year. Both spacecraft were designed to be stable platforms for their vidicon cameras, which used red, green and blue filters to produce full-color images. They

GOLDEN RECORD: Each Voyager carries a golden record (*left*) of sounds and images from Earth in case the spacecraft are intercepted by an extraterrestrial civilization. Engineers put the cap on Voyager 1's record before its launch (*right*).

NASA/JPL-Caltech

The Longest Voyage

Forty-five years after their 1977 launch, the twin Voyager 1 and 2 spacecraft are traveling where no Earth-made vehicle has gone before. The mission, originally intended to last just four years and fly by Jupiter and Saturn, is still going. Voyager 2 went on to visit Uranus and Neptune, and both spacecraft eventually exited the heliosphere—the region of the sun's influence—and entered the area between stars called interstellar space. Although the Voyagers are sending back information about this unexplored territory, scientists will begin turning off some of their instruments this year in hopes that the remaining devices can continue to phone home until around 2030.



The Planetary Mission

September 5, 1977
August 20, 1977

LAUNCH

The mission was designed to take advantage of a rare arrangement of the outer planets. Voyager 2 launched first, but reached Jupiter and Saturn after Voyager 1. Shortly after launch, Voyager 1 returned the first photograph of Earth and the moon taken from a spacecraft.

1977–1980
1977–1981

PRIME MISSION

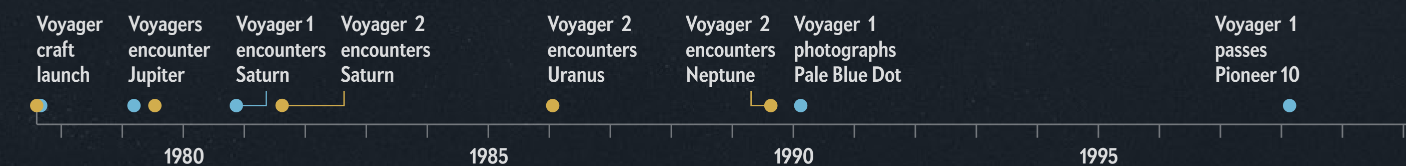
Jupiter and Saturn were planned to be the prime targets of study for both Voyagers. The spacecraft together sent back 52,000 images of Jupiter, Saturn and their moons and discovered 10 new moons.

November 12, 1980

UP AND OUT

After encountering Saturn and its moon Titan, Voyager 1's trajectory was directed northward out of the elliptical plane of the solar system.

VOYAGER'S MILESTONES



Consultants: John Richardson (principal investigator, Voyager Plasma Science, Massachusetts Institute of Technology, Center for Space Research) and Merav Opher (professor, Department of Astronomy, Boston University)

1990

February 14, 1990

THE PALE BLUE DOT

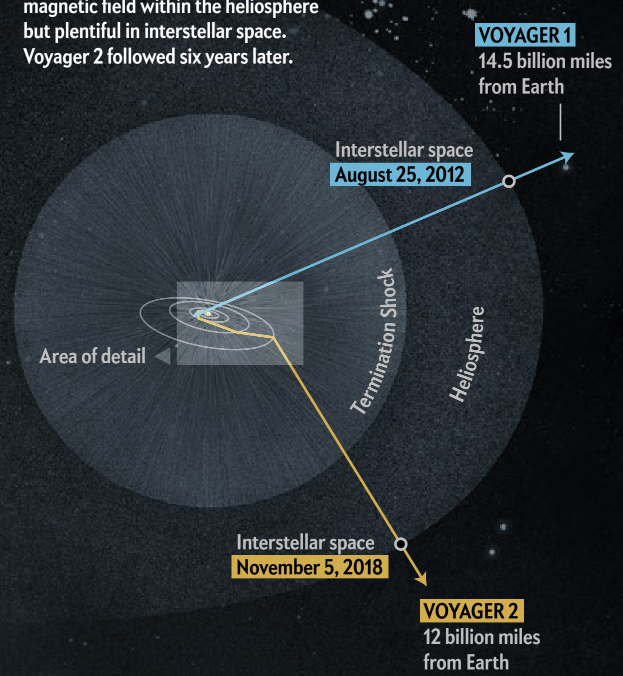
More than nine years after its encounter with Saturn, 3.7 billion miles from Earth, scientists directed Voyager 1 to turn its camera around and take one last photograph, capturing Earth as "a mote of dust, suspended in a sunbeam," in the words of Voyager scientist Carl Sagan.

The Interstellar Mission

August 25, 2012
November 5, 2018

MAKING AN EXIT

Voyager 1 was the first craft to exit the heliosphere, scientists think. This boundary is murky, but its clearest sign came when the vehicle encountered a marked rise in the intensity of cosmic rays, which are blocked by the sun's magnetic field within the heliosphere but plentiful in interstellar space. Voyager 2 followed six years later.



Neptune
August 25, 1989

Voyager 2 leaves plane of the solar system

48°

1990

January 24, 1986

OUTER EDGES

The original plan deemed it too expensive for the spacecraft to travel to Uranus and Neptune, but Voyager 2's trajectory preserved the option. After a successful visit to Saturn, the probe appeared to be capable of making it to Uranus with all instruments operating, so NASA provided additional funding.

TODAY

The Voyager spacecraft are still operating 45 years after launch, sending back data from billions of miles away. Both are now in interstellar space, a region never before visited by human-made probes.

Graphic by Matthew Twombly and Juan Velasco (5W Infographic)

Protective Bubble

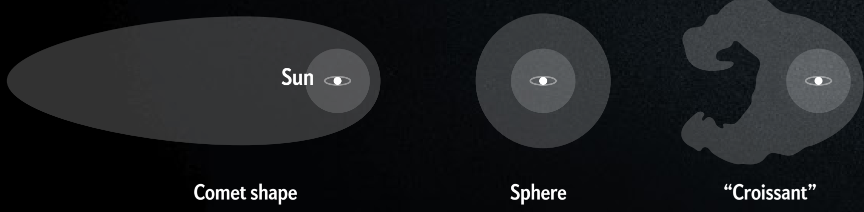
Our part of the solar system is encased in a bubble called the heliosphere, a region where the solar wind of charged particles that flows from the sun carries the sun's magnetic field with it. This area extends to about four times the distance between the sun and Neptune but does not stretch to the full extent of the solar system, which includes the spherical cloud of cometlike objects called the Oort cloud, about halfway to the next star.

BUBBLE SHAPE

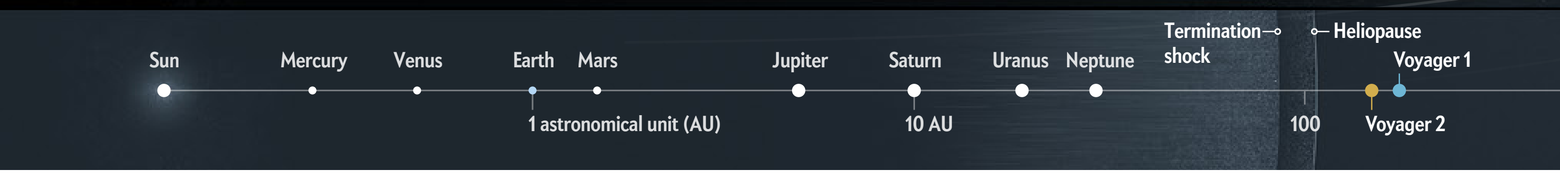
The shape of the heliosphere remains a mystery. Often depicted as a sphere or a cometlike shape with a tail, new research suggests it may be a croissant shape, with a slinkylike magnetic field that funnels the solar wind.

HELIOSPHERE

The solar wind becomes supersonic near the sun. After a point called the termination shock, it slows and follows a shape that is confined by the magnetic fields of the interstellar medium.



ASTRONOMICAL DISTANCES



hardly spin at all as they speed through space—their rotational motion is more than 15 times slower than the crawl of a clock's hour hand, minimizing the risk of blurred images. Standing-room crowds at JPL watched as the spacecraft started transmitting the first pictures of Jupiter while still about three or four months away from the planet.

"In all of the main conference rooms and in the hallways, they had these TV monitors set up," Spilker says. "So as the data came down line by line, each picture would appear on a monitor. The growing anticipation and the expectation of what we were going to see when we got up really, really close—that was tremendously exciting."

Cummings vividly recalls the day he caught his first glimpse of Jupiter's third-largest moon, Io. "I was going over to a building on the Caltech campus where they were showing a livestream [of Voyager's images]," he says. "I walk in, and there's this big picture of Io, and it's all orange and black. I thought, okay, the Caltech students had pulled a prank, and it's a picture of a poorly made pizza."

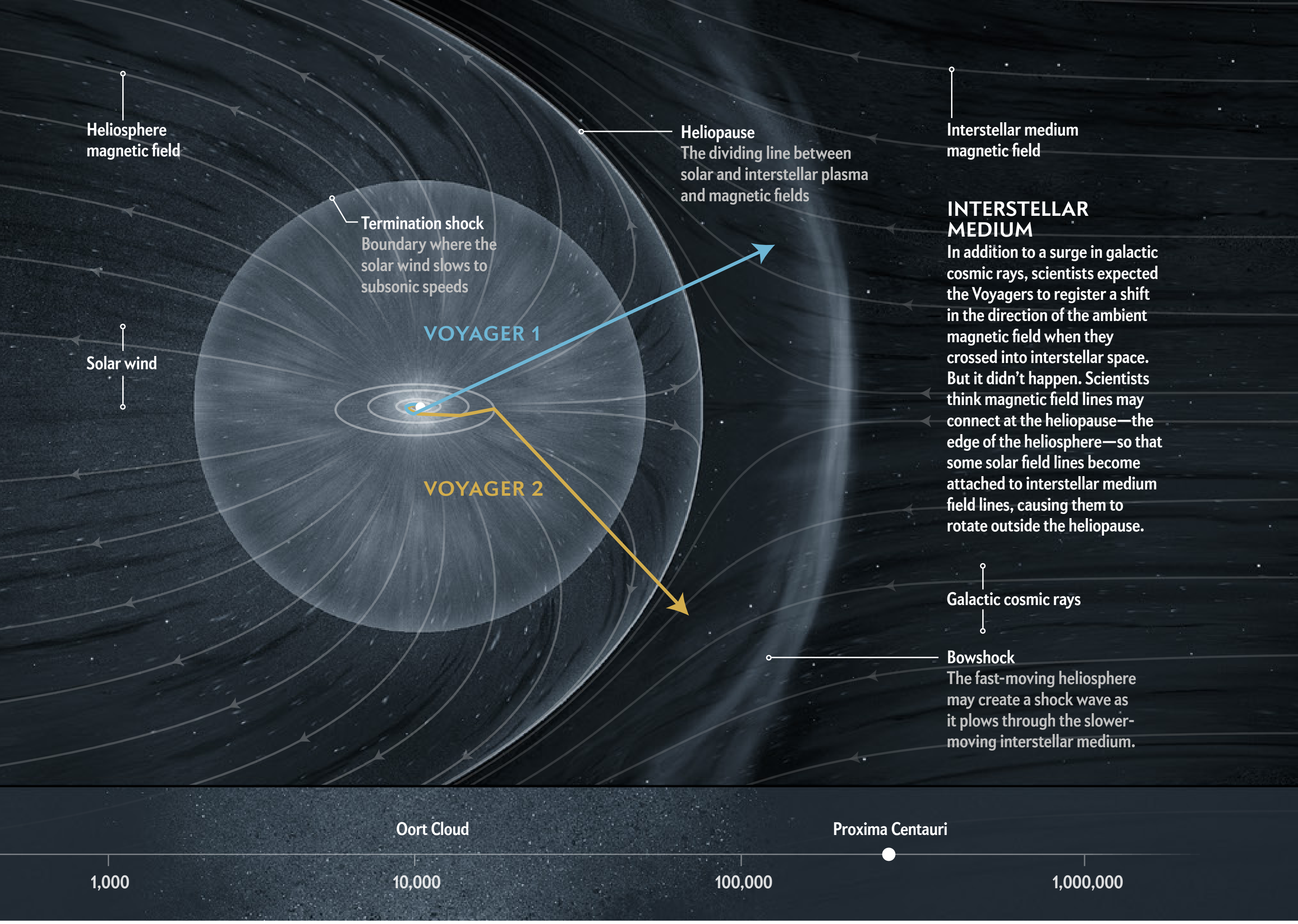
Io's colorful appearance was completely unexpected. Before the Voyagers proved otherwise, the assumption had been that all moons in the solar system would be more or less alike—drab and cratered. No one anticipated the wild diversity of moonscapes the Voyagers would discover around Jupiter and Saturn.

The first hint that there might be more kinds of moons in the heavens than astronomers had dreamed of came while the Voyagers were still about a million miles from Jupiter. One of their instruments—the Low-Energy Charged Particle [LECP] detector system—picked up some unusual signals. "We started seeing oxygen and sulfur ions hitting the detector," says Stamatios Krimigis, who designed the LECP and is now emeritus head of the space department at Johns Hopkins APL. The density of oxygen and sulfur ions had shot up by three orders of magnitude compared with the levels measured up to that point. At first, his team thought the instrument had malfunctioned. "We scrutinized the data," Krimigis says, "but there was nothing wrong."

The Voyagers' cameras soon solved the mystery: Io had active volcanoes. The small world—it is slightly larger than Earth's moon—is now known to be the most volcanically active body in the solar system. "The only active volcanoes we knew of at the time were on Earth," says Edward Stone, who has been the project scientist for the Voyager missions since 1972. "And here suddenly was a moon that had 10 times as much volca-

Consultants: John Richardson (principal investigator, Voyager Plasma Science, Massachusetts Institute of Technology, Center for Space Research) and Merav Opher (professor, Department of Astronomy, Boston University)

Graphic by Matthew Twombly and Juan Velasco (5W Infographic)



nic activity as Earth." Io's colors—and the anomalous ions hitting Krimigis's detector—came from elements blasted from the moon's volcanoes. The largest of Io's volcanoes, known as Pele, has blown out plumes 30 times the height of Mount Everest; debris from Pele covers an area about the size of France.

Altogether, the Voyagers took more than 33,000 photographs of Jupiter and its satellites. It felt like every image brought a new discovery: Jupiter had rings; Europa, one of Jupiter's 53 named moons, was covered with a cracked icy crust now estimated to be more than 60 miles thick. As the spacecraft left the Jupiter system, they got a farewell kick of 35,700 miles per hour from a gravity assist. Without it they would not have been able to overcome the gravitational pull of the sun and reach interstellar space.

At Saturn, the Voyagers parted company. Voyager 1 hurtled through Saturn's rings (taking thousands of hits from dust grains), flew past Titan, a moon shrouded in orange smog, and then headed "north" out of the plane of the planets. Voyager 2 continued alone to Uranus and Neptune. In 1986 Voyager 2 found 10 new moons around Uranus and added the planet to the growing list of ringed worlds. Just four days after Voyager 2's closest approach to Uranus, however, its discoveries were overshadowed when the space shuttle *Challenger* exploded shortly after launch. All seven of *Challenger*'s crew members were killed, including Christa McAuliffe, a high school teacher from New Hampshire who would have been the first civilian to travel into space.

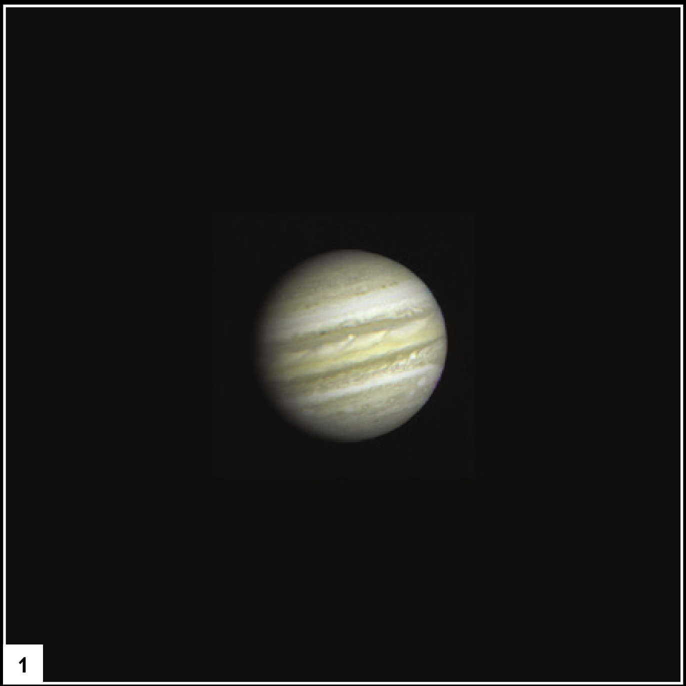
Three years later, passing about 2,980 miles above Neptune's azure methane atmosphere, Voyager 2 measured the highest wind speeds of any planet in the solar system: up to 1,000 mph. Neptune's largest moon, Triton, was found to be one of the coldest places in the solar system, with a surface temperature of −391 degrees Fahrenheit (−235 degrees Celsius). Ice volcanoes on the moon spewed nitrogen gas and powdery particles five miles into its atmosphere.

Voyager 2's images of Neptune and its moons would have been the last taken by either of the spacecraft had it not been for astronomer Carl Sagan, who was a member of the mission's imaging team. With the Grand Tour officially completed, NASA planned to turn off the cameras on both probes. Although the mission had been extended with the hope that the Voyagers would make it to interstellar space—it had been officially renamed the Voyager Interstellar Mission—there would be no photo ops after Neptune, only the endless void and impossibly distant stars.

Voyagers' Greatest Hits

The twin spacecraft took a grand tour through the giant planets of the solar system, passing by Jupiter (*1, 2*) and Saturn (*5, 6*) and taking the first close-up views of those planets' moons.

Jupiter's satellite Europa (*3*), for instance, turned out to be covered with ice, and its moon Io (*4*) was littered with volcanoes—discoveries that came as a surprise to scientists who had assumed the moons would be gray and crater-pocked like Earth's. Voyager 2 went on to fly by Uranus (*7*) and Neptune (*8*), and it is still the only probe to have visited there.



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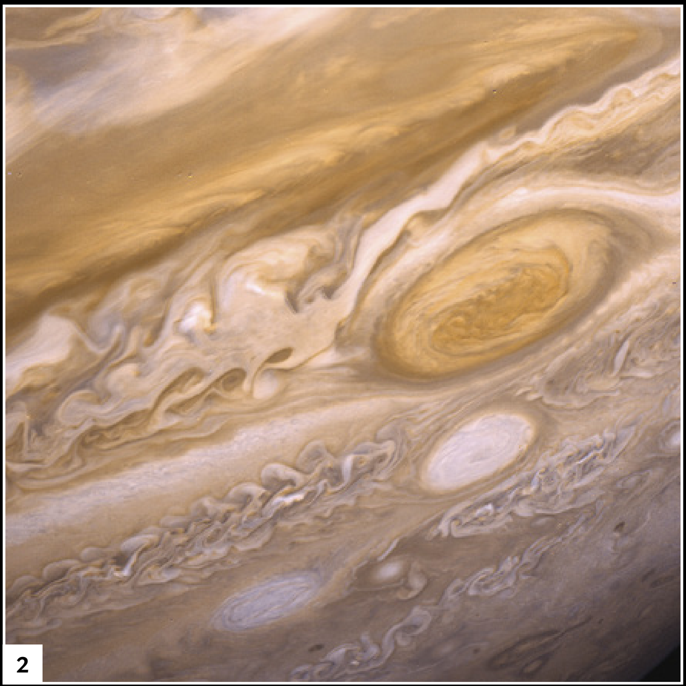

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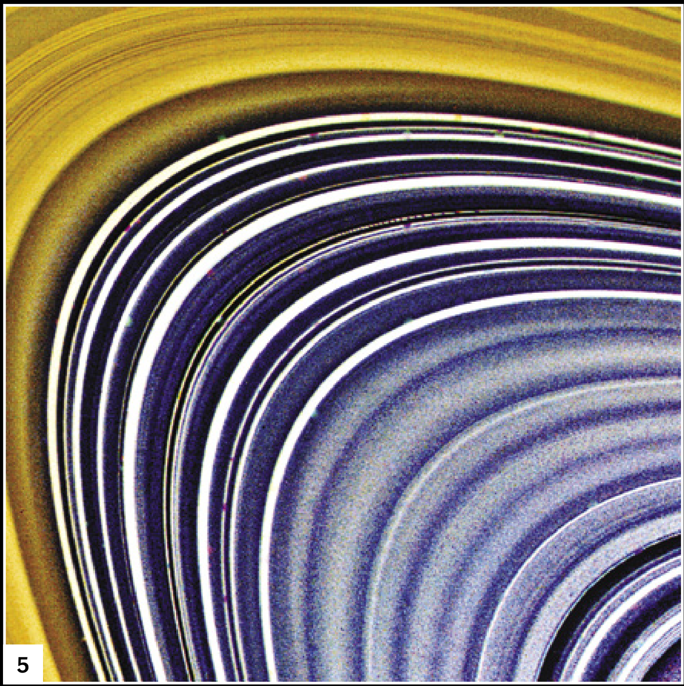

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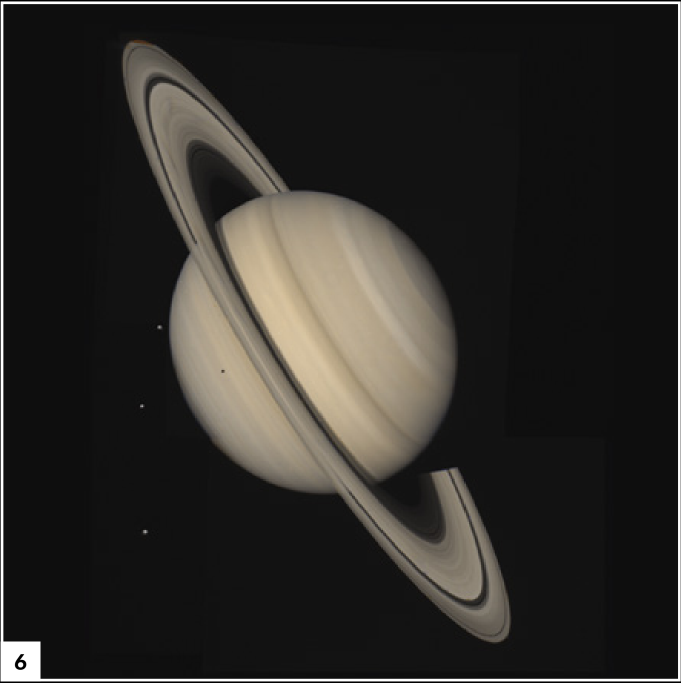

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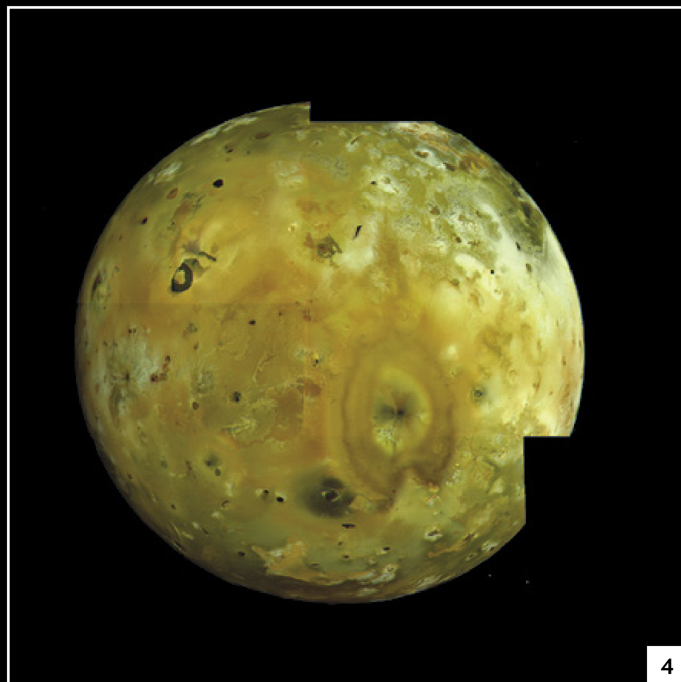
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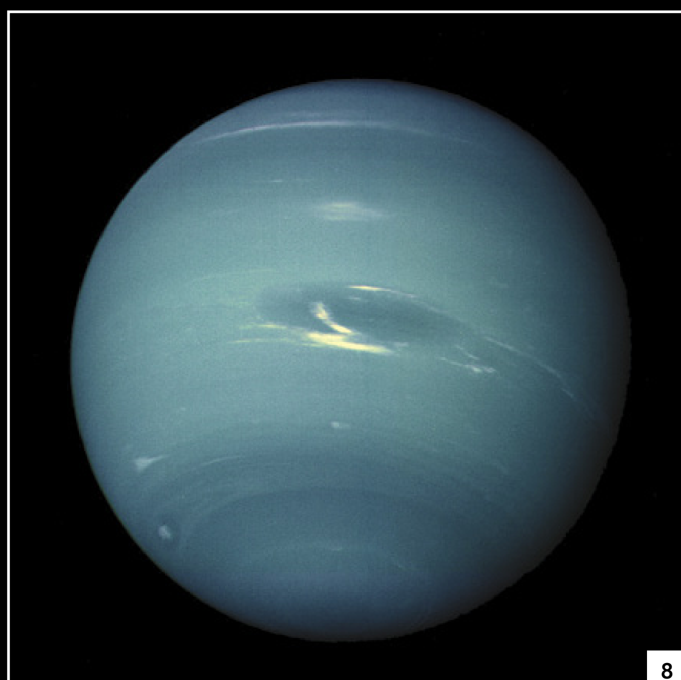
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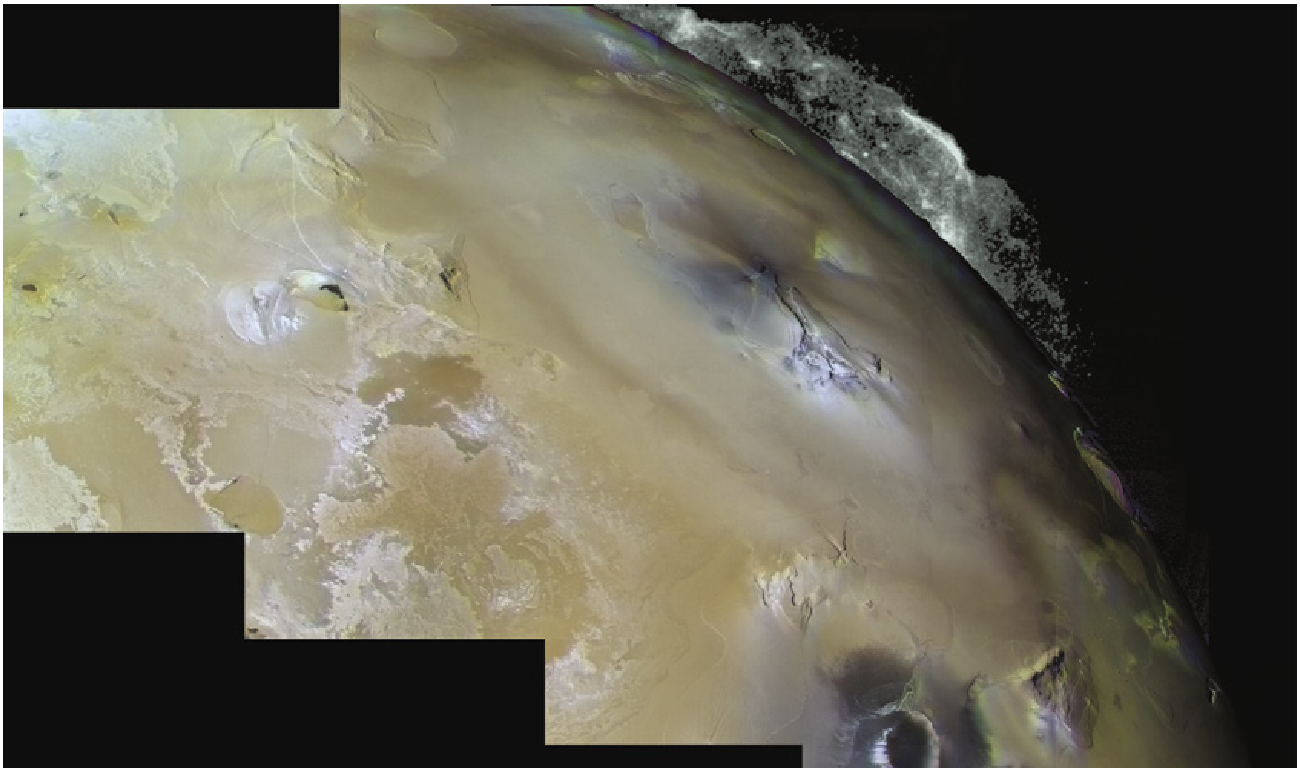

NASA/JPL/USGS

ERUPTION: The discovery of the volcano Pele, shown in this photograph from Voyager 1, confirmed that Jupiter's moon hosts active volcanism.

Sagan urged NASA officials to have Voyager 1 transmit one last series of images. So, on Valentine's Day in 1990, the probe aimed its cameras back toward the inner solar system and took 60 final shots. The most haunting of them all, made famous by Sagan as the "Pale Blue Dot," captured Earth from a distance of 3.8 billion miles. It remains the most distant portrait of our planet ever taken. Veiled by wan sunlight that reflected off the camera's optics, Earth is barely visible in the image. It doesn't occupy even a full pixel.

Sagan, who died in 1996, "worked really hard to convince NASA that it was worth looking back at ourselves," Spilker says, "and seeing just how tiny that pale blue dot was."

BOTH VOYAGERS ARE NOW so far from Earth that a one-way radio signal traveling at the speed of light takes almost 22 hours to reach Voyager 1 and just over 18 to catch up with Voyager 2. Every day they move away by another three to four light-seconds. Their only link to Earth is NASA's Deep Space Network, a trio of tracking complexes spaced around the globe that enables uninterrupted communication with spacecraft as Earth rotates. As the Voyagers recede from us in space and time, their signals are becoming ever fainter. "Earth is a noisy place," says Glen Nagle, outreach and communications manager at the Deep Space Network's facility in Canberra, Australia. "Radios, televisions, cell phones—everything makes noise. And so it gets harder and harder to hear these tiny whispers from the spacecraft."

Faint as they are, those whispers have upended astronomers' expectations of what the Voyagers would find as they entered the interstellar phase of the mission. Stone and other Voyager scientists I spoke with cautioned me not to conflate the boundary of interstellar space with that of the solar system. The solar system includes the distant Oort cloud, a spherical collection of cometlike bodies bound by the sun's gravity that may stretch halfway to the closest star. The Voyagers won't reach its near edge for at least another 300 years. But interstellar space lies much closer at hand. It begins where a phenomenon called the solar wind ends.

Like all stars, the sun emits a constant flow of charged particles and magnetic fields—the solar wind. Moving at hypersonic speeds, the wind blows out from the sun like an inflating balloon, forming what astronomers call the heliosphere. As the solar wind billows into space, it pulls the sun's magnetic field along for the ride. Eventually pressure from interstellar matter checks the heliosphere's expansion, creating a boundary—preceded by an enormous shock front, the "termination shock"—with interstellar space. Before the Voyagers' journeys, estimates of the distance to that boundary with interstellar space, known as the heliopause, varied wildly.

"Frankly, some of them were just guesses," according to Gurnett. One early guesstimate located the heliopause as close as Jupiter. Gurnett's own calculations, made in 1993, set the distance at anywhere from 116 to 177 astronomical units, or AU—about 25 times more distant. (One AU is the distance between Earth and the sun, equal to 93 million miles.) Those numbers, he says, were not very popular with his colleagues. By 1993 Voyager 1 already had 50 AU on its odometer. "If [the heliopause] was at 120 AU, that meant we had another 70 AU to go." If Gurnett was right, the Voyagers, clipping along at about 3.5 AU a year, wouldn't exit the heliosphere for at least another two decades.

That prediction raised troubling questions: would the Voyagers—or the support of Congress—last that long? The mission's funding had been extended on the expectation that the spacecraft would cross the heliopause at about 50 AU. But the spacecraft left that milestone behind without finding any of the anticipated signs of interstellar transit. Astronomers had expected the Voyagers to detect a sudden surge in galactic cosmic rays—high-energy particles sprayed like shrapnel at nearly the speed of light from supernovae and other deep-space cataclysms. The vast magnetic cocoon formed by the heliosphere deflects most low-energy cosmic rays before they can reach the inner solar system. "[It] shields us from at least 75 percent of what's out there," Stone says.

The Voyager ground team was also waiting for the spacecraft to register a shift in the prevailing magnetic field. The interstellar magnetic field, thought to be generated by nearby stars and vast clouds of ionized gases, would presumably have a different orientation from the magnetic field of the heliosphere. But the Voyagers had detected no such change.

Gurnett's 1993 estimates were prescient. Almost 20 years passed before one of the Voyagers finally made it to the heliopause. During that time the mission narrowly survived threats to its funding, and the Voyager team shrank from hundreds of scientists and engineers to a few dozen close-knit lifers. Most of them remain on the job today. "When you have such a long-lived mission, you start to regard people like family," Spilker says. "We had our kids around the same time. We'd take vacations together. We're spanning multiple generations now, and some of the younger people on Voyager were not even born [when the spacecraft] launched."

The tenacity and commitment of that band of brothers and sisters were rewarded on August 25, 2012, when Voyager 1 finally crossed the heliopause. But some of the data it returned were baffling. "We delayed announcing that we had reached interstellar space because we couldn't come to an agreement on the fact," Cummings says. "There was lots of debate for about a year."

Although Voyager 1 had indeed found the expected jump in plasma density—its plasma-wave detector, an instrument designed by Gurnett, inferred an 80-fold increase—there was no sign of a change in the direction of the ambient magnetic field. If the vehicle had crossed from an area permeated by the sun's magnetic field to a region where the magnetic field derived from other stars, shouldn't that switch have been noticeable? "That was a shocker," Cummings says. "And that still bothers me. But a lot of people are coming to grips with it."

When Voyager 2 reached the interstellar shoreline in November 2018, it, too, failed to detect a magnetic field shift. And the spacecraft added yet another puzzle: it encountered the heliopause at 120 AU from Earth—the same distance marked by its twin six years earlier. That did not jibe with any theoretical models, all of which said the heliosphere should expand and contract in sync with the sun's 11-year cycle. During that period the solar wind ebbs and surges. Voyager 2 arrived when the solar wind was peaking, which, if the models were correct, should have pushed the heliopause farther out than 120 AU. "It was unexpected by all the theorists," Krimigis says. "I think the modeling, in terms of the findings of the Voyagers, has been found wanting."

Now that the Voyagers are giving theorists some real field data, their models of the interaction between the heliosphere and the interstellar environment are becoming more complex. "The sort of general picture is that [our sun] emerged from a hot, ionized region" and entered a spotty, partly ionized area in the galaxy, says Gary Zank, an astrophysicist at the University of Alabama in Huntsville. The hot region likely formed in the aftermath of a supernova—some nearby ancient star, or perhaps a few, exploded at the end of its life and heated up the space, stripping electrons off their atoms in the process. The boundary around that region can be thought of as "kind of like the seashore, with all the water and the waves swirling and mixed up. We're in that kind of turbulent region ... magnetic fields get twisted up, turned around. It's not like the smooth magnetic fields that theorists usually like to draw," although the amount of turbulence seen can differ depending on the type of observation. The Voyagers' data show little field variation at large scales but many small-scale fluctuations around the heliopause, caused by the heliosphere's influence on the interstellar medium. At some point, it is thought, the spacecraft will leave those roiling shoals behind and at last encounter the unalloyed interstellar magnetic field.

Or maybe that picture is completely wrong. A few researchers believe that the Voyagers have not yet left the heliosphere. "There is no reason for the magnetic fields in the heliosphere and the interstellar medium to have exactly the same orientation," says Len A. Fisk, a space plasma scientist at the University of Michigan and a former NASA administrator. For the past several years Fisk and George Gloeckler, a colleague at Michigan and a longtime Voyager mission scientist, have been working on a model of the heliosphere that pushes its edge out by another 40 AU.

Most people working in the field, however, have been convinced by the dramatic uptick in galactic cosmic rays and plasma density the Voyagers measured. "Given that," Cummings says, "it's very difficult to argue that we're not really in interstellar space. But then again, it's not like everything fits. That's why we need an interstellar probe."

McNutt has been pushing for such a mission for decades. He and his colleagues at Johns Hopkins recently completed a nearly 500-page report outlining plans for an interstellar probe that would launch in 2036 and potentially could reach the heliosphere within 15 years, shaving 20 years off Voyager 1's flight time. And unlike the Voyager missions, the interstellar probe would be designed specifically to study the outer edge of the heliosphere and its environs. Within the next two years the National Academies of Sciences, Engineering, and Medicine will decide whether the mission should be one of NASA's priorities for the next decade.

An interstellar probe could answer one of the most fundamental questions about the heliosphere. "If I'm looking from the outside, what the devil does this structure look like?" McNutt asks. "We really don't know. It's like trying to understand what a goldfish bowl looks like from the point of view of the goldfish. We [need to] be able to see the bowl from the outside." In some models, as the heliosphere cruises along at 450,000 mph, interstellar matter flows smoothly past it, like water around the bow of a ship, resulting in an overall comet-like shape. One recent computer model, developed by astronomer Merav Opher and her colleagues at Boston University, predicts that more turbulent dynamics give the heliosphere a shape like a cosmic croissant.

"On the whole," Stamatios Krimigis says, "I think the mission lasted so long because almost everything was hardwired. Today's engineers don't know how to do this.… Voyager is the last of its kind."

"You can start multiple fights at any good science conference about that," McNutt says, "but it's going to take getting out there and actually making some measurements to be able to see what's going on. It would be nice to know what the neighborhood looks like."

Some things outlive their purpose—answering machines, VCRs, pennies. Not the Voyagers—they transcended theirs, using 50-year-old technology. "The amount of software on these instruments is slim to none," Krimigis says. "There are no microprocessors—they didn't exist!" The Voyagers' designers could not rely on thousands of lines of code to help operate the spacecraft. "On the whole," Krimigis says, "I think the mission lasted so long because almost everything was hardwired. Today's engineers don't know how to do this. I don't know if it's even possible to build such a simple spacecraft [now]. Voyager is the last of its kind."

It won't be easy to say goodbye to these trailblazing vehicles. "It's hard to see it come to an end," Cummings says. "But we did achieve something really amazing. It could have been that we never got to the heliopause, but we did."

Voyager 2 now has five remaining functioning instruments, and Voyager 1 has four. All are powered by a device that converts heat from the radioactive decay of plutonium into electricity. But with the power output decreasing by about four watts a year, NASA has been forced into triage mode. Two years ago the mission's engineers turned off the heater for the cosmic-ray detector, which had been crucial in determining the heliopause transit. Everyone expected the instrument to die.

"The temperature dropped like 60 or 70 degrees C, well outside any tested operating limits," Spilker says, "and the instrument kept working. It was incredible."

The last two Voyager instruments to turn off will probably be a magnetometer and the plasma science instrument. They are contained in the body of the spacecraft, where they are warmed by heat emitted from computers. The other instruments are suspended on a 43-foot-long fiberglass boom. "And so when you turn the heaters off," Dodd says, "those instruments get very, very cold."

How much longer might the Voyagers last? "If everything goes really well, maybe we can get the missions extended into the 2030s," Spilker says. "It just depends on the power. That's the limiting point."

Even after the Voyagers are completely muted, their journeys will continue. In another 16,700 years, Voyager 1 will pass our nearest neighboring star, Proxima Centauri, followed 3,600 years later by Voyager 2. Then they will continue to circle the galaxy for millions of years. They will still be out there, more or less intact, eons after our sun has collapsed and the heliosphere is no more, not to mention one Pale Blue Dot. At some point in their travels, they may manage to convey a final message. It won't be transmitted by radio, and if it's received, the recipients won't be human.

The message is carried on another kind of vintage technology: two records. Not your standard plastic version, though. These are made of copper, coated with gold and sealed in an aluminum cover. Encoded in the grooves of the Golden Records, as they are called, are images and sounds meant to give some sense of the world the Voyagers came from. There are pictures of children, dolphins, dancers and sunsets; the sounds of crickets, falling rain and a mother kissing her child; and 90 minutes of music, including Bach's Brandenburg Concerto No. 2 and Chuck Berry's "Johnny B. Goode."

And there is a message from Jimmy Carter, who was the U.S. president when the Voyagers were launched. "We cast this message into the cosmos," it reads in part. "We hope someday, having solved the problems we face, to join a community of galactic civilizations. This record represents our hope and our determination, and our good will in a vast and awesome universe." SA

FROM OUR ARCHIVES

Engineering Voyager 2's Encounter with Uranus. Richard P. Laeser, William I. McLaughlin and Donna M. Wolff; November 1986.

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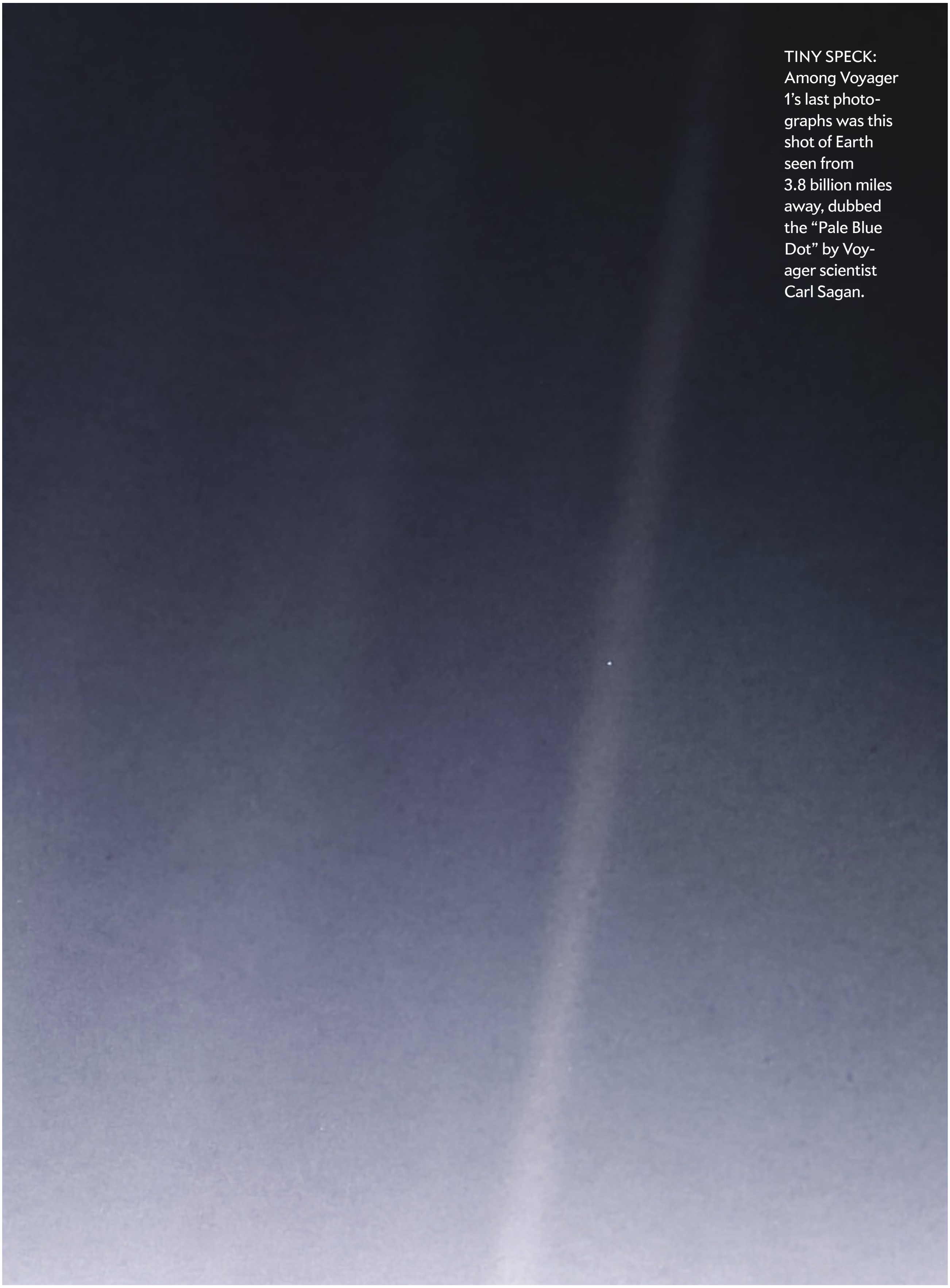

TINY SPECK: Among Voyager 1’s last photographs was this shot of Earth seen from 3.8 billion miles away, dubbed the “Pale Blue Dot” by Voyager scientist Carl Sagan.

NASA/JPL-Caltech

EDUCATION

Climate Miseducation

How oil and gas representatives manipulate the standards for courses and textbooks, from kindergarten to 12th grade

By Katie Worth

Illustrations by Taylor Callery

Katie Worth is a freelance writer in Boston. She is author of *Miseducation: How Climate Change Is Taught in America* (Columbia Global Reports, 2021).

IN A DRAB HEARING ROOM IN AUSTIN, TEX., MEMBERS OF THE STATE BOARD OF EDUCATION, seated at small desks arranged in a broad, socially distanced circle, debated whether eighth grade science students should be required to "describe efforts to mitigate climate change." One board member, a longtime public school science teacher, argued in favor of the proposed new requirement. Another, an in-house attorney for Shell Oil Company, argued to kill it.

The attorney won. In the end, the board voted to require that eighth grade science students "describe the carbon cycle" instead.

Over the past two years school board meetings around the country have erupted into shout fests over face masks, reading lists and whether to ban education about structural racism in classrooms. In Texas, a quieter political agenda played out during the lightly attended process to set science education standards—guidelines for what students should learn in each subject and grade level. For the first time, the state board considered requiring that students learn something about human-caused climate change. That requirement came under tense dispute between industry representatives interested in encouraging positive goodwill about fossil fuels and education advocates who think students should learn the science underlying the climate crisis unfolding around them.

Standards adoptions are an exercise in bureaucracy, but the results wield great power over what is taught in classrooms. Publishers consult them as they write textbooks. State education officials use them as the basis of standardized tests. School districts call on them as they shape curricula. Teachers refer to them as they devise lesson plans. Every state adopts its own standards, but Texas adoptions have long had influence far beyond the state's borders.

In 2020 two major education advocacy groups—the National Center for Science Education and the Texas Freedom Network—hired experts to grade the science standards of all 50 states and Washington, D.C., based on how they covered the climate crisis. Thirty states and D.C. made As or Bs. Texas was one of six states that made an F. But because Texas is one of the largest textbook purchasers in the nation—and because its elected 15-member State Board of Education has a history of applying a conservative political lens to those textbooks—publishers pay close attention to Texas standards as they create materials they then sell to schools across America. As a former science textbook editor once told me, "I never heard anyone explicitly say, 'We can't talk about environmentalism because of Texas.' But we all kind of knew. Everybody kind of knows." In this way, the proceedings in an Austin boardroom influence what millions of children nationwide are taught.

Most Americans favor teaching kids about the climate crisis. A 2019 nationwide poll by NPR/Ipsos found that nearly four in five respondents—including two of three Republicans—thought schoolchildren should be taught about climate change. When the Texas Education Agency surveyed science educators across the state about what should be added to the standards, one in four wrote in asking for climate change or something adjacent, such as alternative energy. No one asked for more content on fossil fuels.

And yet, as I learned when I watched 40 hours of live and archived board hearings, reviewed scores of public records and interviewed 15 people involved in the standard-setting process, members of the fossil-fuel industry participated in each stage of the Texas science standards adoption process, working to influence what children learn in the industry's favor. Texas education officials convened teams of volunteers to rewrite the existing standards, and industry members volunteered for those writing teams and shaped the language around energy and climate. Industry members rallied to testify each time proposals to revise standards got a public hearing. When the board considered the rewritten standards for final approval, the industry appealed to members to advance their favored amendments, ensuring that the seemingly local drama in Austin will have outsized consequences.

For at least a decade the fossil-fuel industry has tried to green its public image. The Texas proceedings show that its actions do not always reflect that image. In little-watched venues, the industry continues to downplay the crisis it has wrought, impeding efforts to provide clear science about that crisis to a young generation whose world will be defined by it.

THE LAST TIME the board overhauled the Texas Essential Knowledge and Skills (TEKS) for Science, in 2009, it was chaired by Don McLeroy, a dentist from east-central Texas. McLeroy made his views on science education clear when he declared at one meeting, "Somebody's got to stand up to experts!" The board spent much of that adoption cycle clashing over evolution, but it also required that high school environmental science students debate something scientists hadn't debated for a long time: whether global warming is happening. McLeroy told a reporter he was pleased because "conservatives like me think the evidence is a bunch of hooey."

At the end of 2019, when it was time to begin another overhaul, McLeroy was gone. The board made it clear to the 85 volunteers recruited by the Texas Education Agency to draft the new standards that it hoped there would not be a fight over evolution again. It soon became clear the group would fight about climate science instead.

To start the process, board members carved the standards into three tranches that they would consider one at a time: first, high school core sciences, then high school elective sciences and finally grades K–8 sciences. The board would give each tranche to writing teams composed of volunteers. Professional content advisers, most nominated by board members, would provide feedback to the board on proposed changes.

Over the summer of 2020 one team took on the first tranche, the high school core subjects: biology, chemistry, physics, and an integrated chemistry and physics class. The core science standards were important for two reasons. The classes had sky-high enrollment; every year nearly half a million students took biology alone. And what happened with these classes would set the tone for the high school electives and for K–8. To the climate education advocates' dismay, when the Texas Education Agency posted the writing groups' results on its Web site in July 2020, the draft standards didn't contain a single reference to modern-day climate change. But there was still a chance to fix that omission. The state board would present the draft standards for public testimony, hearings and amendments.

The first major hearing took place in September 2020, held in person and virtually on Zoom because of the COVID pandemic. More than 30 teachers, parents and other education advocates showed up to testify that the climate crisis has biological, chemical and physical aspects that make it relevant to all the core classes.

After hours of testimony, Robert Unger appeared to represent the Texas Energy Council, and he had some suggestions.

Three and a half hours into that meeting, however, someone with a different message appeared on the Zoom screen: Robert Unger, a silver-haired engineer from Dallas who had worked for the oil and gas industry for more than 45 years. He was representing the Texas Energy Council, and he had some suggestions.

The Texas Energy Council is a coalition of about 35 industry organizations, predominantly from the oil and gas sector, collectively made up of more than 5,000 members. Some months earlier the council had begun recruiting volunteers to participate in the standards adoption process. "The earth sciences and the oil/gas industry in particular have suffered significant degradation in the K–12 curriculum over time," a page on the council's Web site said. In hopes of reversing that trend, the council enlisted 17 people—geoscientists, petroleum engineers, professors, attorneys and other fossil-fuel careerists—who, the site said, "shared its vision of ensuring that oil/gas is portrayed in a balanced fashion as a critical contribution to the Texas, U.S. and worldwide energy mix." Unger had helped organize the volunteers. (Several members of the organization, including Unger, declined to be interviewed for this story. In an e-mail exchange, Michael Cooper, president of the council, took issue with some of this article's findings but said he would be unable to provide a comprehensive response without reviewing a complete draft.)

Unger asked the board to remove a line in the introductory material for each of the high school core classes that discussed social justice and ethics, terms he said "do not belong in the course material." Instead, he said, the standards should include the concept of cost-benefit analysis.

Most board members had expressed little reaction to the many people testifying in favor of climate education, but Unger's testimony got their attention. Longtime Republican member Barbara Cargill, a former biology teacher from north of Houston serving her last few months on the board, asked Unger how cost-benefit analysis might be incorporated into the science TEKS. He gave an example: The main benefit of fossil fuels is the energy they produce, and the costs are "environmental issues that our industry is already regulating." But oil and gas aren't the only fuels with a cost, Unger said. Take solar: "It seems like the benefits are wonderful, but the costs, in fact, are the mining of rare minerals to create batteries," he said. "Wind equally has cost and benefit to it." A science teacher could weigh these things with students, he noted, "and not get into the ambiguities of social injustice and social ethics." Cargill promised to consider Unger's proposal.

All sources of energy come with costs. But a fixation on "cost-benefit analysis" is a plank in a raft of arguments supporting what climate scientist Michael Mann has called "inactivism"—a tactic that doesn't deny human-caused climate change but downplays it, deflects blame for it and seeks to delay action on it. Sure, this brand of thinking goes, fossil fuels have their ills. But what form of energy doesn't? Mann and others have criticized such arguments for their false equivalencies: the environmental and health costs of rare earth minerals for certain renewable energy sources are small compared with those of fossil fuels.

The next day, when the board met to consider amendments to the standards, Cargill delivered. She proposed removing social justice from the standards and adding cost-benefit analysis. Fellow Republican Pat Hardy, a retired history teacher and curriculum developer representing suburbs near Dallas–Fort Worth, eagerly supported the addition. "People talk about electric cars like they're saving the universe," Hardy said, captured on a video of the meeting. "And the answer is no, they are not." The board voted to accept the changes. It was the Texas Energy Council's first major victory.

The climate education advocates did get a win on the final day of the hearings. Marisa Pérez-Díaz, a Democratic board member from San Antonio and the youngest Latina to ever be elected to any state's education board, had heard their pleas. She proposed adding the words "and global climate change" to the end of a standard that asked students to examine a variety of human impacts on the environment. Remarkably, the board approved the motion. It wasn't a big win; the wording applied to just one standard, for the integrated physics and chemistry course, which is taken by a fifth of the students who take biology. But for the advocates it was a hopeful sign—certainly a step up from "a bunch of hooey."

IN THE FOLLOWING MONTHS, AS THE BOARD CONsidered the next two tranches—the high school electives and the K–8 standards—Texas Energy Council volunteers showed up at meeting after meeting. Sometimes they pursued changes that the climate education advocates found reasonable, such as requiring that students learn the laws of geology and encouraging the use of resources such as museums and mentors. But they kept a relentless focus on adding cost-benefit analysis to the standards, and they added new petitions. They insisted on removing the terms "renewable" and "nonrenewable" to describe different energy sources; they preferred to describe all the options as "natural resources." And they frequently brought up energy poverty—the lack of access to affordable electricity. "Energy poverty is one of the gravest but least talked-about dangers facing humanity," testified Jason Isaac, director of an energy initiative for a conservative think tank, at one meeting. He suggested just one solution: "Right here in Texas the key to ending global energy poverty lies under our feet."

The climate education advocates on the board expected to lose some of these battles. But they hoped the Texas Energy Council volunteers would stand down when it came to including clear information about the science of the climate crisis. During the next set of deliberations, it became evident that would not be the case.

In January 2021 the board held the first hearings for high school electives: environmental science, aquatic science, earth science and astronomy. Far fewer students take the electives than take biology, chemistry or physics, but the earth science and environmental science course standards were the only ones that already mentioned climate change.

In the months leading up to the hearings, the 23 people on the electives writing teams had met about every two weeks to draft the new standards. The old standards for the earth science course had asked students to "analyze the empirical relationship between the emissions of carbon dioxide, atmospheric carbon dioxide levels, and the average global temperature trends over the past 150 years," a reference to the period since industrialization, during which atmospheric carbon dioxide levels have soared. That language didn't sit well with William J. Moulton, a longtime geophysicist for the petroleum industry. Encouraged by the Texas Energy Council, he and several other industry representatives had applied to the Texas Education Agency for a seat on a writing group and had been placed. Moulton was on the team rewriting the earth science and astronomy courses.

Moulton agreed that climate change should be mentioned in some way because students would hear about it anyway. But he felt students should not be led to believe the science is settled. He argued that the phrase "the past 150 years" should be removed. The group agreed to that change and to several of Moulton's other language tweaks. When those already diluted standards came before the board in January, four other Texas Energy Council volunteers appeared on Zoom, all recommending amendments. One person said the standards should focus on the dangers of rare earth minerals. Another said it was important for children to learn that the inception of the fossil-fuel industry stopped the practice of whaling for blubber that could be turned into fuel. "Oil and gas literally saved the whales," she said.

The industry also had a new champion on the board: Will Hickman, who had just been elected in November 2020 for a district outside of Houston. Hickman's experience in education included serving on parent groups at his kids' schools, coaching community sports and teaching Sunday school. He'd held the same day job since 2004: senior legal counsel at Shell Oil.

In the January hearing, Hickman's first, his opening question was where in the proposed standards he could find the advantages and disadvantages of various forms of energy. The next day he offered an example that might be raised in class: "Everyone thinks renewable power's a great idea, and Germany adopted it on a large scale," he said. "But the cost-benefit—it ended up raising their power prices to about 2.5 times our power prices."

The writing committees had already included a reference to cost-benefit analysis in the "scientific and engineering practices" section of each of the elective courses, and the standard for the environmental science course had a second mention. But at the next board hearings, in April, Hickman pressed for more. Another member, Rebecca Bell-Metereau, a professor of English and film at Texas State University, who had just been elected to represent Austin, pressed back: "The very phrase 'costs and benefits' places the primary emphasis on money, not on society or well-being or human health." The board nonetheless approved a motion by Hickman to add another mention of costs and benefits, to aquatic sciences.

Moulton began showing up at the board hearings with additional proposed changes. His colleagues on the writing group had accepted some of his suggestions but not all of them, so he wanted the board to consider adding them as amendments. In the final hearing in June, board member Hardy asked Moulton if he'd heard the "newest stuff that's been coming out on climate," which, she said, was that the climate crisis was not unfolding as scientists had predicted. Moulton suggested that the consensus about warming had been exaggerated by scientists in pursuit of grant money.

Hardy began proposing amendments word for word from Moulton's suggestions. This elicited an outcry from Bell-Metereau. "Do you not think that if someone's area of work is in fossil fuels that they might have some bias on this issue?" she asked Hardy. "It might be that *I* have a bias for the fossil-fuel industry," Hardy answered.

Bell-Metereau and others on the board threatened to delay the entire adoption if Hardy insisted on moving the changes forward. Ultimately Hardy dropped the proposals. But Moulton and the council had already succeeded in important ways: The new electives standards had multiple references to cost-benefit analysis. The terms "renewable energy" and "nonrenewable energy" were removed in several places. The single mention of the effects of burning fossil fuels in the old standards was gone, and the strongest description of climate change had been weakened.

THE CLIMATE EDUCATION ADVOCATES had failed to install a robust presentation of the science surrounding the climate crisis in any of the high school core or elective classes, as they had watched the Texas Energy Council volunteers achieve one goal after another. But they held out hope for the K–8 standards. Nearly every middle schooler takes the same sciences, and the classes cover weather and climate systems, an obvious and effective place to discuss the crisis for a generation of students that would have to live with its consequences.

"Inactivism" doesn't deny human-caused climate change but downplays it, deflects blame for it and seeks to delay action on it.

On a 96-degree day at the end of August 2021, the board held a public hearing on the K–8 standards, in person and virtually. The writing groups had labored over the drafts, adding a single passage mentioning climate change. Eighth grade science students, the draft declared, would be expected to "use scientific evidence to describe how human activities can influence climate, such as the release of greenhouse gases." One writing group, which included the executive director of a natural gas foundation, had also appended a note stating it had not been able to reach consensus on a proposal to add another line: "Research and describe the costs and benefits of reducing greenhouse gas emissions versus global energy poverty."

At the hearing, two of the professional content advisers who had reviewed the standards gave the board radically different opinions. Ron Wetherington, a retired anthropology professor from Southern Methodist University nominated by Pérez-Díaz, argued that the climate standards needed significant strengthening. Among other things, he advocated that the word "can" be dropped from the phrase "describe how human activities can influence climate." "Can" implies that something is a possibility, but an abundance of evidence shows that the influence is already taking place. He also asked the board to add an expectation that students explore efforts to mitigate the crisis. Because students would learn that it's happening, he posited, they should learn what people are doing to fix it.

Gloria Chatelain, a longtime educator and CEO of her own consulting firm called Simple Science Solutions, who had been nominated by Hardy and Cargill, stood in absolute opposition. She began her testimony by praising the "absolutely amazing job" the Texas Energy Council had already done in improving the

standards. She also said human-caused climate change should be treated very lightly in middle school, if at all. “Our goal is not to produce angry children but children who love science. We’re challenging them to go solve some of these exciting problems but not turn them into Gretas,” she said, referring to the teenage climate activist Greta Thunberg of Sweden. Instead, she contended, the board should add an expectation that students “research and describe the role of energy in improving the quality of life in reducing malnutrition and global poverty,” language the council had suggested. “I think it needs to go in, guys. It’s very, very important that we address it,” Chatelain said.

For three days that week the board considered the K–8 language. Over the protests of Democrats, Hardy moved to add “cost-effectiveness” to each middle school class. She and Hickman persuaded the conservative board majority to change multiple references to renewable and nonrenewable energy to “natural resources” in the elementary standards.

On the second day climate education advocates landed two unexpected victories. Pérez-Díaz proposed rewording the climate standard to “describe how human activities over the past 150 years, including the release of greenhouse gases, influence climate.” Then she proposed adding a separate line: “Describe efforts to mitigate climate change, including a reduction in greenhouse gas emissions.” The amendments both carried. But on the third day the board axed the reference to the past 150 years and added the word “can” back in. The details of recent climate change, Hardy argued, would simply be too hard for eighth graders to grasp.

Aicha Davis, a board member from Dallas who spent 11 years teaching science before pursuing her Ph.D. in education leadership and policy, spoke up. “With all respect to my colleague, you’ve never taught eighth grade science,” she said, her voice tinged with forbearance. “We absolutely can’t let the oil and gas industry dictate what our kids need to learn when it comes to science. It shouldn’t be about the Texas Energy Council. It should be about what’s best for our students.” Neither scientists nor educators had voiced concern about teaching climate change to eighth graders, she noted. “So let’s call this what it is. At this point we’re only making votes based on what oil and gas wants us to do.”

Hickman, the Shell attorney, turned on his micro-phone. "A few thoughts and reactions," he said. "One is I think our permanent school fund is generally funded by oil and gas," referring to a major source of education funding maintained in part by proceeds from fossil fuels reaped from public lands. "All of us are probably going to get home using oil and gas.... If all of this is true—greenhouse gases are evil—what do we do? Do we ban gasoline and stop using gasoline-powered cars? Do we ban diesel for trucks? How do we get our Amazon and Walmart purchases?" The board chair suggested they table the issue until the final round of hearings, scheduled for November 2021.

As they waited for the last round, the National Center for Science Education and the Texas Freedom Network organized. They recruited 67 Texan climate scientists to join a letter asking, among other things, that the word "can" be dropped from the climate passage and that the mitigation language stay put not only because it consisted of "basic knowledge" that every citizen should have but because it would provide students with a sense of hope.

Nevertheless, the final round of deliberations in November was a slaughter. Climate change had been added in a limited way to the standards, and the conservative majority supported that. But it rejected a motion to strike the word "can." It blocked a motion to remove cost-benefit analysis from the middle school sciences. It approved new language about "the critical role of energy resources" to modern life. It inserted a reference to rare earth elements. It introduced the concept of global energy poverty.

Last, Hickman moved to drop the climate mitigation standard that Pérez-Díaz had managed to add in September, arguing that the subject was more appropriate for social studies than for science and that it "just seems above and beyond for an eighth grade student and teacher." The board Democrats fought the change, but they were outnumbered. The board replaced the mitigation standard with the line "Describe the carbon cycle."

The Texas Energy Council and two allied organizations issued a press release praising the State Board of Education for adopting standards that "emphasize the critical role of energy in modern life." The Texas Freedom Network hit a more ambivalent note in its year-end report. "The State Board of Education could have—and should have—done much better. But our campaign resulted in new science standards that for the first time make clear to Texas public school students that climate change is real and that human activity is the cause."

The fossil-fuel industry, like some others, has worked for decades to get its messages in front of schoolchildren. I have found examples across the U.S. Petroleum companies regularly fund teacher trainings incentivized by free classroom supplies. Industry organizations have spent millions of dollars producing and distributing energy lesson plans. I witnessed an oil and gas industry employee give a PowerPoint presentation radically downplaying the climate crisis to a class of seventh graders.

Even with abundant online educational materials, just 9 percent of high school science teachers say they never use a textbook. The nation's most popular middle school science textbooks are replete with language that conveys doubt about climate change, subtly or otherwise. In one textbook that, as of 2018, was in a quarter of the nation's middle schools, students read that "some scientists propose that global warming is due to natural climate cycles." In fact, the number of climate scientists who support that idea is effectively zero.

"Let's call this what it is," Aicha Davis said. "At this point we're only making votes based on what oil and gas wants us to do."

Texas isn't the only major buyer of textbooks. Other large states such as California have adopted standards that embrace the science of climate change, leading to a divide. Textbook publishers create one set of products to sell in Texas and states that lean the same way and a second set of products for states aligned with California. This poses an equity problem: the education a child receives on an issue central to the modern world depends on what state they happen to live in.

In April 2022 the Texas Education Agency issued a call for textbooks based on the new standards. Publishers have a year to submit materials to the agency. Review panels, made up of educators, will search the textbooks for errors and rate how closely they follow the standards. Then the materials go before the state board for approval or rejection. Texas school districts have the option of establishing their own textbook adoption process but still must choose books that comply with the standards. Most just defer to the board's choices. The new science textbooks should be on classroom shelves starting in the fall of 2024.

The Texas Energy Council's Moulton told me he found the standards adoption process energizing, and he hopes to stay involved. As soon as he gets the chance, he said, he'll start reviewing the new textbooks and will head back to the board to give them his thoughts. SA

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scientificamerican.com/magazine/sa

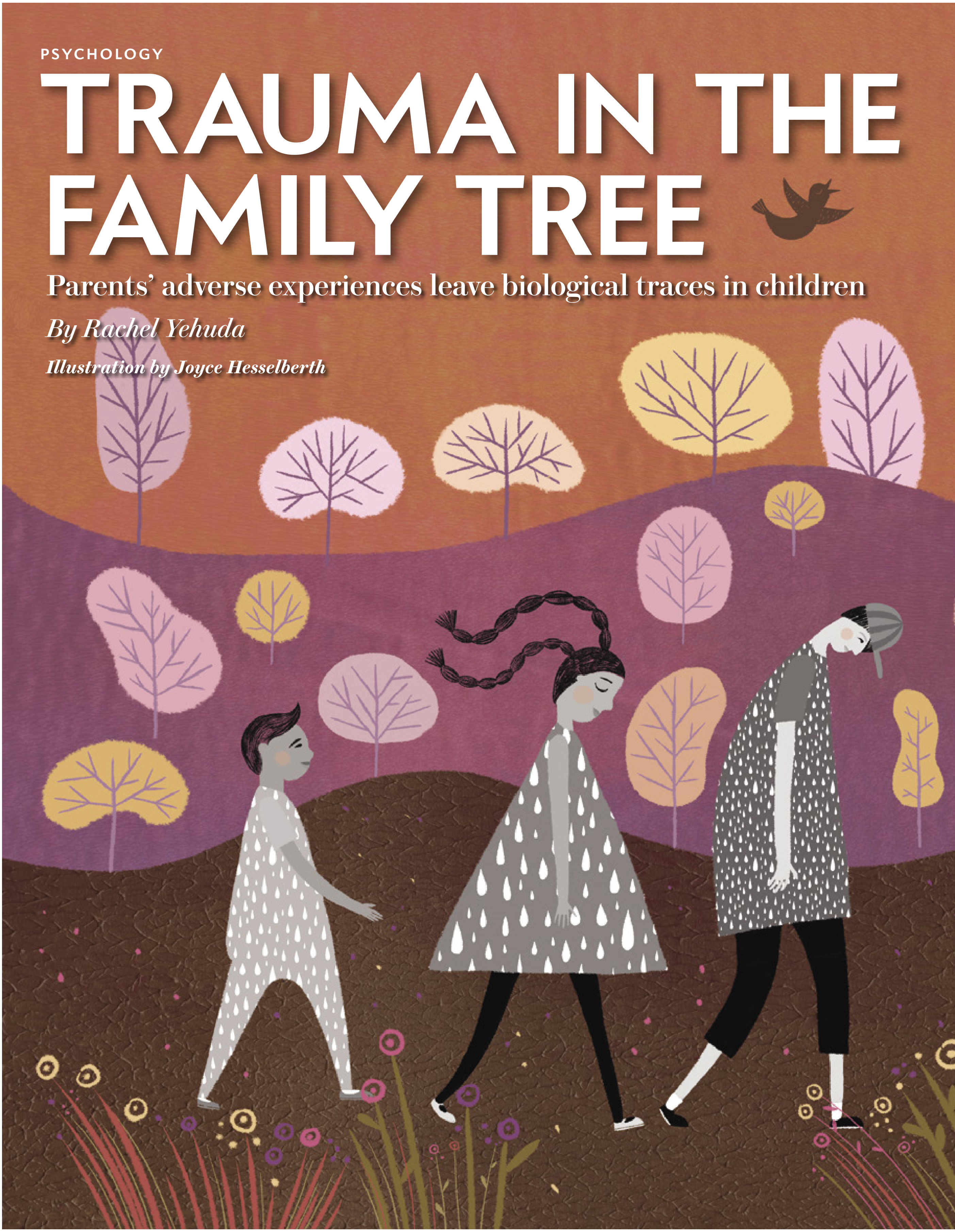
PSYCHOLOGY

TRAUMA IN THE FAMILY TREE

Parents' adverse experiences leave biological traces in children

By Rachel Yehuda

Illustration by Joyce Hesselberth



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AFTER THE TWIN TOWERS OF THE WORLD TRADE CENTER COLLAPSED on September 11, 2001, in a haze of horror and smoke, clinicians at the Icahn School of Medicine at Mount Sinai in Manhattan offered to check anyone who'd been in the area for exposure to toxins. Among those who came in for evaluation were 187 pregnant women. Many were in shock, and a colleague asked if I could help diagnose and monitor them. They were at risk of developing post-traumatic stress disorder, or PTSD—experiencing flashbacks, nightmares, emotional numbness or other psychiatric symptoms for years afterward. And were the fetuses at risk?

My trauma research team quickly trained health professionals to evaluate and, if needed, treat the women. We monitored them through their pregnancies and beyond. When the babies were born, they were smaller than usual—the first sign that the trauma of the World Trade Center attack had reached the womb. Nine months later we examined 38 women and their infants when they came in for a wellness visit. Psychological evaluations revealed that many of the mothers had developed PTSD. And those with PTSD had unusually low levels of the stress-related hormone cortisol, a feature that researchers were coming to associate with the disorder.

Surprisingly and disturbingly, the saliva of the nine-month-old babies of the women with PTSD also showed low cortisol. The effect was most prominent in babies whose mothers had been in their third trimester on that fateful day. Just a year earlier a team I led had reported low cortisol levels in adult children of Holocaust survivors, but we'd assumed that it had something to do with being raised by parents who were suffering from the long-term emotional consequences of severe trauma. Now it looked like trauma leaves a trace in offspring even before they are born.

In the decades since, research by my group and others has confirmed that adverse experiences may influence the next generation through multiple pathways. The most apparent route runs through parental behavior, but influences during gestation and even changes in eggs and sperm may also play a role. And all these channels seem to involve epigenetics: alterations in the way that genes function. Epigenetics potentially explains why effects of trauma may endure long after the immediate threat is gone, and it is also implicated in the diverse pathways by which trauma is transmitted to future generations.

The implications of these findings may seem dire, suggesting that parental trauma predisposes offspring to be vulnerable to mental health conditions. But there is some evidence that the epigenetic response may serve as an adaptation that might help the children of traumatized parents cope with similar adversities. Or could both possible outcomes be true?

IN THE AFTERMATH

MY FIRST ENCOUNTER with intergenerational transmission of trauma was in the 1990s, soon after my team documented high rates of PTSD among Holocaust survivors in my childhood community in Cleveland. The first study of its kind, it garnered a lot of publicity; within weeks I found myself heading a newly created Holocaust research center at Mount Sinai staffed largely by professional volunteers. The phone was ringing off the hook. The callers weren't all Holocaust survivors, though; most were the adult children of Holocaust survivors. One particularly persistent caller—I'll call him Joseph—insisted that I study people like him. "I'm a casualty of the Holocaust," he claimed.

When he came in for an interview, Joseph didn't look like a casualty of anything. A handsome and wealthy investment banker in an Armani suit, he could've stepped off the pages of a magazine. But Joseph lived each day with a vague sense that something terrible was going to happen and that he might need to flee or fight for his life. He'd been preparing for the worst since his early 20s, keeping cash and jewelry at hand and becoming proficient in boxing and martial arts. Lately he was tormented by panic attacks and nightmares of persecution, possibly triggered by reports of ethnic cleansing in Bosnia.

Joseph's parents had met in a displaced-persons camp after surviving several years at Auschwitz, then arrived penniless in the U.S. His father worked 14 hours a day and said very little, never mentioning the war. But almost every night he woke the family with shrieks of terror from his nightmares. His mother spoke endlessly about the war, telling vivid bedtime stories about how relatives had been murdered before her eyes. She was determined that her son succeed, and his decision to remain unattached and childless infuriated her. "I didn't survive Auschwitz so that my own child would end the family line," she'd say. "You have an obligation to me and to history."

We ended up talking to many people like Joseph: adult children of Holocaust survivors who suffered from anxiety, grief, guilt, dysfunctional relationships and intrusions of Holocaust-related imagery. Joseph was right—I needed to study people like him. Because those who were calling us were (in research-speak) self-selecting, we decided to evaluate the offspring of the Holocaust survivors we had just studied in Cleveland. The results were clear. Survivors' adult children were more likely than others to have mood and anxiety disorders, as well as PTSD. Further, many Holocaust offspring also had low cortisol levels—something that we had observed in their parents with PTSD.

FIGHT, FLIGHT—OR FREEZE

WHAT DID IT ALL MEAN? Unraveling the tangle of trauma, cortisol and PTSD has occupied me and many other researchers for the decades since. In the classic fight-or-flight response, identified in the 1920s, a threatening encounter triggers the release of stress hormones such as adrenaline and cortisol. The hormones prompt a cascade of changes, such as quickening the pulse and sharpening the senses to enable the threatened person or animal to focus on and react to the immediate danger. These acute effects were believed to dissipate once the danger receded.

In 1980, however, psychiatrists and other advocates for Vietnam War veterans won a prolonged struggle to get post-traumatic stress included in the third edition of the *Diagnostic and Statistical Manual of Mental Disorders* (*DSM-III*). It was the first official recognition that trauma could have long-lasting effects. But the diagnosis was controversial. Many psychologists believed that its inclusion in the *DSM-III* had been politically, rather than scientifically, driven—in part because there were no scientific explanations for how a threat could continue to influence the body long after it was removed.

Complicating matters, studies of Vietnam veterans were generating perplexing results. In the mid-1980s neuroscientists John Mason, Earl Giller and Thomas Kosten of Yale University reported that veterans with PTSD had high levels of adrenaline but lower levels of cortisol than patients with other psychiatric diagnoses. Because stress usually causes stress hormones, including cortisol, to rise, many researchers, including myself, were skeptical of these observations. When I joined the Yale laboratory as a postdoctoral fellow a year later, I studied a different group of veterans using other methods for measuring cortisol. To my astonishment, I replicated the finding.

I still couldn't believe that the low cortisol levels had anything to do with trauma. Surely the Holocaust was as terrible as the Vietnam War, I reasoned—and growing up as a rabbi's daughter in a community full of Holocaust survivors, many of them my friends' parents, I'd noticed nothing out of the ordinary about them. I was sure that they didn't have either PTSD or low cortisol, I told my mentor, Giller. "That's a testable hypothesis," he responded. "Why don't you study that, instead of conjecturing?"

So my team of five people landed in Cleveland, along with a centrifuge and other equipment. We stayed in my parents' home, walking door to door to interview people by day and returning to test blood and urine samples in the evening. When the results came in, they were clear: half the Holocaust survivors had PTSD, and those with PTSD had low cortisol. There was no question about it—even if the traumatic experience was long ago, PTSD went hand in hand with low cortisol.

A shape was emerging that connected childhood adversity with low cortisol and the possibility of future PTSD.

But why? And which came first? An important clue came from a 1984 review by Allan Munck and other researchers at the Geisel School of Medicine at Dartmouth. They noted that among stress hormones, cortisol played a special, regulatory role. High levels of stress hormones, if sustained for a long time, harm the body in multiple ways—weakening the immune system and increasing susceptibility to problems such as hypertension. But in a context of acute trauma, cortisol may paradoxically also have a protective effect. It shuts down the release of stress hormones—including itself—reducing the potential damage to organs and the brain. Such a trauma-induced feedback loop could conceivably reset the cortisol "thermostat" to a lower level.

I picked up another piece of the puzzle and placed it. In the early 1990s we'd shown that Vietnam veterans were more likely to develop PTSD if they'd been abused as children. Slowly a shape was emerging that connected intense childhood adversity—a period of "freeze" because a child usually cannot fight or flee—with low cortisol and the possibility of future PTSD. We studied people who'd been raped or who'd been in auto accidents when they came into emergency rooms, finding that those with lower cortisol levels were more likely to develop PTSD after the attack or accident.

Could low cortisol levels have been present before the event that brought them into the emergency room? I wondered. If someone with low cortisol was subjected to a traumatic experience, we reasoned, the cortisol levels in their bodies might be too low to tamp down the stress reaction. Adrenaline levels might then shoot way up, searing the memory of the new trauma into the brain—from where it might later surface as flashbacks or nightmares. Perhaps low cortisol marked a vulnerability to developing PTSD.

The study of Holocaust offspring supported this conjecture. Children of Holocaust survivors with PTSD tended to have low cortisol even if they did not have their own PTSD. As we'd suspected, low cortisol seemed related to vulnerability to PTSD.

THE FEEDBACK LOOP

BUT WHAT MECHANISM connected trauma exposure to low cortisol to future PTSD? We began a series of studies to answer this question. Significantly, we found that Vietnam veterans with PTSD had a greater number of glucocorticoid receptors. These are proteins to which cortisol binds to exert its diverse influences. That suggested a greater sensitivity to cortisol: a small increase in the hormone's concentration would precipitate a disproportionate physiological reaction. But it wasn't until we looked more closely at the molecular underpinnings of cortisol functioning—in part by examining epigenetics—that we understood how exposure to trauma might reset the cortisol feedback loop.

In the 1990s scientists were realizing that the output of our genes is sensitive to factors not written directly into our genetic code. Genes provide the templates for producing proteins. But much like cakes baked using the same ingredients may turn out differently depending on variations in the oven's temperature, how much of those proteins gets produced, or "expressed," depends on the environment. The discovery gave rise to epigenetics, the study of what influences gene expression and how. It proved crucial to understanding both the neurobiology of PTSD and the intergenerational effects of trauma.

Epigeneticists explore the switches that turn gene expression on and off. One such mechanism, called methylation, involves a methyl group—a methane molecule that is missing one of its four hydrogen atoms, leaving a chemical bond free to attach to another atom or molecule. Methylation is a process by which, in the presence of specific enzymes, methyl groups attach to key sites on a strand of DNA or within the complex of DNA and proteins known as chromatin. By occupying these sites like roadblocks on a highway, methyl groups can alter transcription, a basic step in gene expression where a piece of RNA is made from a DNA template. Increased methylation generally impedes RNA transcription, whereas less methylation enhances transcription. These changes are enduring in that they survive normal cell division and require specific enzymes for their removal.

In 2015 our group became one of the first to pinpoint epigenetic changes on stress-related genes of veterans with PTSD. These alterations partially explained why trauma's effects were so persistent, lasting for decades. Specifically we observed reduced methylation in an important region of *NR3C1,* a gene that encodes the glucocorticoid receptor, likely increasing the sensitivity of these receptors.

This epigenetic modification suggests a potential explanation for how trauma might reset cortisol levels. The body regulates the stress response through a complicated feedback mechanism. A rise in cortisol levels will prompt the body to produce less of the hormone, which may drive up the numbers and responsiveness of glucocorticoid receptors. Given the epigenetic and other changes occurring with sustained responses to trauma, the feedback loop might become recalibrated. In people who have already endured trauma, their stress systems might be sensitized and their cortisol levels diminished—increasing their adrenaline response to further trauma and leading to PTSD.

EPIGENETIC INHERITANCE

COULD SOME OF THESE epigenetic changes in trauma survivors also be found in the children of trauma survivors? Finding low cortisol in the 9/11 babies back in 2002 had told us that we'd been thinking about some things all wrong. We'd assumed all along that trauma was behaviorally transmitted: Joseph's problems seemed to result from the stressful, bereaved atmosphere in his childhood home. But now it looked like the uterine environment also played a role. So did the sex of the traumatized parent.

In our early studies of Holocaust offspring, we had selected only those people with two parents who were Holocaust survivors. We redid the studies to figure out if the sex of the parent mattered—and it did. Those whose mother (or both parents) had PTSD tended to exhibit lower cortisol levels and showed evidence of more sensitive glucocorticoid receptors. In contrast, those whose fathers, but not mothers, had PTSD showed the opposite effect.

Taking a closer look, we again discovered lower methylation within the glucocorticoid receptor gene, *NR3C1,* in Holocaust offspring whose mothers, or both parents, had PTSD. These changes mirrored what we'd observed in the maternal survivors themselves. But in offspring with only paternal PTSD, we observed more methylation—the opposite effect. These findings raised the possibility that PTSD in mothers and fathers might lead to different epigenetic changes on the glucocorticoid receptor in children.

In a second series of studies beginning in 2016, we examined methylation within another gene, *FKBP5,* which encodes a protein involved in regulating the ability of the glucocorticoid receptor to bind cortisol. The findings showed related methylation patterns within the *FKBP5* gene in both Holocaust parents and their children. But because of the small number of participants in that study—by this time it was difficult to find many living Holocaust survivors who could participate with their offspring—we couldn't examine how factors such as the parents' PTSD status might contribute to *FKBP5* methylation.

We were able to replicate and extend this work in a substantially larger sample of just the Holocaust offspring, however. In 2020 we reported lower levels of *FKBP5* methylation in the adult children whose mothers—and not fathers—were exposed to the Holocaust during childhood. This effect was independent of whether the mother had PTSD or not. It suggested that trauma might have affected the mothers' eggs decades before her children were conceived, while she was herself a child.

Given the obvious difficulties in studying generations of people, scientists often resort to animal studies to explore epigenetic transmission. In 2014 Brian Dias and Kerry Ressler, both at the Emory University School of Medicine, reported an intergenerational epigenetic pathway that ran through sperm. They gave a male mouse a mild electric shock as it smelled a cherry blossom scent, stimulating a fear response to the odor. The response was accompanied by epigenetic changes in its brain and sperm. Intriguingly, the male offspring of the shocked mice demonstrated a similar fear of cherry blossoms—as well as epigenetic changes in their brain and sperm—without being exposed to the shock. These effects were passed down for two generations. In other words, the lesson the grandfather mouse learned, that the cherry blossom scent means danger, was transmitted to its son and grandson.

In a recent study, my colleagues and I experimented with genome-wide gene expression, a tool that can identify links between protein expression and specific conditions across the entire human genome. With this approach, we again observed distinct patterns of gene expression linked with maternal and paternal trauma exposure and PTSD.

IN THE WOMB

APART FROM ALTERING the eggs and sperm that encapsulate our genetic inheritance, sometimes decades before conception, trauma also seems to influence the uterine environment. Meticulous studies of the offspring of women who were pregnant during the Dutch Famine—a six-month period during World War II when the Nazis blocked the food supply to the Netherlands, causing widespread starvation—provided an early indication of in utero effects. Researchers discovered that the combined effects of extreme stress and nutritional deprivation, such as deficits in metabolism and susceptibility to cardiovascular illness, depended on the trimester of exposure.

The 9/11 babies were also impacted in the womb, with those in the third trimester having significantly lower cortisol levels. What this condition meant for their future development I sadly never found out. At the wellness visit, mothers who had PTSD (and low cortisol) were more likely to report that their nine-month-olds were unusually anxious and afraid of strangers. But we didn't get the funding to follow the babies into adulthood.

How might the uterine environment leave a trauma trace in the offspring? Our work on Holocaust survivors and their adult children provided some clues. The story is again complicated, and it involves an enzyme known as 11-beta-hydroxysteroid dehydrogenase type 2 (11β-HSD2). Holocaust survivors had lower levels of the enzyme than those who hadn't lived through the Holocaust—and such effects were particularly pronounced in those who were the youngest during World War II. The enzyme is normally concentrated in the liver, kidneys and brain. Under conditions of food deprivation, however, the body can lower levels of 11β-HSD2 to increase metabolic fuel in the interest of promoting survival. In adults, the enzyme level will return to what it was when there is no more starvation, but in children, the level may remain low. Our findings suggested that 11β-HSD2 levels might have been altered during childhood when Holocaust survivors were exposed to long periods of malnourishment; the change persisted well into old age.

In the children of women who were Holocaust survivors, however, we saw quite the opposite: 11β-HSD2 levels were higher than in Jewish control subjects. The result might seem contradictory, but there is a logic to it. During pregnancy, 11β-HSD2 also acts in the placenta, protecting the fetus from exposure to circulating maternal cortisol, which can be toxic to the developing brain. The enzyme, which is particularly active in the third trimester, converts maternal cortisol into an inactive form, creating a kind of chemical shield in the placenta that protects the fetus from the hormone's harmful effects. The high levels of this enzyme in the offspring of Holocaust survivors may thus reflect an adaptation, an effort to protect the fetus from the lowered 11β-HSD2 levels in their mothers.

All of this means that offspring are not always passive recipients of their parents' scars. Just as a parent was able to survive trauma by means of biological adaptations, offspring can sometimes adapt to the biological impact of their parents' trauma.

How traumatized parents interact with their children, of course, also influences their development. One of the most powerful nonfiction accounts of growing up with Holocaust survivor parents was Art Spiegelman's serialized graphic novel *Maus;* it broke through a cultural barrier, helping others to open up about their suffering. Many psychologists and neuroscientists have examined the traumatized family, finding ever more subtleties, and the story will continue to unfold for decades to come.

An important question is whether epigenetic alterations in stress-related genes, particularly those reflected in the offspring of traumatized parents, are necessarily markers of vulnerability or whether they may reflect a mechanism through which offspring become better equipped to cope with adversity. This is an area we're actively exploring.

Epigenetic inheritances may represent the body's attempts to prepare offspring for challenges similar to those encountered by their parents.

It is tempting to interpret epigenetic inheritance as a story of how trauma results in permanent damage. Epigenetic influences might nonetheless represent the body's attempts to prepare offspring for challenges similar to those encountered by their parents. As circumstances change, however, the benefits conferred by such alterations may wane or even result in the emergence of novel vulnerabilities. Thus, the survival advantage of this form of intergenerational transmission depends in large part on the environment encountered by the offspring themselves.

Moreover, some of these stress-related and intergenerational changes may be reversible. Several years ago we discovered that combat veterans with PTSD who benefited from cognitive-behavioral psychotherapy showed treatment-induced changes in *FKBP5* methylation. The finding confirmed that healing is also reflected in epigenetic change. And Dias and Ressler reconditioned their mice to lose their fear of cherry blossoms; the offspring conceived after this "treatment" did not have the cherry blossom epigenetic alteration, nor did they fear the scent. Preliminary as they are, such findings represent an important frontier in psychiatry and may suggest new avenues for treatment.

The hope is that as we learn more about the ways catastrophic experiences have shaped both those who lived through those horrors and their descendants, we will become better equipped to deal with dangers now and in the future, facing them with resolution and resilience.

FROM OUR ARCHIVES

The Long Shadow of Trauma. Diana Kwon; January 2022.

scientificamerican.com/magazine/sa

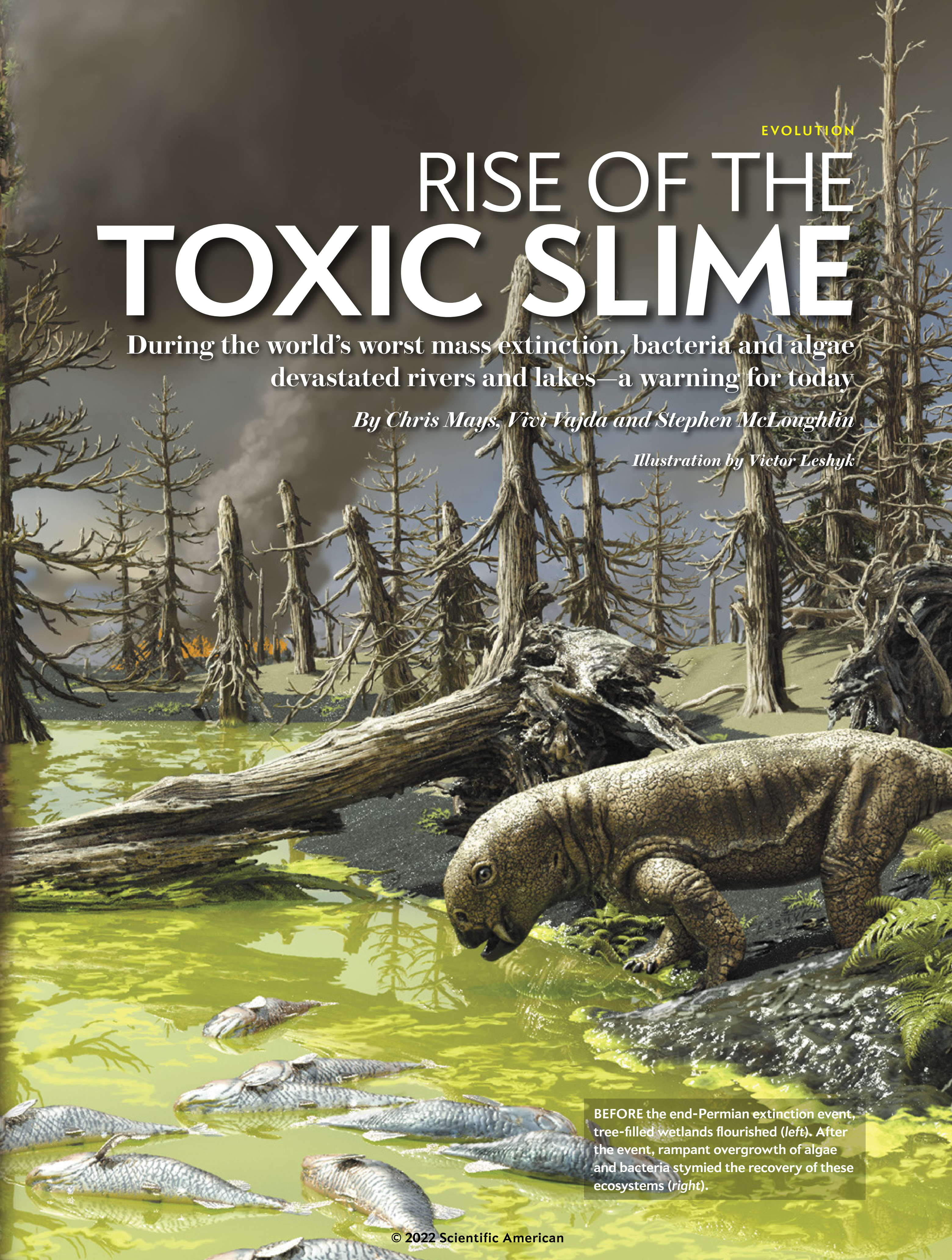
EVOLUTION

RISE OF THE TOXIC SLIME

During the world's worst mass extinction, bacteria and algae devastated rivers and lakes—a warning for today

By Chris Mays, Vivi Vajda and Stephen McLoughlin

Illustration by Victor Leshyk



BEFORE the end-Permian extinction event, tree-filled wetlands flourished (*left*). After the event, rampant overgrowth of algae and bacteria stymied the recovery of these ecosystems (*right*).

Chris Mays is a lecturer in paleontology at University College Cork in Ireland. His research focuses on mass extinctions and how polar plants and animals responded to warming events in the past.

Vivi Vajda is a geologist at the Swedish Museum of Natural History who specializes in microscopic fossils, including those of plankton and algae. She studies vegetation changes through time to better understand mass extinctions.

Stephen McLoughlin is curator of the Paleozoic and Mesozoic plant fossil collections at the Swedish Museum of Natural History. His research interests revolve around the evolution and extinction of plant life on Earth.

AT SUNRISE ON A SUMMER DAY IN AUSTRALIA, ABOUT AN HOUR'S DRIVE FROM SYDNEY, we clambered northward along the base of a cliff on a mission. We were searching for rocks that we hoped would contain clues to the darkest chapter in our planet's history.

Life on Earth has experienced some terrifyingly close calls in the past four billion years—cataclysmic events in which the species driven to extinction outnumbered the survivors. The worst crisis occurred 252 million years ago, at the end of the Permian Period. Conditions back then were the bleakest that animals ever faced. Wildfires and drought scoured the land; oceans became intolerably hot and suffocating.

Very few creatures could survive in this hellscape. Ultimately more than 70 percent of land species and upward of 80 percent of ocean species went extinct, leading some paleontologists to call this dismal episode the Great Dying.

This calamity has been etched in stone across the globe but perhaps nowhere as clearly as on the rocky coasts of eastern Australia. By midmorning we had found our target: an outcrop of coal within the cliff face. Sedimentologist Christopher Fielding of the University of Connecticut, one of our longtime colleagues, had recently identified these rocks as river and lake sediments deposited during the end-Permian event. Following his lead, we had come to sift through the sediments for fossil remains from the few survivors of the arch extinction.

From our vantage point on the outcrop, we could see our first hint of ancient devastation: the absence of coal beds in the towering sandstone cliffs above us. During our dawn scramble across the rocks, we had spotted numerous coal beds sandwiched between the sandstones and mudstones in the lower rock levels. These coals date to the late Permian (around 259 million to 252 million years ago). They represent the compacted remains of the swamp forests that existed across a vast belt of the southern supercontinent Gondwana. In contrast, the younger, overlying rocks that span the early part of the subsequent Triassic Period, some 252 million to 247 million years ago, are devoid of coal. In fact, not a single coal seam has been found in rocks of this vintage anywhere in the world. Instead these strata reflect the peaceful deposition of sand and mud by rivers and lakes, seemingly undisturbed by life.

Historically ignored because of its paucity of fossil fuels for humans to exploit, this so-called coal gap has recently emerged as a key to understanding the history of life on Earth. We now know it was a symptom of a sick world. At the end of the Permian, not only did terrestrial and marine ecosystems collapse, but so, too, did freshwater ones. Recent studies by our team have shown that as global temperatures surged at the close of the Permian, blooms of bacteria and algae choked rivers and lakes, rendering them largely uninhabitable. Our findings help to explain why the ensuing mass extinction was so devastating—and raise concerns about the future of biodiversity in our warming world.

SCORCHED EARTH

AS THE SUN ROSE higher in the sky, its heat beat down on us relentlessly. We managed to pack in a few produc-

LAST COAL DEPOSIT of the Permian Period, which appears as a black band in the exposed rock layers, is overlain by cliffs of fossil-barren Early Triassic sandstone.

Chris Mays

tive hours of fossil and rock collection before the outcrop became unbearably hot. At that time, in the early summer of 2018, it seemed warmer than the previous field season. Maybe it really was warmer, or maybe it was just because we had recently arrived from chilly Stockholm, where we work at the Swedish Museum of Natural History. Regardless, by midmorning we retreated to the shade for a couple of hours to cool down and ponder what we had seen.

We found the coals to consist almost entirely of compacted leaves, roots and wood belonging to trees in the genus *Glossopteris*. *Glossopteris* trees flourished in wetlands and readily formed peat, a precursor to coal. Directly above the coals we saw no fossils at first. All the outcrops of similar age around Sydney seemed to contain a fossil dead zone. There were no leaves or roots and scarcely a fossil of any kind, with one critical exception: simple, curved sand-filled burrows up to two meters long. Based on the sizes and shapes of these burrows, we concluded that they were most likely excavated by small mammal-like reptiles roughly the size of modern gophers or mole rats. The busy burrowers had made their homes in the muddy dead zone, implying that these animals had survived the end-Permian catastrophe. Moreover, their burrowing strategy was probably key to their success: it provided a refuge from the scorching surface.

All organisms must bend to the forces of nature. Like our ancestors that survived the end-Permian event, we sought a reprieve from the punishing temperatures during our fieldwork. Fortunately, we had to hide for just a few hours before we could emerge. But what if the insufferable heat had lasted months—or millennia?

Before long the sun crept westward, casting us in the cliff's shadow, and we concluded the day's work by collecting more rock samples to analyze back in the laboratory. For most paleontologists, the absence of observable fossils, as occurs within the dead zone of a mass extinction, makes for a short expedition. But we suspected that the full story lay hidden in fossils that couldn't be seen with the naked eye.

We combined the day's samples with those we had collected from other rocks of the same age around Sydney, then split them into three batches. We sent one batch off to Jim Crowley of Boise State University and

Bob Nicoll of Geoscience Australia to obtain precise age estimates for the extinction event. The second batch went to our colleague Tracy Frank of the University of Connecticut so she could calculate the temperatures that prevailed during the late Permian. We took the third batch with us to the Swedish Museum of Natural History, where we sifted through the samples for microscopic fossils of plant spores and pollen, as well as microbial algae and bacteria, to build a blow-by-blow account of the ecological collapse and recovery.

As expected, our analyses of the microfossils showed that abundances of plant spores and pollen dropped off precisely at the top of the last Permian coal deposit, reflecting near-total deforestation of the landscape. To our surprise, however, we also found that algae and bacteria had proliferated soon after the extinction, infesting freshwater ecosystems with noxious slime. In fact, they reached concentrations typical of modern microbial blooms, such as the record-breaking blooms in Lake Erie in 2011 and 2014. Because explosive microbial growth leads to poorly oxygenated waters, and many microbes produce metabolic by-products that are toxic, these events can cause animals to die en masse. In the wake of the end-Permian devastation, the humblest of organisms had inherited the lakes and rivers and established a new freshwater regime. We wondered how these microbes came to flourish to such a great extent and what the consequences of their burgeoning were. To answer these questions, we needed more context.

Insights came from analyses of the other two samples. The age estimates revealed that the ecosystem collapse coincided with the first rumblings of tremendous volcanic eruptions in a "large igneous province" known as the Siberian Traps, in what is now Russia. The term "volcanic" seems inadequate in this context; the volume of magma in the Siberian Traps was a whopping several million cubic kilometers. Thus, the Siberian Traps province is to a volcano as a tsunami is to a ripple in your bathtub. Studies have consistently implicated the Siberian Traps igneous event as the ultimate instigator of the end-Permian mass extinction, in large part because of the composition of the rocks in the area. Prior to this event, the rocks underneath Siberia were rich in coal, oil and gas. When the Siberian Traps erupted, the heat of the intrusive magma vaporized these hydrocarbons into greenhouse gases, which were then emitted into the atmosphere. Atmospheric carbon dioxide levels increased sixfold as a result.

The timing lined up with Tracy's new geochemical temperature estimates, which revealed an increase of 10 to 14 degrees Celsius in the Sydney region. The age estimates also nailed down the duration of the observed changes in the Sydney area: the temperature spike and ecosystem collapse had occurred within tens of thousands of years. This geologically rapid change in conditions drove animals from temperate zones to extinction or compelled them to live part-time in the cooler temperatures underground. It also triggered the widespread microbial blooms we detected in our microfossil studies: the slime revolution had begun.

The ancient recipe for this toxic soup relied on three main ingredients: high carbon dioxide, high temperatures and high nutrients. During the end-Permian event, the Siberian Traps provided the first two ingredients. Sudden deforestation created the third: when the trees were wiped out, the soils they once anchored bled freely into the rivers and lakes, providing all the nutrients that the aquatic microbes needed to multiply. In the absence of "scum-sucking" animals such as fish and invertebrates that would otherwise keep their numbers down, these microbes proliferated in fits and starts over the following 300 millennia. Once this new slime dynasty had established its reign, microbe concentrations at times became so high that they made the water toxic, preventing animals from recovering their preextinction diversity for perhaps millions of years. We had just discovered that freshwater, the last possible refuge during that apocalyptic time, was no refuge at all.

A RECURRENT SYMPTOM

AUTHOR TERRY PRATCHETT once wrote of revolutions: "They always come around again. That's why they're called revolutions." Although the end-Permian was uniquely ruinous to life, it was probably just the end of a spectrum of warming-driven extinction events in Earth's history. If the environmental conditions that led to the end-Permian microbial blooms are typical for mass extinctions, then other ecological disasters of the past should reveal similar uprisings. Indeed, almost all past mass extinctions have been linked to rapid and sustained CO_2-driven warming. One might therefore expect to see similar, albeit less dramatic, microbial signatures for many other events.

From the precious little previously published data we found on freshwater systems during other mass extinctions, the pattern held up. So far, so good. But the best sign that we were onto something significant came when we placed the end-Permian event, along with the others, on a spectrum from least to most severe. The extinctions appeared to show a "dose-response relationship." This term is often used to describe the reaction of an organism to an external stimulus, such as a drug or a virus. If the stimulus is really the cause of a reaction, then you would expect a higher dose of it to cause a stronger response. When we applied this reasoning, we saw that the global severity of these microbial "infections" of freshwater ecosystems really seemed to have increased with higher doses of climate warming. The relatively mild warming events barely elicited a microbial response at all, whereas the severe climate change of the end-Permian gave rise to a metaphorical pandemic of aquatic microbes.

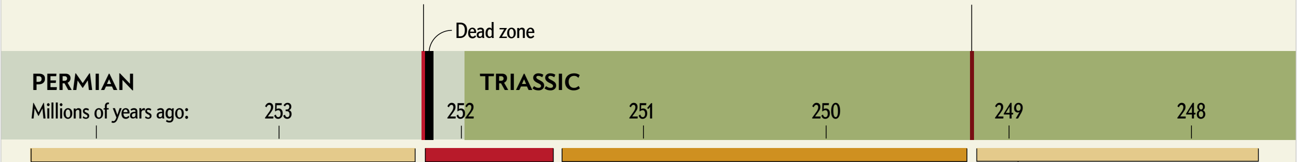
We then compared this pattern with the most famous mass extinction of all: the end-Cretaceous event that took place 66 million years ago and led to the loss of most large-bodied vertebrate groups, including the nonbird dinosaurs. In a matter of days some of the most awesome animals to walk the land, swim the seas or fly the skies were snuffed out. Although massive volcanic eruptions are known to have occurred at this time, the majority of extinctions from this event are generally attributed to the impact of an asteroid at least 10 kilometers in diameter that struck an area off the coast of modern-day Mexico at a speed of up to 20 kilometers a second. The resultant global cloud of dust, soot and aerosols may have inhibited the proliferation of photosynthetic microbes in the immediate aftermath of the event. Once the sun broke through, some microbes did multiply, but their reign was short-

Deadly Blooms

Researchers have long known that at the end of the Permian Period, terrestrial and marine ecosystems became inhospitable because of global warming. Analyses of fossil-bearing rocks from the Sydney Basin of Australia have shown that rivers and lakes—once thought to be the only safe havens during this apocalyptic time—had turned deadly, too, choked with toxic blooms of algae and bacteria. The collapse of these freshwater settings dramatically slowed the recovery of life on Earth.

END-PERMIAN EXTINCTION EVENT
Surging temperatures and CO_2 levels extinguished more than 70 percent of land species and 80 percent of ocean species.

SMITHIAN-SPATHIAN CLIMATIC EVENT
Nearly three million years passed before temperatures and CO_2 returned to moderate levels that allowed ecosystem recovery.



BEFORE THE EXTINCTION EVENT
Wetland ecosystems dominated by an extinct genus of trees known as *Glossopteris* prevailed. Understory ferns and bryophytes, among other plants, thrived, too.

ECOSYSTEM COLLAPSE
Widespread wildfires and deforestation led to rising water tables and the pooling of water in lowland areas. Algae and bacteria in these freshwater ecosystems became abundant, fueled by nutrient influx.

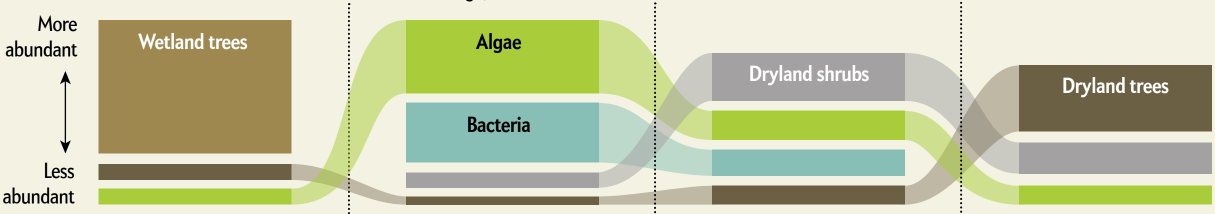
SUPPRESSED RECOVERY
Blooms of algae and bacteria depleted oxygen in lakes and rivers and infused them with toxic metabolic by-products, probably delaying the recovery of freshwater ecosystems for millions of years.

STEADY RECOVERY
Global climatic cooling brought about vegetation shifts, including the recovery of seed-producing plants, and let animals return. Nearly three million years after the planet went to hell, life on Earth began to bounce back.

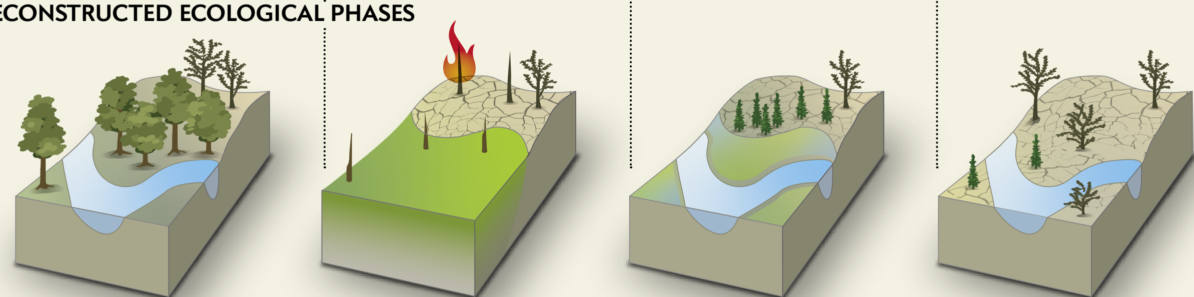
TEMPERATURE AND CO_2 LEVELS

Before the extinction event	Ecosystem collapse	Suppressed recovery	Steady recovery
Moderate	Very high	High	Moderate

DOMINANT ORGANIC MATERIAL (for each stage, based on fossil evidence)



RECONSTRUCTED ECOLOGICAL PHASES



Source: "Lethal Microbial Blooms Delayed Freshwater Ecosystem Recovery following the End-Permian Extinction," by Chris Mays et al., in *Nature Communications,* Vol. 12; September 17, 2021 *(reference material)*

Graphic by Jen Christiansen

lived and relatively restricted, probably because of the modest increases in global CO_2 and temperature.

Without a simmering Earth to prop them up, we found, a new world order for microbes quickly breaks down. The contrasting microbial responses to magma- and asteroid-driven extinction events highlight the importance of high CO_2 and temperature for fueling harmful algal and bacterial blooms. This link between greenhouse gas–driven warming and toxic microbial blooms is both satisfying and alarming: an elegant theory of freshwater mass extinction is emerging, but it may be simpler than we thought to cause widespread biodiversity loss—and it all seems to start with rapid CO_2 emissions.

Andy Morrison/The Blade/AP Photo

ON THE RISE

TODAY HUMANS ARE providing the ingredients for toxic microbial soup in generous amounts. The first two components—CO_2 and warming—are by-products of powering our modern civilization for nearly 200 years. Our species has been industriously converting underground hydrocarbons into greenhouse gases with far more efficiency than any volcano. The third ingredient—nutrients—we have been feeding into our waterways in the form of fertilizer runoff from agriculture, eroded soil from logging, and human waste from sewage mismanagement. Toxic blooms have increased sharply as a result. Their annual costs to fisheries, ecosystem services such as drinking water, and health are measured in the billions of dollars and are set to rise.

Wildfires can exacerbate this problem. In a warming world, droughts intensify, and outbreaks of fire become more common even in moisture-rich environments, such as the peat forests of Indonesia and the Pantanal wetlands of South America. Wildfires not only increase nutrient levels in water by exposing the soil and enhancing nutrient runoff into the streams, but they also throw immense quantities of soot and micronutrients into the atmosphere, which then land in oceans and waterways. Recent studies have identified algal blooms in freshwater streams of the western U.S. in the wake of major fire events. Farther afield, in the aftermath of the 2019–2020 Australian Black Summer wildfires, a widespread bloom of marine algae was detected downwind of the continent in the Southern Ocean.

Wildfire could have helped nourish aquatic microbes in the deep past, too. Our investigation of the sediments above the coal seams around Sydney revealed abundant charcoal, a clear sign of widespread burning in the last vestiges of the Permian coal swamps. As in the modern examples, a combination of surface runoff and wildfire ash may well have led to nutrient influx into late-Permian waterways and the proliferation of deadly bacteria and algae.

These ancient mass extinctions hold lessons for the present and the future. Consider the following two premises of Earth system science. First, the atmosphere, hydrosphere, geosphere and biosphere are linked. If one is significantly modified, the others will react in predictable ways. Second, this principle is as true today as it was throughout Earth's past. The Intergovernmental Panel on Climate Change (IPCC) applied this logic in its latest assessment of the causes and impacts of global warming.

Drawing on ice, rock and fossil records, this consortium of more than 200 scientists concluded that the world has not experienced the present levels of CO_2 in more than two million years. In periods with such levels of CO_2 in the past, how high were sea levels? How did these conditions affect soil-weathering rates? How were the forests distributed? In other words, how did this difference in the air affect the oceans, land and life? Our society should be desperate to answer such questions in relation to our modern CO_2 levels of 415 parts per million (ppm), not to mention 800 or 900 ppm, which is where the IPCC estimates we'll be by the year 2100 if the world continues to burn fossil fuels at the current rate. As CO_2 keeps rising, we need to look further back in time for clues about what to expect. The records of past extreme warming events are only becoming more relevant.

The analogy between the end-Permian event and today breaks down in at least two important ways, yet these discrepancies may not be as comforting as we might hope. For one thing, the pace of warming was

probably different. Life struggles to cope with large environmental changes on short timescales, so perhaps the end-Permian event, the worst struggle in history, occurred much more quickly than modern warming. It is more likely that modern warming is much faster, however. Our team and others have shown that the sixfold increase in CO_2 during the end-Permian collapse happened over the course of perhaps tens of thousands of years. At business-as-usual rates, the IPCC projects the same increase in CO_2 concentration within hundreds, not thousands, of years.

A second strike against the analogy is the human element. Humans are becoming a force of nature, like a magma plume or a rock from space, but the diversity of ecological stressors they exert is unique in Earth's history. For this reason, we argue that extreme warming events from the past, such as the one that occurred at the end of the Permian, potentially provide a clear signal of the consequences of climate change. If we listen carefully enough, the fossils and rocks can tell us the results of warming alone, without additional, possibly confounding influences from humans such as nutrient influx from agriculture, deforestation via logging or extinctions from poaching.

Here is the message these past events are telling us with increasing clarity: one can cause the extinction of a large number of species simply by rapidly releasing a lot of greenhouse gas. It does not matter where the gases come from—whether the source is volcanoes, airplanes or coal-fired power plants, the results end up being the same. When we add to that mix the myriad other stressors generated by humans, the long-term forecast for biodiversity seems bleak.

There is, however, a third way in which our species could break the analogy, one that is far more hopeful. Unlike the species that suffered the mass extinctions of the past, we can prevent biodiversity loss through the intelligent application of our ideas and our technologies. Case in point: we can prevent a microbial takeover by keeping our waterways clean and curbing our greenhouse gas emissions.

It is increasingly clear that we are living through the sixth major mass extinction. Freshwater microbial blooms, wildfires, coral bleaching and spikes in ocean temperature are becoming more frequent and intense in our warming world. Where along the extinction-event spectrum the present warming will place us is, for the first time in Earth's history, up to just one species. SA

TOXIC BLOOMS of microbes in freshwater ecosystems such as Lake Erie (*left*) are on the rise as carbon dioxide, temperatures and nutrient runoff increase. Wildfires such as those in the Pantanal wetlands of Brazil (*right*) can worsen the problem.

Jonne Roriz/Bloomberg Creative/Getty Images

FROM OUR ARCHIVES

The Mother of Mass Extinctions. Douglas H. Erwin; July 1996.

scientificamerican.com/magazine/sa

MASSIVE GALAXY CLUSTER MACSJ0717.5+3745: Studies of such clusters and other large cosmic structures are revealing troubling inconsistencies in scientists' assumptions about the universe.

ASTRONOMY

Cosmic Conflict

A debate over measurements of key cosmological properties is set to shape the next decade of astrophysics

By Anil Ananthaswamy

Anil Ananthaswamy is author of *The Edge of Physics* (Houghton Mifflin Harcourt, 2010), *The Man Who Wasn't There* (Dutton, 2015), and *Through Two Doors at Once: The Elegant Experiment That Captures the Enigma of Our Quantum Reality* (Dutton, 2018).

HOW FAST IS THE UNIVERSE EXPANDING? HOW MUCH DOES MATTER CLUMP UP IN OUR cosmic neighborhood? Scientists use two methods to answer these questions. One involves observing the early cosmos and extrapolating to present times, and the other makes direct observations of the nearby universe. But there is a problem. The two methods consistently yield different answers. The simplest explanation for these discrepancies is merely that our measurements are somehow erroneous, but researchers are increasingly entertaining another, more breathtaking possibility: These twin tensions—between expectation and observation, between the early and late universe—may reflect some deep flaw in the Standard Model of cosmology, which encapsulates our knowledge and assumptions about the universe. Finding and fixing that flaw could transform our understanding of the cosmos.

One way or another, an answer seems certain to emerge over the coming decade, as new space and terrestrial telescopes give astronomers clearer cosmic views. "Pursuing these tensions is a great way to learn about the universe," says astrophysicist and Nobel laureate Adam Riess of Johns Hopkins University. "They give us the ability to focus our experiments on very specific tests, rather than just making it a general fishing expedition."

These new telescopes, Riess anticipates, are about to usher in the third generation of precision cosmology. The first generation came in the 1990s and early 2000s with the Hubble Space Telescope and with NASA's WMAP satellite, which sharpened our measurements of the universe's oldest light, the cosmic microwave background (CMB). This first generation was also shaped by eight-meter-class telescopes in Chile and the twin 10-meter Keck behemoths in Hawaii.

Collectively, these observatories helped cosmologists formulate the Standard Model, which holds that the universe is a cocktail of 5 percent ordinary matter, 27 percent dark matter and 68 percent dark energy. The Standard Model can account with uncanny accuracy for most of what we observe about galaxies, galaxy clusters, and other large-scale structures and their evolution over cosmic time. Ironically, by its very success, the model highlights what we do not know: the exact nature of 95 percent of the universe.

Driven by even more precise measurements of the CMB from the European Space Agency's Planck satellite and various ground-based telescopes, the second generation of precision cosmology supported the Standard Model but also brought to light the tensions. The focus shifted to reducing so-called systematics: repeatable errors that creep in because of faults in the design of experiments or equipment.

The third generation is only now starting to take the stage with the successful launch and deep-space deployment of Hubble's successor, the James Webb Space Telescope (JWST). On Earth, radio telescope arrays such as the Simons Observatory in the Atacama Desert in Chile and the CMB-S4, a future assemblage of 21 dishes and half a million cryogenically cooled detectors that will be divided between sites in the Atacama and at the South Pole, should take CMB measurements with Planck-surpassing levels of precision.

The centerpieces of the third generation will be telescopes that stare at wide swaths of the sky. The first of these is likely to be the ESA's 1.2-meter Euclid space telescope, due for launch in 2023. Euclid will study the shapes and distributions of billions of galaxies with a gaze that spans about a third of the sky. Its observations will dovetail with those of NASA's Nancy Grace Roman Space Telescope, a 2.4-meter telescope with a field of view about 100 times bigger than Hubble's, which is slated for launch in 2025. Finally, when it begins operations in the mid-2020s, the ground-based Vera C. Rubin Observatory in Chile will map the entire overhead sky every few nights with its 8.4-meter mirror and a three-billion-pixel camera, the largest ever built for astronomy. "We're not going to be limited by noise and by systematics, because these are independent observatories," says astrophysicist Priyamvada Natarajan of Yale University. "Even if we have a systematic in our framework, we should [be able to] figure it out."

SCALING THE DISTANCE LADDER

RIESS WOULD LIKE to see a resolution of the Hubble tension, which arises from differing estimates of the value of the Hubble constant, H_0—the rate at which the universe is expanding. Riess leads

NASA/ESA/HST Frontier Fields team (STScI) (*preceding pages*)

NOCTURNAL VIEW of the South Pole Telescope, one of several radio observatories mapping patterns in the cosmic microwave background.

Danvis Collection/Alamy Stock Photo

a project called Supernovae, H_0, for the Equation of State of Dark Energy (SH0ES). The goal is to measure H_0, starting with the first rung of the so-called cosmic distance ladder, a hierarchy of methods to gauge ever greater celestial expanses.

The first rung—the one concerning the nearest cosmic objects—relies on determining the distance to special stars called Cepheid variables, which pulsate in proportion to their intrinsic luminosity. The longer the pulsation, the brighter the Cepheid. This relation between variability and luminosity makes Cepheids benchmark "standard candles" for determining distances around the Milky Way and nearby galaxies. They also form the basis of the cosmic distance ladder's second rung, in which astronomers gauge distances to more remote galaxies by comparing Cepheid-derived estimates with those from another, more powerful set of standard candles called type Ia (pronounced "one A") supernovae, or SNe Ia.

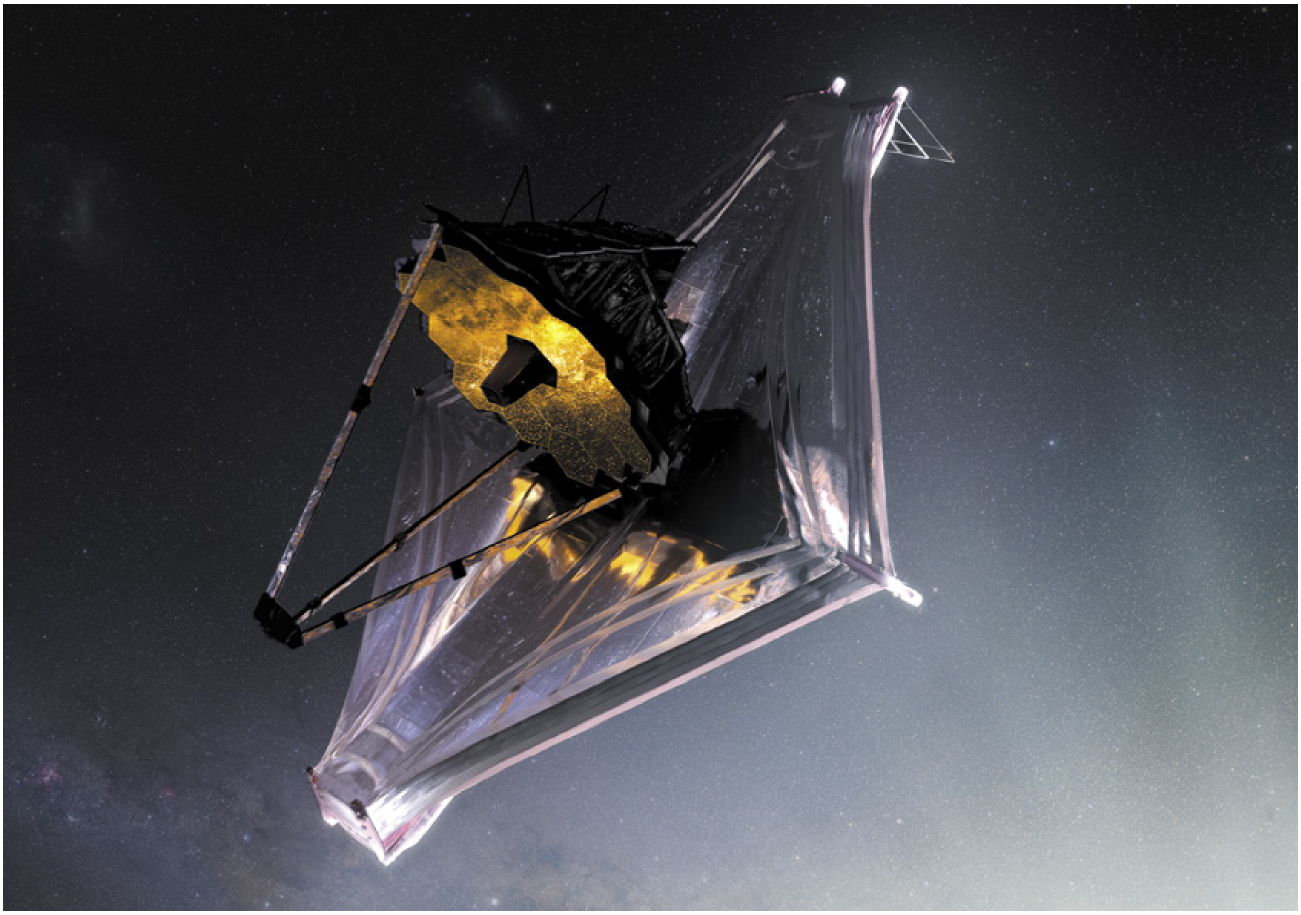
Ascending further, astronomers locate SNe Ia in even more far-flung galaxies, using them to establish a relation between distance and a galaxy's redshift, a measure of how fast it is moving away from us. The result is an estimate of H_0.

In December, Riess says, "after a couple of years of taking a deep dive on the subject," the SH0ES team and the Pantheon+ team, which has compiled a large data set of type Ia supernovae, announced the results of nearly 70 different analyses of their combined data. The data included observations of Cepheid variables in 37 host galaxies that contained 42 type Ia supernovae, more than double the number of supernovae studied by SH0ES in 2016. Riess and his co-authors suspect this latest study represents the Hubble's last stand, the outer limits of that hallowed telescope's ability to help them climb higher up the cosmic scale. The set of supernovae now includes "all suitable SNe Ia—of which we are aware—observed between 1980 and 2021" in the nearby universe. In their analysis, H_0 comes out to be 73.04 ± 1.04 kilometers per second per megaparsec.

That number is way off the value obtained by an entirely different method that looks at the other end of cosmic history—the so-called epoch of recombination, when the universe became transparent to light, about 380,000 years after the big bang. The light from this epoch, now stretched to microwave wavelengths because of the universe's subsequent expansion, is detectable as the all-pervading cosmic microwave background. Tiny fluctuations in temperature and polarization of the CMB capture an important signal: the distance a sound wave travels from almost the beginning of the universe to the epoch of recombination.

This length is a useful metric for precision cosmology and can be used to estimate the value of H_0 by extrapolating to the present-day universe using the standard LCDM model. (L stands for lambda or dark energy, and CDM for cold dark matter; cold refers to the assumption that dark matter particles are relatively slow-moving.) Published a year ago, the latest analysis combined data from the Planck satellite and two ground-based instruments, the Atacama Cosmology Telescope and the South Pole Telescope, to arrive at an H_0 of 67.49 ± 0.53.

The discrepancy between the two estimates has a statistical significance of five sigma, meaning there is only about a one-in-a-million chance of its being a statistical fluke. "It's certainly at the level that people should take seriously," Riess says. "And they have."



ARTIST'S CONCEPTION of the James Webb Space Telescope, which is poised to perform breakthrough studies of both the early and current universe.

NASA/GSFC/CIL/Adriana Manrique Gutierrez

HOW CLUMPY IS THE COSMOS?

THE OTHER TENSION that researchers are starting to take seriously concerns a cosmic parameter called S_8, which depends on the density of matter in the universe and the extent to which it is clumped up rather than evenly distributed. Estimates of S_8 also involve, on one end, measurements of the CMB and, on the other, measurements of the local universe. The CMB-derived value of S_8 in the early universe, extrapolated using LCDM, generates a present-day value of about 0.834.

The local universe measurements of S_8 involve a host of different methods. Among the most stringent are so-called weak gravitational lensing observations, which measure how the average shape of millions of galaxies across large patches of the sky is distorted by the gravitational influence of intervening concentrations of dark and normal matter. Astronomers used the latest data from the Kilo-Degree Survey, which more than doubled its sky coverage from 350 to 777 square degrees of the sky (the full moon, by comparison, spans a mere half a degree) and estimated S_8 to be about 0.759. The tension between the early- and late-universe estimates of S_8 has grown from 2.5 sigma in 2019 to three sigma now (or a one-in-740 chance of being a fluke). "This tension isn't going away," says astronomer Hendrik Hildebrandt of Ruhr University Bochum in Germany. "It has hardened."

There is yet another way to arrive at the value of S_8: by counting the number of the most massive galaxy clusters in some volume of space. Astronomers can do that directly—for example, by using gravitational lensing. They can also count clusters by studying their imprint on the cosmic microwave background, thanks to something called the Sunyaev-Zeldovich effect. (This effect causes CMB photons to scatter off the hot electrons in clusters of galaxies, creating shadows in the CMB that are proportional to the mass of the cluster.)

A detailed 2019 study that used data from the South Pole Telescope estimated S_8 to be 0.749—again, way off from the CMB+LCDM-based estimates. These numbers could be reconciled if the estimates of the masses of these clusters were wrong by about 40 to 50 percent, Natarajan says, although she thinks such substantial revisions are unlikely. "We are not that badly off in the measurement game," she says. "So that's another kind of internal inconsistency, another anomaly pointing to something else."

BREAKING THE TENSIONS

GIVEN THESE TENSIONS, it is no surprise that cosmologists are anxiously awaiting fresh data from the new generation of observatories. For instance, David Spergel of Princeton University is eager for astronomers to use JWST to study the brightest of the so-called red-giant-branch stars. These stars have a well-known luminosity and can be used as standard candles to measure galactic distances—an independent rung on the cosmic ladder, if you will. In 2019 Wendy Freedman of the University of Chicago and her colleagues used this technique to estimate H_0, finding that their value sits smack in the middle of the early- and late-universe estimates. "The error bars on the current tip of the red-giant-branch data are such that they're consistent with both possibilities," Spergel says. Astronomers are also planning to use JWST to recalibrate the Cepheids surveyed by Hubble, and separately the telescope will help create another new rung for the distance ladder by targeting Mira stars (which, like Cepheids, have a luminosity-periodicity relation useful for cosmic cartography).

Whereas JWST might resolve or strengthen the H_0 tension, the wide-field survey data from the Euclid, Roman and Rubin observatories could do the same for the S_8 tension by studying the clustering and clumping of matter. The sheer amount of data expected from this trio of telescopes will reduce S_8 error bars enormously. "The statistics are going to go through the roof," Natarajan says.

Meanwhile theoreticians are already having a field day with the twin tensions. "This is a playground for theorists," Riess says. "You throw in some actual observed tensions, and they are having more fun than we are."

The most recent theoretical idea to receive a great deal of interest is something called early dark energy (EDE). In the canonical LCDM model, dark energy only started dominating the universe relatively late in cosmic history, about five billion years ago. But, Spergel says, "we don't know why dark energy is the dominant component of the universe today. Because we don't know why it's important today, it could have also been important early on." That is partly the rationale for invoking dark energy's effects much earlier, before the epoch of recombination. Even if dark energy was just 10 percent of the universe's energy budget during those times, that would be enough to accelerate the early phases of cosmic expansion, causing recombination to occur sooner and shrinking the distance traversed by primordial sound waves. The net effect would be to ease the H_0 tension.

"What I find most interesting about these models is that they can be wrong," Spergel says. Cosmologists' EDE models make predictions about the resulting EDE-modulated patterns in the photons of the CMB. In February 2022 Silvia Galli, a member of the Planck collaboration at the Sorbonne University in Paris, and her colleagues published an analysis of observations from Planck and ground-based CMB telescopes, suggesting that they collectively favor EDE over LCDM by a statistical smidgen. Confirming or refuting this tentative result will require more and better data—which could come soon from upcoming observations by same ground-based CMB telescopes. But even if EDE models prove to be better fits and fix the H_0 tension, they do little to alleviate the tension from S_8.

Potential fixes for S_8 exhibit a similarly vexing lack of overlap with H_0. In March, Guillermo Franco Abellán of the University of Montpellier in France and his colleagues published a study in *Physical Review D* showing that the S_8 tension could be eased by the hypothetical decay of cold dark matter particles into one massive particle and one "warm" massless particle. This mechanism would lower the value of S_8 arising from CMB-based extrapolations, bringing it more in line with the late-universe measurements. Unfortunately, it does not solve the H_0 tension. "It seems like a robust pattern: whatever model you come up with that solves the H_0 tension makes the S_8 tension worse, and the other way around," Hildebrandt says. "There are a few models that at least don't make the other tension worse, but [they] also don't improve it a lot."

"WE ARE MISSING SOMETHING"

ONCE FRESH DATA ARRIVE, Spergel foresees a few possible scenarios. First, the new CMB data could turn out to be consistent with early dark energy, resolving the H_0 tension, and the upcoming survey telescope observations could separately ease the S_8 tension. That would be a win for early dark energy models—and would constitute a major shift in our understanding of the opening chapters of cosmic history. It's also possible that both H_0 and S_8 tensions resolve in favor of LCDM. This would be a win for the Standard Model and a possibly bittersweet victory for cosmologists hoping for paradigm-shifting breakthroughs. Of course, it might turn out that neither tension is resolved. "Outcome three would be both tensions become increasingly significant as the data improve—and early dark energy isn't the answer," Spergel says. Then, LCDM would presumably have to be reworked differently, although how is unclear.

Natarajan thinks that the tensions and discrepancies are probably telling us that LCDM is merely an "effective theory," a technical term meaning that it accurately explains a certain subset of the current compendium of cosmic observations. "Perhaps what's really happening is that there is an underlying, more complex theory," she says. "And that LCDM is this [effective] theory, which seems to have most of the key ingredients. For the level of observational probes we had previously, that effective theory was sufficient." But times change, and the data deluge from precision cosmology's third generation of powerful observatories may demand more creative and elaborate theories.

Theorists, of course, are happy to oblige. For instance, Spergel speculates that if early dark energy could interact with dark matter (in LCDM, dark energy and dark matter do not interact), this arrangement could suppress the fluctuations of matter in the early universe in ways that would resolve the S_8 tension while simultaneously taking care of the H_0 tension. "It makes the models more baroque," Spergel says, "but maybe that's what nature will demand."

As an observational astronomer, Hildebrandt is circumspect. "If there was a convincing model that beautifully solves these two tensions, we'd already have the next Standard Model," he says. "That we're instead still talking about these tensions and scratching our heads is just reflecting the fact that we don't have such a model yet." Riess agrees. "After all, this is a problem of using a model based on an understanding of physics and the universe that is about 95 percent incomplete, in terms of the nature of dark matter and dark energy," he says. "It wouldn't be crazy to think that we are missing something." SA

FROM OUR ARCHIVES

A Cosmic Crisis. Richard Panek; March 2020.

scientificamerican.com/magazine/sa

COMPUTER SCIENCE

COOL COMPUTING

Tomorrow's computers might break through a canonical boundary on information processing

By Philip Ball

Illustration by Thomas Fuchs


Q W E R T
A S D F G
Z X C V B

Philip Ball is a science writer and former *Nature* editor based in London.

IN CASE YOU HADN'T NOTICED, COMPUTERS ARE HOT—LITERALLY. A LAPTOP CAN PUMP OUT thigh-baking heat, and data centers consume an estimated 200 terawatt-hours every year, comparable to the energy consumption of some medium-sized countries. The carbon footprint of information and communication technologies as a whole is close to that of fuel use in the aviation industry. And as computer circuitry gets ever smaller and more densely packed, it becomes more prone to melting from the energy it dissipates as heat.

Now physicist James Crutchfield of the University of California, Davis, and graduate student Kyle Ray have proposed a new way to carry out computation that would dissipate only a small fraction of the heat produced by conventional circuits. In fact, their approach, described in a recently submitted study still awaiting peer-reviewed publication, could bring heat dissipation below even the theoretical minimum that the laws of physics impose on today's computers. That could greatly reduce the energy needed to both perform computations and keep circuitry cool. And it could all be done, the researchers say, using microelectronic devices that already exist.

In 1961 physicist Rolf Landauer of IBM's Thomas J. Watson Research Center in Yorktown Heights, N.Y., showed that conventional computing incurs an unavoidable cost in energy dissipation—basically, in the generation of heat and entropy. That's because a conventional computer has to sometimes erase bits of information in its memory circuits to make space for more. Each time a single bit (with the value 1 or 0) is reset, a certain minimum amount of energy is dissipated—which Ray and Crutchfield have christened "the Landauer." Its value depends on ambient temperature: in your living room, one Landauer would be around 10^{-21} joule. (For comparison, a lit candle emits on the order of 10 joules of energy per second.)

Computer scientists have long recognized that Landauer's limit on how little heat a computation produces can be undercut by *not* erasing any information. A computation done that way is fully reversible because throwing no information away means that each step can be retraced. It might sound as though this process would quickly fill up a computer's memory. But in the 1970s Charles Bennett, also at IBM, showed that instead of discarding information at the end of the computation, one could set it up to "decompute" intermediate results that are no longer needed by reversing their logical steps and returning the computer to its original state. The catch is that, to avoid transferring any heat—to be what physicists call an adiabatic process—the series of logical operations in the computation must usually be carried out infinitely slowly. In a sense, this approach avoids any "frictional heating" in the process but at the cost of taking infinitely long to complete the calculation.

In that case, it hardly seems a practical solution. "The conventional wisdom for a long time has been that the energy dissipation in reversible computing is proportional to speed," says computer scientist Michael Frank of Sandia National Laboratories in Albuquerque, N.M.

TO THE LIMIT—AND BEYOND

SILICON-BASED COMPUTING does not get near the Landauer limit anyway: currently such computing produces around a few thousand Landauers in heat per logical operation, and it's hard to see how even some superefficient silicon chip of the future could get below 100 or so. But Ray and Crutchfield say that it is possible to do better by encoding information in electric currents in a new way: not as pulses of charge but in the *momentum* of the moving particles. They say that this would enable computing to be done reversibly without having to sacrifice speed.

The two researchers and their co-workers introduced the basic idea of momentum computing in 2021. The key concept is that a particle's momentum can provide a kind of memory "for free" because it carries information about the particle's past and future motion, not just its instantaneous state. "Previously, information was stored positionally: 'Where is the particle?'" Crutchfield says. For example, is a given electron in *this* channel or *that* one? "Momentum computing uses information in position *and* in velocity," he notes.

This extra information can then be leveraged for reversible computing. For the idea to work, the logical operations must happen much faster than the time taken for the bit to come into thermal equilibrium with its surroundings, which will randomize the bit's motion and scramble the information. In other words, "momentum computing *requires* that the device runs at high speed," Crutchfield says. For it to work, "you must compute fast"—that is, nonadiabatically.

The researchers considered how to use the idea to implement a logical operation called a bit swap, in which two bits simultaneously flip their value: 1 becomes 0, and vice versa. Here no information is discarded; it's just reconfigured, meaning that, in theory, it carries no erasure cost.

Yet if the information is encoded just in a particle's position, a bit swap—say, switching particles between a left-hand channel and right-hand one—means that their identities get scrambled and therefore cannot be distinguished from their "before" and "after" states. But if the particles have opposite momenta, they stay distinct, so the operation creates a genuine and reversible change.

A PRACTICAL DEVICE

RAY AND CRUTCHFIELD have described how this idea might be implemented in a practical device—specifically, in superconducting flux quantum bits, or qubits, which are the standard bits used for most of today's quantum computers. "We're being parasites on the quantum computing community!" Crutchfield merrily admits. These devices consist of loops of superconducting material interrupted by structures called Josephson junctions (JJs), where a thin layer of a nonsuperconducting material is interposed between two superconductors.

The information in JJ circuits is usually encoded in the direction of their so-called supercurrent's circulation, which can be switched using microwave radiation. But because supercurrents carry momentum, they can be used for momentum computing, too. Ray and Crutchfield performed simulations that suggest that, under certain conditions, JJ circuits should be able to support their momentum computing approach. If cooled to liquid-helium temperatures, the circuitry could carry out a single bit-swap operation in less than 15 nanoseconds.

"While our proposal is grounded in a specific substrate to be as concrete as possible and to accurately estimate the required energies," Crutchfield says, "the proposal is much more general than that." It should work, in principle, with normal (albeit cryogenically cooled) electronic circuits or even with tiny, carefully insulated mechanical devices that can carry momentum (and thus perform computation) in their moving parts. An approach with superconducting bits might be particularly well suited, though, Crutchfield says, because "it's familiar microtechnology that is known to scale up very well."

Crutchfield should know: Working with Michael Roukes and his collaborators at the California Institute of Technology, Crutchfield has previously measured the cost of erasing one bit in a JJ device and has shown that it is close to the Landauer limit. In the 1980s Crutchfield and Roukes even served as consultants for IBM's attempt at building a reversible JJ computer, which was eventually abandoned because of what were, at the time, overly demanding fabrication requirements.

FOLLOW THE BOUNCING BALL

HARNESSING A PARTICLE'S VELOCITY for computing is not an entirely new idea. Momentum computing is closely analogous to a reversible-computing concept called ballistic computing that was proposed in the 1980s: in it, information is encoded in objects or particles that move freely through the circuits under their own inertia, carrying with them some signal that is used repeatedly to enact many logical operations. If the particle interacts elastically with others, it will not lose any energy in the process. In such a device, once the ballistic bits have been "launched," they alone power the computation without any other energy input. The computation is reversible as long as the bits continue bouncing along their trajectories. Information is erased, and energy is dissipated, only when their states are read out.

In ballistic computing, a particle's velocity simply transports it through the device, allowing the particle to ferry information from input to output, Crutchfield says. But in momentum computing, a particle's velocity and position collectively allow it to embody a unique and unambiguous sequence of states during a computation. This latter circumstance is the key to reversibility and thus low dissipation, he adds, because it can reveal exactly where each particle has been.

Researchers, including Frank, have worked on ballistic reversible computing for decades. One challenge is that, in its initial proposal, ballistic computing is dynamically unstable because, for example, particle collisions may be chaotic and therefore highly sensitive to the tiniest random fluctuations: they cannot then be reversed. But researchers have made progress in cracking the problems. For example, Kevin Osborn and Waltraut Wustmann, both at the University of Maryland, have proposed that JJ circuits might be used to make a reversible ballistic logical circuit called a shift register, in which the output of one logic gate becomes the input of the next in a series of "flip-flop" operations.

"Superconducting circuits are a good platform for testing reversible circuits," Osborn says. His JJ circuits, he adds, seem to be very close to those stipulated by Ray and Crutchfield and might therefore be the best candidate for testing their idea.

"I would say that all our groups have been working from an intuition that these methods can achieve a better trade-off between efficiency and speed than traditional approaches to reversible computing," Frank says. Ray and Crutchfield "have probably done the most thorough job so far of demonstrating this at the level of the theory and simulation of individual devices." Even so, Frank warns that all the various approaches for ballistic and momentum computing "are still a long way from becoming a practical technology."

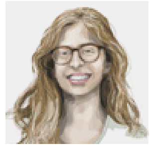
Crutchfield is more optimistic. "It really depends on getting folks to support ramping up," he says. He thinks small, low-dissipation momentum-computing JJ circuits could be feasible in a couple of years, with full microprocessors debuting within this decade. Ultimately he anticipates consumer-grade momentum computing could realize energy-efficiency gains of 1,000-fold or more over current approaches. "Imagine [if] your Google server farm housed in a giant warehouse and using 1,000 kilowatts for computing and cooling [was instead] reduced to only one kilowatt—equivalent to several incandescent light bulbs," Crutchfield says.

But the benefits of the new approach, Crutchfield says, could be broader than a practical reduction in energy costs. "Momentum computing will lead to a conceptual shift in how we see information processing in the world." SA

FROM OUR ARCHIVES

The Fundamental Physical Limits of Computation. Charles H. Bennett and Rolf Landauer; July 1985.

scientificamerican.com/magazine/sa



Kayla Good is a Ph.D. candidate at Stanford University pursuing research in developmental psychology. **Alex Shaw** is an associate professor of psychology at the University of Chicago. He studies how children and adults make social judgments about others.

Schoolkids' Secret Fears

Young children can worry that classmates view them as stupid when they ask for help

By Kayla Good and Alex Shaw

Adults are often embarrassed about asking for aid. It's an act that can make people feel vulnerable. The moment you ask for directions, after all, you reveal that you are lost. Seeking assistance can feel like you are broadcasting your incompetence.

New research suggests young children don't seek help in school, even when they need it, for the same reason. Until relatively recently, psychologists assumed that children did not start to care about their reputation and peers' perceptions until around age nine. But a wave of findings in the past few years has pushed back against that assumption. This research has revealed that youngsters as young as age five care deeply about the way others think about them. In fact, kids sometimes go so far as to cheat at simple games to look smart.

Our research suggests that as early as age seven, children begin to connect asking for help with looking incompetent in front of others. At some point, every child struggles in the classroom. But if they are afraid to ask for help because their classmates are watching, learning will suffer.

To learn more about how children think about reputation, we applied a classic technique from developmental psychology. Kids' reasoning about the world around them can be quite sophisticated, but they can't always explain what's going on in their mind. So we crafted simple stories and then asked children questions about these scenarios to allow kids to showcase their thinking.

Across several studies, we asked 576 children, ages four to nine, to predict the behavior of two kids in a story. One of the characters genuinely wanted to be smart, and the other merely wanted to *seem* smart to others. In one study, we told children that both kids did poorly on a test. We then asked which of these characters would be more likely to raise their hand in front of their class to ask the teacher for help.

The four-year-olds were equally likely to choose either of the two kids as the one who would seek help. But by age seven or eight, children thought that the kid who wanted to seem smart would be less likely to ask for assistance. And children's expectations were truly "reputational" in nature—they were specifically thinking about how the characters would act in front of peers. When assistance could be sought privately (on a computer rather than in person), children thought both characters were equally likely to ask for it.

We also asked kids about other scenarios. We found that they recognize several more behaviors that might make a child appear less smart in front of fellow kids, such as admitting to failure or modestly downplaying successes. Children are therefore acutely aware of several ways in which a person's actions might make them appear less astute in the eyes of others.

When children themselves are the ones struggling, it seems quite possible they, too, might avoid seeking out help when others are present, given our findings. Their reluctance could seriously impede academic progress. To improve in any domain, one must work hard, take on challenging tasks (even if those tasks might lead to struggle or failure), and ask questions. These efforts can be difficult when someone is concerned with their appearance to others. Research suggests that we may underestimate just how uncomfortable others feel when they ask for assistance.

Such reputational barriers likely require reputation-based solutions. First, adults should lower the social stakes of seeking help. For instance, teachers could give children more opportunities to seek assistance privately by making themselves available to students for one-on-one conversations while classmates tackle group work. Teachers should couple this effort with steps that help students perceive asking questions in front of others as normal, positive behavior. For example, instructors could create activities in which each student becomes an "expert" on a different topic, and then children must ask one another for help to master all of the material.

Seeking help could even be framed as socially desirable. Parents could point out how a child's question kicked off a valuable conversation in which the entire family got to talk and learn together. Adults could praise kids for seeking assistance. These responses send a strong signal that other people value a willingness to ask for aid and that seeking help is part of a path to success. SA

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Illustration by Olga Hashim

FICTION

Power on Trial

In a future where people hold the perpetrators of the climate crisis to account, what has changed?

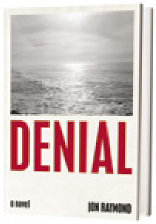
Review by Sam J. Miller

Writing science fiction is often a form of activism. The act of writing fiction generally can be said to spring from a place of hope—a celebration of what's best in us, an attempt to imagine a less terrible reality. But most genres lack the audacity to scrap the rules of physics and technology to create worlds where the seemingly intractable problems of today can be solved or transformed so dramatically that we set aside our preconceived notions to embrace a fresh perspective.

This is why storytelling plays such a crucial role in the fight to find a way out of the climate crisis. If we're going to make the huge sacrifices that are needed—if we're going to change as a species, in other words—we'll have to replace our old, outdated narratives. That's the power of great activism.

Jon Raymond's *Denial* is premised on this kind of radically hopeful outlook. It's set in a future that's been devastated by climate change—but not as badly as it could have been, thanks to the kind of unified, difficult, transformative change that our current world seems so incapable of making. Protest movements have successfully broken the power of the companies that profited from environmental devastation, and the executives who masterminded such exploitation were put on trial and locked up for life.

I want so badly to believe in this future, that we can change our behavior and hold the worst profiteers accountable. But *Denial* does not go far enough to convince me that it's possible. Oddly, the world itself seems too familiar and even banal, even though we're repeatedly assured that big shifts have taken place. There are occasional references to distant wildfires and hologram communications, but coffee shops, basketball games and road trips all remain unchanged. At one point the protagonist's car breaks down in a small Mexican village, and he's unable to meaningfully communicate with Spanish speakers. Yet the technology for effortless (if imperfect) translation *already* exists on every smartphone, and the fact that Raymond missed this opportunity to imagine a future with realistic details is one of many glaring distractions.



Denial: A Novel
by Jon Raymond. Simon & Schuster, 2022 ($26)

I can appreciate the desire to present a world that's similar enough to our own—to connect the dots between the bleak present and a scenario where only the worst outcomes were avoided. But certainly any forces that are strong enough to crumble structures of power would shift culture and progress as well.

It has been said that genre is a conversation, and anyone is welcome to join in at any point. *Denial* is Raymond's fourth novel and seems to be his first work of science fiction. Some of my favorite works of speculative fiction, for instance, are by genre outsiders, such as Kazuo Ishiguro's *Never Let Me Go* and Colson Whitehead's *The Underground Railroad*. But if you're dropping into a dialogue that has a rich history, contributions that might seem compelling and new to you may already have been discussed at length.

The impression one gets is of a writer excited about the possibilities and history of the genre but not clued in to its diverse present.

In the end, the book's biggest challenge is not a matter of genre but of character. The protagonist is a journalist who tracks down one of the most notorious corporate executives who escaped punishment—a kind of climate change version of Eichmann in Argentina—and befriends him to nail him with a spectacular on-camera confrontation and arrest. I love this fresh concept, exploring how we could hold people accountable for crimes against the planet.

The problem is, our journalist narrator doesn't give much attention to the underlying issues at stake. He grapples in the abstract with the ethics of sentencing a kind old man to die in prison while acknowledging that the man deserves to be punished. But he himself has no strong feelings on the larger themes of climate destruction or the ambivalence many of us feel toward radical, necessary change. If he'd hated the former executive's guts or believed that punishing individuals for collective behavior is profoundly wrong, I would have cared more about the character and his arc. But his motivation feels flimsy. Given the promising plot, the experience of watching it unfold is curiously empty.

Climate fiction (often shortened to "cli-fi") is its own genre now, with many emotionally resonant novels and short stories that successfully imagine better futures and galvanize readers to action. Recent books such as Claire North's *Notes from the Burning Age* and Becky Chambers's *A Psalm for the Wild-Built* have imagined bright, beautiful—and hard, troubling—futures while rooting us in a vibrant central character who wants and feels things so strongly that the reader does, too. In these worlds, humanity has changed at a great cost and after great suffering while retaining a strong familiarity. This is the exciting tension that the best stories about the climate crisis navigate well: Which parts of "human nature" are immutable, and which are socially determined and subject to change?

We need more brave books like *Denial* that imagine a future that's not dystopic—but that can show us how we might get there and who we'll become when we do.

Sam J. Miller is the Nebula Award–winning author of *Blackfish City*.

Illustration by London Ladd

NONFICTION

Lively Numbers

Finding awe in unsolved equations


How does one imagine the size of a black hole?

Event Horizon Telescope Collaboration

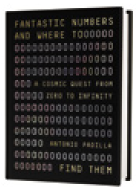
Cosmologist Antonio Padilla's *Fantastic Numbers and Where to Find Them* is an exceptional compilation of modern mathematics and its real-world applications. Nothing is clearer than Padilla's love for his work, which will be particularly inviting to lay readers. In a subject that can cause some eyes to glaze over, this is a fast-paced and dramatic telling of the history of mathematics that is ultimately concerned with convincing us why we should care. As Padilla guides readers from the imperceptibly small numbers (what does 10^{-120} really look like?) to the existentially large ones (the rate of expansion of our known universe) that surround, bump up against and bounce off us all, he performs the herculean task of not getting lost in the minutiae.

Conceptualizing the real-world application of abstract mathematics is every professor's dream for their students, and Padilla makes it a reality. In conversational style, he jokes with the reader, frequently making colloquial asides and drawing pictures—using twin sea snakes, for instance, to portray frequency in electromagnetic radiation. Padilla bends light through Jell-O, explains entropy by invoking the soccer rivalry between Manchester and Liverpool, and walks us through Max Planck's work by referencing *Squid Game,* the massively popular Korean TV series.

Readers are urged to consider heady concepts such as the relativity of time through popular knowledge (such as Usain Bolt's sprinting speed)—but never without guidance. Padilla takes great effort to hold our hands through the discoveries he wants us to make; just as we're feeling existentially overwhelmed in imagining the squeeze of spacetime, he leads us to the uncertainty principle, for example, with a punny line to assure us that we've safely made it to the finish line. There is no quantum entanglement to be found here.

Physics and the mathematical equations we use to understand our universe can seem almost impossible, too big or too small or too weird to be real. But Padilla shows us there is nothing more exciting than a math equation left unsolved: Is gravity real? What does the surface of a black hole look like, and is it actually black? Is googol a number any actual layperson has ever needed to use? Why are the answers to these questions not so simple?

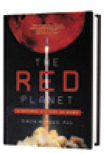
Perusing this book will leave readers with awe, enough fun facts for many cocktail parties, and a deep appreciation for mathematicians like Padilla who can explain how understanding a googolplex leads us to the existence of doppelgängers. *—Brianne Kane*



Fantastic Numbers and Where to Find Them: A Cosmic Quest from Zero to Infinity
by Antonio Padilla. Farrar, Straus and Giroux, 2022 ($30)

IN BRIEF

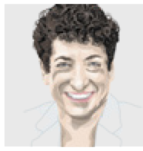
The Red Planet: A Natural History of Mars
by Simon Morden. Pegasus Books, 2022 ($26.95)



Contemplating outer space can just as easily spark existential dread as it can incite wonder. But *The Red Planet,* a geological and historical survey of our solar system neighbor, reads more like a compelling travel guide. Simon Morden, an award-winning science-fiction writer with a doctorate in geophysics, embraces both these backgrounds with gusto whether he's explaining the emergence of volcanoes on the planet or fantasizing about swimming in Martian saltwater. When the planet was in its infancy, Morden situates readers on the "ropey" and "blocky" surface; later in Mars's life, dust storms create "a low susurrus of sound, a thousand whispers just on the other side of our spacesuit helmets." The *Red Planet* does not break new ground in terms of scientific findings (don't expect big scoops about life on Mars, for instance). But this is space writing at its finest, laying out extraterrestrial mysteries and convincing us to care. *—Maddie Bender*

The Mind of a Bee
by Lars Chittka. Princeton University Press, 2022 ($29.95)

Complex alien minds are all around us and deserve more of our curiosity and respect. This is the argument at the heart of *The Mind of a Bee,* a thorough and thoughtful primer on the interiority of bees. Once thought of as a simple, hive-minded species where individuals operate like cogs in a machine, bees are revealed here to be deeply intelligent and capable of rich sensory experiences. Recent work, for example, indicates that they can picture shapes and objects in their minds. Author Lars Chittka pulls from his background as a behavioral ecologist, deftly weaving between history and primary and secondary research to map the ways bees learn about the world around them, develop unique personalities, and perhaps even understand self and emotion. His reflections prompt questions about how bees are treated by humans, making this intimate portrait of one of Earth's most important species appealing to enthusiasts and researchers alike. *—Mike Welch*



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

Climate Damage from Science

Researchers need to reduce their large carbon footprint

By Naomi Oreskes

What is science worth? For many researchers, the answer is "priceless." It's not just that science has provided the basis for modern life through sanitation and energy and electricity and telecommunications or that technology gives us useful things. It's that science deepens our understanding of the world around us in a way the transcends material benefits. Poet William Blake may not have been thinking about science when he described seeing "a World in a Grain of Sand/And a Heaven in a Wild Flower," but he could have been. To me, the deepest value of science is the way in which it can make us feel connected to the scale of the universe, the power of natural forces.

That said, science can be expensive, and recently some researchers have raised challenging questions about one particular cost: its carbon footprint. Large-scale scientific research uses a lot of carbon-based energy and emits a very large amount of greenhouse gases, contributing to our current climate crisis. So, even while scientists are helping us to understand the world, they are also doing some damage to it.

In a recent case study of computer science, Steven Gonzalez Monserrate—a researcher at the Massachusetts Institute of Technology—argues that the environmental costs of this research field, particularly computer cloud storage and data centers, are huge and rising. The cloud, he contends, is a "carbonivore": a single data center can use the same amount of electricity as 50,000 homes. The entire cloud has a greater carbon footprint than the entire airline industry.

And the carbon problem in research is hardly limited to computer science.

Large astronomical observatories and space-based telescopes are big emitters. One study, published earlier this year in the journal *Nature Astronomy,* found that over the course of their lifetimes the world's leading astronomical observatories will produce about 20 million metric tons of carbon dioxide equivalent (CO_{2e}). In a news conference announcing their results, the authors said that if the world is to meet the challenge of net-zero greenhouse gas emissions by 2050, astronomers will have to reduce the carbon footprint of their research facilities by up to a factor of 20. That might mean building fewer big observatories. When these researchers analyzed their own facility, the Institute for Research in Astrophysics and Planetology (IRAP) in Toulouse, France, they found the average greenhouse gas emissions per person were 28 metric tons of CO_{2e} a year, compared with 4.24 metric tons per person for the average French citizen.

Other scientists have focused on the carbon footprint of research conferences. One of climate science's most important gatherings is the annual meeting of the American Geophysical Union (AGU), usually held in San Francisco. Climate modeler Milan Klöwer and his colleagues calculated the travel-related carbon footprint of the 2019 AGU meeting at 80,000 metric tons of carbon dioxide—about three metric tons per attending scientist. That per person output was almost as much as the annual output of an average person living in Mexico. Klöwer offered footprint-reducing ideas: moving the meeting to a central U.S. city to shorten travel, holding the conference biennially and encouraging virtual participation. Taken together, these changes could reduce the travel footprint by more than 90 percent. The AGU has said it plans to rotate locations in the future and use a hybrid meeting format.

But as the analyses of astronomy and computer science show, it's the research, not just travel, that enlarges the scientific carbon footprint. Emma Strubell, a computer scientist at Carnegie Mellon University, and her colleagues concluded—in a study that has not yet been peer-reviewed—that from a carbon budget standpoint, the extreme amount of energy spent training a neural network "might better be allocated to heating a family's home." Similar complaints have been raised about bioinformatics, language modeling and physics.

This is a hard reality to face. But as time runs out to prevent a climate calamity, scientists will have to find a way to do more of their work with much less of our energy. SA

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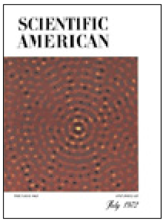
Illustration by David Plunkert

50, 100 & 150 YEARS AGO

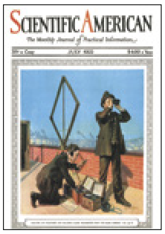
INNOVATION AND DISCOVERY AS CHRONICLED IN *SCIENTIFIC AMERICAN*

Compiled by Mark Fischetti

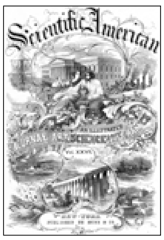
JULY



1972



1922



1872

1972 Faster Photography

"Edwin H. Land, founder of the Polaroid Corporation, gave the first extensive account of his firm's newest system of photography at a recent meeting. Under the title 'Absolute One-Step Photography,' Land demonstrated the new camera and color film that Polaroid expects to place on the market later this year. The new system, Land said, is a compact, automatic camera capable of making a succession of color photographs virtually as fast as the photographer can push the button. The camera weighs 26 ounces and when folded for carrying is roughly the size of a 400-page paperback book."

1922 Swords to Plowshares

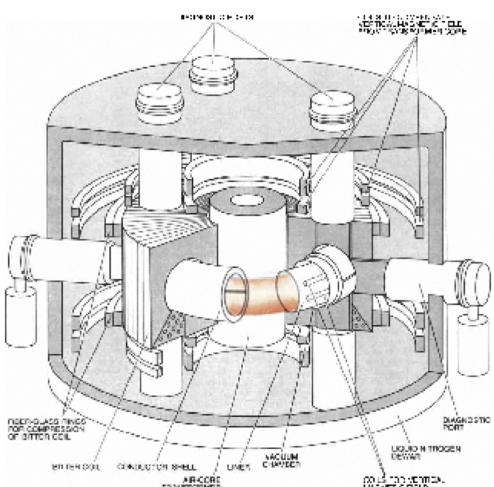
"The Limitation of Armament Conference, in Washington, by restricting the United States naval program from approximately 1,370,000 tons to 525,000 tons, is responsible for the new industry of ship scrapping. The most powerful oxyacetylene and electric torches have been developed. The 50-odd destroyers purchased by the Hitner firm are being ripped apart by powerful chisels operated with compressed air devices. Ten-ton crocodile shears bite through the destroyer plating as though it were cheese, and these pieces are re-melted into ingots and rolled into various shapes for structural steel, rails, sheet plate and other industrial uses. Total annihilation is not the fate of all the former fighting craft. The hulls of some will be converted into fruit boats."

Artificial Lightning

"By means of a special apparatus, the laboratory of Charles P. Steinmetz, chief consulting engineer of the General Electric Company, is producing artificial lightning, which has about one five-hundredth of the horsepower possessed by the lightning flash of nature. It has only one five-hundredth as much voltage. But it is exactly the same sort of energy, stored up and discharged in the same way as in an electrical storm in the heavens. Any object that is placed in the path of the artificial lightning stroke is torn to pieces just as truly as it would be by natural lightning."

Time for Batteries

"For many years the bugbear of clock-makers has been the main-spring. Spring tension and driving power are greater when the spring is tight than when it is partly run down; regulation to insure running at a uniform rate is the most difficult part of clock-making. A new clock, now on the market after some six years of development, has done away with the main-spring. The driving force is electric, and comes from a battery guaranteed to run for a year. The reason is mainly that current is used intermittently. At each tick of the clock the circuit is closed, and the current flows for an extremely short interval of time; during by far the larger part of each second no 'juice' is used."



1972, FUSION: There is "growing awareness that most energy sources have severe deficiencies. Progress in experiments to contain a hot plasma needed for fusion reactions has encouraged hope that proof of the feasibility of a thermonuclear reactor may be attained in the not too distant future." A toroidal-diffuse-pinch machine is portrayed.

Scientific American, Vol. 227, No. 1; July 1972

1872 Count Women as Workers

"According to the census, the United States contains 38,558,371 inhabitants and 12,505,923 working people; 10,669,436 are males, and 1,836,487 females. Between the ages of ten and fifteen years, the males outnumber the females nearly three to one; between sixteen and fifty-nine years, the ratio increases to nearly six to one. This is accounted for by women marrying and settling down to the drudgery of the household. These women are not considered as workers in the census calculations, and here we consider a mistake has been made. The cares of housekeeping and the rearing of children are the heaviest of burdens, and a woman who fulfils her perpetual round of duties ought surely to be classed first on the list of those who earn their bread by hard work. In reality we find that there is a balance on the side of women, in the shape of unending labor, the most monotonous and thankless in existence."

Cement from Sewage

"A new method of disposing of sewage, by making it into cement, has been successfully tested at Ealing, west of London. The principle consists in mixing, with the sewage, quantities of lime and clay, combining with the carbonic acid of the fecal matters to form carbonate of lime, in an impalpable powder. The lime and clay destroy the slimy glutinous character of the sewage 'sludge' and keep the sewer outlet drain free from the festering and putrefying deposit which otherwise tends to choke it. It is claimed that the operation can be profitable, independent of the advantages gained by thus deodorizing and [decontaminating] the excrementitious matters of towns, which must otherwise be disposed of in a manner more or less unhealthy, and very often at great expense."

Text by Clara Moskowitz | Graphic by Jen Christiansen

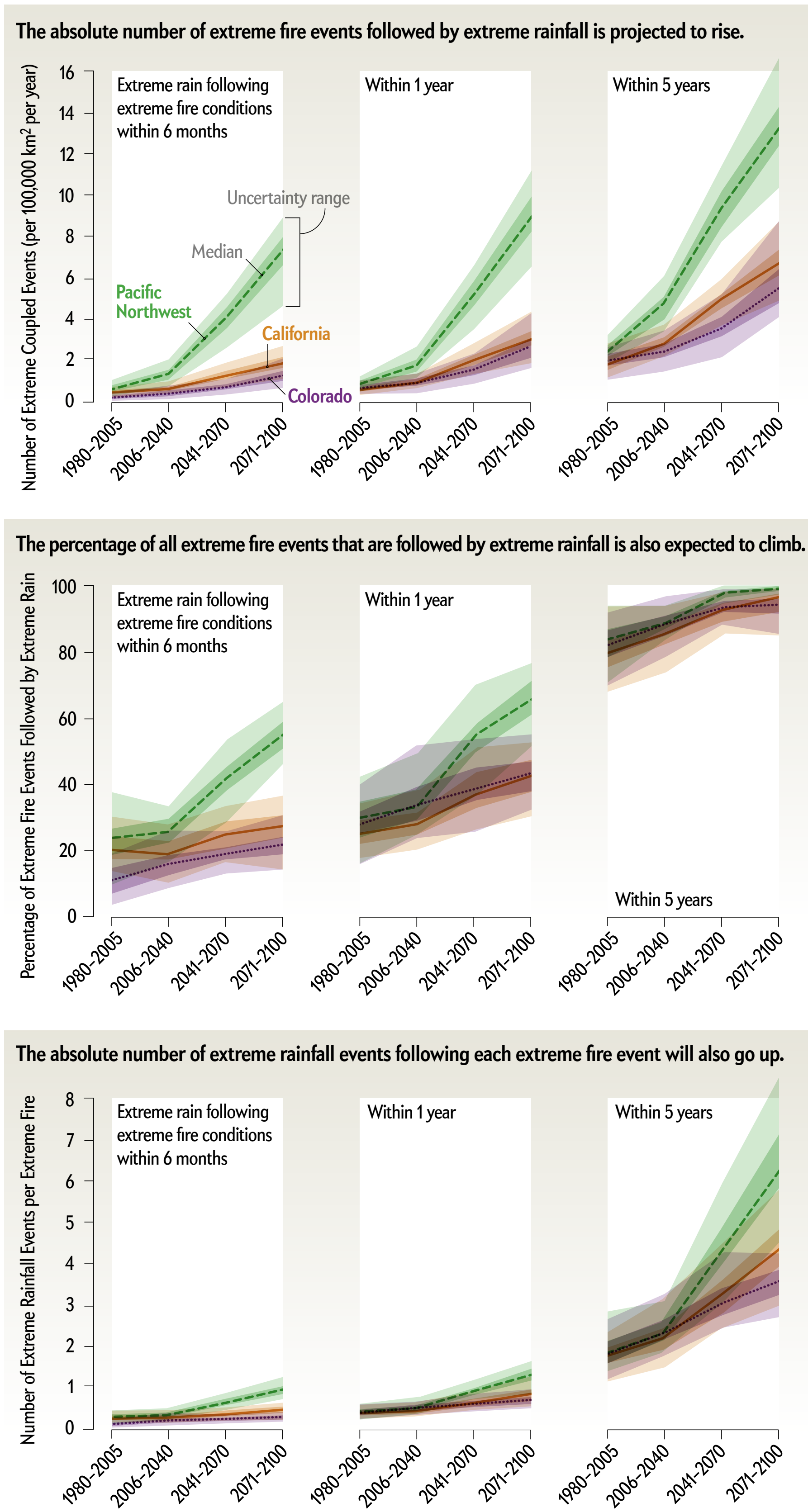
Wild Weather

Western states can expect deluges of rain after fires have scorched the land

Climate change tends to bring out the worst in the weather, be it extreme cold or heat, rain or fire. A new study found that the warming atmosphere increases the likelihood that a wildfire in the Western U.S. will be followed by intense rainfall. This confluence of events raises the risk of landslides and flash floods.

"Once you've had a wildfire burn through, you kill off all the vegetation, and you don't have any root structures there holding the soil in place, so it's a lot more vulnerable," says University of California, Santa Barbara, climate scientist Samantha Stevenson, who was a coauthor on the study.

The fires aren't causing the storms, but the same rising temperatures that lead fires to become more severe allow the atmosphere to carry more moisture, causing rain events to dump more water quickly. "We're talking about super-strong rainstorms, the 99.9th percentile," Stevenson says.



Source: "Climate Change Increases Risk of Extreme Rainfall following Wildfire in the Western United States," by Danielle Touma et al., in *Science Advances*, Vol. 8, No. 13; April 1, 2022 *(data)*


REFORESTATION IS ABOUT MORE THAN PLANTING TREES.
IT'S ABOUT GROWING HEALTHY FORESTS.
Reforestation isn't a silver bullet climate change solution, but planting the right trees in the right place at the right time is an essential part of a holistic climate change mitigation strategy.
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Hey. Maybe we could start fresh?
—Earth
Our world is trying to tell us something.
For humans to thrive, we must rethink our values and systems to craft a framework for a healthy future relationship with our planet that isn't at odds with prosperity. Better is possible. Join us!
globalfutures.asu.edu
ASU Julie Ann Wrigley Global Futures Laboratory
Arizona State University
Reshaping our relationship with our world