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The Future of Particle Physics

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HOW EVOLUTION MADE US THIRSTY

Our need for water helped drive human history

JULY 2021

VOLUME 325, NUMBER 1

SCIENTIFIC AMERICAN

DOUGLAS FOX

ON THE COVER

Humans have evolved to survive in the heat. Our enhanced ability to sweat helps keep us cool during physical activity but elevates our risk of dehydration. We have developed a wide range of behavioral strategies for meeting our water needs.
Photograph by I Am a Photographer and an Artist, Getty Images.

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Scientific American (ISSN 0036-8733), Volume 325, Number 1, July 2021, published monthly by Scientific American, a division of Springer Nature America, Inc., 1 New York Plaza, Suite 4600, New York, N.Y. 10004-1562. Periodicals postage paid at New York, N.Y., and at additional mailing offices. Canada Post International Publications Mail (Canadian Distribution) Sales Agreement No. 40012504. Canadian BN No. 127387652RT; TVQ1218059275 TQ0001. Publication Mail Agreement #40012504. Return undeliverable mail to Scientific American, P.O. Box 819, Stn Main, Markham, ON L3P 8A2. **Individual Subscription rates:** 1 year $49.99 (USD), Canada $59.99 (USD), International $69.99 (USD). **Institutional Subscription rates:** Schools and Public Libraries: 1 year $84 (USD), Canada $89 (USD), International $96 (USD). Businesses and Colleges/Universities: 1 year $399 (USD), Canada $405 (USD), International $411 (USD). Postmaster: Send address changes to Scientific American, Box 3187, Harlan, Iowa 51537. **Reprints inquiries: RandP@sciam.com. To request single copies or back issues, call (800) 333-1199.**
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FROM THE EDITOR

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

Thirst for Knowledge

I apologize in advance, but our cover story on human water needs might make you thirsty. I've been thinking of it every time I take a drink! We humans are weird animals in a lot of ways, but one of the weirdest is that we're really bad, physiologically, at staying hydrated. In fact, we are more dependent on water than most other mammals. As biologist Asher Y. Rosinger explains, starting on page 38, some of our most distinctive technologies, from clay pots to aqueducts to desalination plants, were developed to let us survive and thrive when and where water is scarce.

One of the great joys of studying, reading about or writing about science is that there's always something new and mind-bending to learn. The abbreviation "TIL" for "today I learned" is a way to celebrate and share that joy. People use it a lot on social media to introduce some bit of knowledge that delighted them, even if it's been known for a while and other people might judge them for having learned it just today. It's such a nice sign of humility and enthusiasm, the opposite of "duh, everybody knows that." The fact that humans are so thirsty is just one of the things I learned while reviewing this month's issue.

TIL: The most common state of matter in our universe is plasma. This ionized gas is the fourth state of matter, one we encounter in our daily lives a lot less than solids, liquids or more familiar gases. But plasma is the main ingredient in stars and is most of what exists outside our planet, as well as in some new types of particle accelerators. Electrical engineering professor Chandrashekhar Joshi (*page 54*) is developing these tools with the aim of revealing new fundamental physics.

Rock from Earth's mantle pokes up through the crust in only a few places, including Canada, California, Japan, New Zealand and Oman. A mantle rock called peridotite reacts with water and air once it's exposed, sucking out carbon dioxide and petrifying it—a lot of it—in newly created minerals. Some geologists estimate that Oman's rocks could make a big dent in greenhouse gases if this natural process is accelerated, as journalist Douglas Fox reports, beginning on page 44. Controlling the climate crisis will require many different solutions, and this one is on the verge of scaling up.

Some of the techniques to reverse or prevent soil erosion are also climate solutions, as biologist and science policy expert Jo Handelsman describes, starting on page 62. She shares a quick, smart, achievable list of farming, fertilizing and grazing practices that would benefit food producers as well as the planet. Would you pay extra for food that's labeled for improving carbon storage in the soil? I gladly pay a small premium for coffee grown in bird-friendly conditions, so I'm sure I'd look for that label.

The science of manipulating and even fashioning new proteins is blazing right now, sped up (as much research has been) by the COVID pandemic. In a thrilling story starting on page 28, writer Rowan Jacobsen shows us the race to create better vaccines that could stimulate the immune system more efficiently than the current versions and even prepare our bodies to resist new coronavirus variants. In the photographs for this story, the confident, determined scientists behind this research seem to be saying, "We've got this."

Our final story, on page 66, started with the images. Photographer Grant Delin was amazed by the efficiency and emotion of the vaccine clinic where he got his own COVID vaccine. He teamed up with writer and *Scientific American* contributing editor Robin Lloyd to capture the drama of people experiencing the most important (and speediest) biomedical achievement of our lifetimes. SA

Illustration by Nick Higgins

March 2021

"There is reason to hope that someday we can get to an equitable society in this country and become that beacon that many wish we were."

GARY WEBSTER *LITTLETON, COLO.*

MOON GAZING

In "Alien Moons," Rebecca Boyle describes several techniques for detecting moons around exoplanets. While such findings to date are rare, there is another method that she failed to mention: gravitational microlensing. This approach is of value in dense star fields when a star is transited by a planet whose moon happens to be in the plane of the planet's orbit and alongside it at that time.

David Shander *Denver*

BOYLE REPLIES: Gravitational microlensing is an interesting technique, but it comes with a significant downside, which is that scientists usually have only one chance to use it. Once the planet passes between Earth and some background star, there likely won't be another opportunity to do follow-up confirmation measurements. For that reason, gravitational microlensing is not well suited to discovering exomoons, although it can be used as a statistical technique to study their frequency. Furthermore, astronomers using this method might never know whether the foreground objects are a small star and a planet or actually a planet and a moon.

HISTORY IN MOVEMENTS

I read Aldon Morris's "The Power of Social Justice Movements" with initial skepticism. I was trained as a physicist and had always treated social science as something of a pseudoscience. After reading this excellent article, I see that I was wrong in so many ways. Morris walks us through the process that led to his indigenous perspective theory and compares it with other theories that I previously thought I was in agreement with. I'm not so sure now.

I have seen many of the same things throughout my life that Morris relates in his article, though from the perspective of a white senior currently living in a conservative suburban area near Denver. The death of Elijah McClain and the exoneration of the Aurora, Colo., police officers who perpetrated his death were the catalysts for much of the Black Lives Matter (BLM) protests in Denver.

It seems that many of us are required to raise our voices for social justice time and again with little to show for it. Morris has reminded us that after all these years of "successful" movements, we still have so far to go. I am encouraged by the volume of the voices that speak for social justice, and there is reason to hope that someday we can get to an equitable society in this country and become that beacon that many wish we were.

Gary Webster *Littleton, Colo.*

Morris's article was superb. As a (very) senior American, I lived through the Civil Rights Movement, marches, court rulings, horrific violence perpetrated and continuing to be perpetrated, and now BLM. To have a sociologist describe and explain the growth of academia's perspective on movements, as well as put this huge—and still painful—part of the U.S.'s story in the spotlight, was enlightening.

Lois Rodenhuis *Dover, N.H.*

I appreciated the depth of detail, insight and personal reflection in Morris's cover story. And I was glad to see the prominence that *Scientific American* afforded the article: it's the right time, and this magazine is the right venue for the material.

I know I'm not alone among those in scientific and technical fields in having failed, for far too long, to take necessary hard looks, ask myself hard questions and do the hard work to bring genuine social justice to our professional fields and our country. Now isn't too late, and I'm glad for your help.

Andrew Boyko *via e-mail*

SCIENCE IN DIPLOMACY

In the March Forum column, Nick Pyenson and Alex Dehgan ably and correctly argue that "The U.S. Needs Scientists in the Diplomatic Corps." There is another arm of international "diplomacy" in which U.S. scientists and engineers contributed their talents with significant effect: European outposts established not long after World War II, such as that of the Office of Naval Research in London. Its staff of scientists and engineers were, in effect, traveling science and technology journalists who visited mainly U.K. and European laboratories and reported back to the U.S. scientific community through the publication *European Scientific Notes*. Other components of the U.S. Department of Defense similarly carried out liaison activities in Europe and Asia.

The interactions between U.S. and foreign scientists were extremely successful and exemplify what we can do by employing our scientific talent for international outreach.

Herb Herman *Distinguished Professor emeritus, Stony Brook University*

In 2001 I was posted as one of the National Science Foundation's (NSF's) first Embassy Science Fellows at the U.S. embassy in Bern, Switzerland. During that time I visited 20 strongholds in nanotechnology and science and helped with the drafting of the U.S.-Swiss science and technology framework. I was in Bern for a month, and after I returned to NSF, I co-organized some workshops with Swiss professors. Doing so brought our countries and research communities closer.

I think such programs are very beneficial for all countries around the world. Science and engineering indeed have no national borders.

Ken P. Chong
George Washington University

WRITING THROUGH NEGATIVITY

In "Coping with Pandemic Stress," Melinda Wenner Moyer describes psychological methods to help people whose mental health has declined because of COVID-19. I was relieved to read about the value of writing about negative emotions, though for reasons unrelated to the pandemic. For several years I went through kidney failure, dialysis and related issues. Throughout all that, I kept writing down what I was dealing with. Once I finally got a transplant (just before the pandemic, as luck would have it), I read what I had been writing for all those years and was surprised at how negative so much of it was. On one hand, I had misgivings about the negative tone. But on the other, it still seemed vitally important that I had done this writing and had this record.

Interestingly, I feel no such compulsion to write about the pandemic in the same way. I guess that as abnormal as life now is, it's still much more normal than my life has been for many years.

Jackie Miller *via e-mail*

THE BOMB AND ME

In "Biden's Nuclear Challenge" [Science Agenda], the magazine's editors remind us that we must worry about nuclear war. I happen to have just come across my third grade newspaper, for which I was editor in chief, from February 1951 at P.S. 114 in the Bronx. In the Poetry Corner, a fellow student named George wrote, "Practice, practice every day/I hope the bomb never comes our way./We know we have to be ready/So let us all be calm and steady." Seventy years have passed!

Jay M. Pasachoff *Williamstown, Mass.*

LETTERS TO THE EDITOR

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Long-Term Care Is Broken

The pandemic showed we must invest more in home care and nursing facilities

By the Editors

The COVID pandemic devastated nursing homes. People living in long-term care facilities represent less than 1 percent of the U.S. population but account for a third of its COVID deaths: more than 174,000 people as of early March. And it wasn't just residents—nursing home workers had one of the deadliest jobs last year.

Problems with long-term care precede COVID. Most Americans say they want to remain at home as long as possible as they age, yet many cannot afford such care and wind up in a nursing facility. Such facilities can cost hundreds of dollars a day. Medicaid covers most charges, yet people must be nearly bankrupt to qualify. The program reimburses nursing homes only for 70 to 80 percent of those costs, so it is harder for them to provide quality care.

Most nursing homes are for-profit, and private equity firms are increasingly gobbling them up to make a buck at the expense of residents. Certified nursing assistants (CNAs), who furnish the bulk of care in nursing homes, earn only about $14 an hour; recruiting and retaining them is a huge challenge. And the current U.S. government system for evaluating nursing facilities—the so-called five-star rating system—is largely based on self-reported data that are easy to manipulate, and independent inspections often fail to flag serious violations in the quality of care, according to a recent *New York Times* investigation.

"This isn't just a bad-actor problem," says David Grabowski, a professor of health-care policy at Harvard Medical School. "It's the system that's broken."

How to fix it? President Joe Biden's proposed $2-trillion infrastructure bill offers a promising start toward helping people age at home. The bill includes $400 billion over eight years for home- and community-based care. It expands Medicaid coverage for such services, which states are not currently required to provide (and those that do often have long waiting lists). The bill, which faces steep opposition from Republicans, also aims to establish more and better-paying jobs for home health workers and to give them the ability to join unions and collectively bargain.

These steps are a good beginning, but they don't do anything to help nursing homes. "Nursing homes must be prioritized at the level of other medical facilities," says Lori Porter, CEO of the National Association of Health Care Assistants, which represents CNAs. "We're taking care of the sickest people in America."

The American Health Care Association (AHCA), a nonprofit that represents nursing homes and other assisted living facilities, and LeadingAge, an association of nonprofit aging service providers, recently released a proposal dubbed the Care for Our Seniors Act. The plan would require at least one registered nurse on duty 24 hours a day at every facility (in addition to CNAs and other staff) and a 30-day supply of personal protective equipment. The act includes provisions to attract and retain employees, such as providing loan forgiveness for new graduates working in long-term care, tax credits for employees, and support for child care and affordable housing. And it aims to create better oversight of facilities by focusing more on improving them than punishing them and by closing chronically poor performers. Most nursing homes are badly outdated; the new proposal calls for renovating them and ensuring all residents have private rooms. AHCA says its plan will cost $15 billion a year. To pay for it, the proposal calls for several strategies, including increasing the federal government match for Medicaid, which states have underfunded, and mandating that states pay facilities at a rate sufficient for them to break even.

The AHCA-LeadingAge proposal is on the right track, but one thing it's missing is increased accountability, according to Grabowski. "There's a lot of skepticism that all those dollars are going to find their way to their intended purposes," he says. Beyond top-level reforms, Porter wants to empower nursing home residents and their families to fight for the care they or their loved ones deserve. Taking a tour of a nursing home doesn't tell you anything about the quality of care, she says. Instead you should request a meeting with the president of the resident council, an advocacy group consisting of residents and their families—and if one doesn't exist, you can form one. They can tell you whether a facility is really as good as it claims to be.

These changes will show that we, as a society, value elderly lives—including our own. SA

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Illustration by Islenia Milien

Chethan Sathya is a pediatric trauma surgeon, director of the Northwell Health Center for Gun Violence Prevention in New York State and a National Institutes of Health–funded researcher in firearm injury prevention. **Sandeep Kapoor** is assistant vice president of addiction services and director of screening, brief intervention and referral to treatment at Northwell Health.

Patient Care Must Include a Gun Talk

Doctors need to make safety discussions part of routine care, just like questions about smoking and diet

By Chethan Sathya and Sandeep Kapoor

"Hello, what brings you here today?" a doctor asks a patient.

"I'm here for my checkup," the patient responds.

"Great, let's start with some routine screening questions to see whether you have any risk factors we need to talk about," the doctor says. "Do you exercise regularly? Do you smoke? Do you consume drugs or alcohol? Do you eat a healthy diet? Do you have access to a firearm inside or outside of your household?"

"No, no, no, no, yes," the patient answers.

"Okay, let's talk about firearm safety," the doctor says.

Sounds simple, right? But it really isn't. For years doctors have considered gun violence to be a public health issue. Nevertheless, most health-care workers still do not talk to their patients about guns. In many settings, questions about firearm safety are taboo except in special cases such as those concerning people who are at risk of suicide, which accounts for roughly 60 percent of the nearly 40,000 gun deaths in the U.S. every year. Such targeted screening, however, can introduce bias and stigmatization, which hinders our ability to normalize conversations about firearm safety with our patients.

If we could figure out how to make such safety checks routine, the harm reduction could be significant—and we could provide policy makers with valuable insights into how to depolarize, depoliticize and humanize discussions surrounding the prevention of firearm injuries. After all, we in the health-care lane have a unique opportunity to use an approach that focuses solely on safety and injury prevention, without involving the Second Amendment. Such universal "we ask everyone" strategies—which can remove the pressure to decide who does and does not need screening—have been used successfully in public health approaches to other polarized issues such as substance use, sexually transmitted diseases and HIV.

So why are many doctors hesitant to bring up firearm injury prevention? The truth is that we do not fully understand why. We know very little about how to normalize and humanize conversations about it—and gun-rights activists don't want us to. A decade ago, for example, Florida went so far as to forbid physicians from asking patients routine gun-related questions (courts ultimately invalidated the law as a violation of doctors' First Amendment rights). We do not have the data we need to inform us on the best way to have these talks. Health-care workers already face a number of evident barriers when it comes to such counseling, including a lack of education on the subject, fear of offending some patients, and inadequate resources for screening and counseling about preventive strategies.

Fortunately, the tide is changing. A combination of recent federal funding for research into firearm injury prevention, momentum in the health-care industry and the staggering level of gun violence in the U.S. might finally push doctors to ask every patient about firearm safety and gun violence risk during routine health visits. We need to work diligently with gun owners, survivors and community-based organizations alike to develop culturally competent education and intervention strategies geared toward making these talks a part of routine checkups.

Being able to ask the questions in the first place is an essential starting point. The country is at last getting behind concerned physicians in supporting a public health approach to gun violence prevention. If we succeed in depolarizing conversations about firearm deaths, as well as about the hundreds of nonfatal firearm injuries that happen every day in the U.S., it could have a ripple effect among the general public, further bolstering our argument that this matter is a public health issue.

Let's make sure we get it right. SA

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Illustration by Diana Bolton

ADVANCES

The pesticide DDT, widely dispersed in the U.S. in the mid-20th century, was banned in 1972.

INSIDE

BETTMANN AND GETTY IMAGES

HEALTH

DDT's Long Shadow

Health costs found in grandchildren of women exposed to the pesticide

Hailed as a miracle in the 1950s, the potent bug killer DDT (dichloro-diphenyl-trichloroethane) promised freedom from malaria, typhus and other insect-borne diseases. Manufacturers promoted it as a "benefactor of all humanity" in advertisements that declared, "DDT Is Good for Me!" Americans sprayed more than 1.35 billion tons of the insecticide—nearly 7.5 pounds per person—on crops, lawns and pets and in their homes before biologist Rachel Carson and others sounded the alarm about its impacts on humans and wildlife. The fledgling U.S. Environmental Protection Agency banned DDT in 1972.

Friends and family often ask Barbara Cohn, an epidemiologist at Oakland's Public Health Institute, why she studies the effects of the long-banned pesticide. Her answer: DDT continues to haunt human bodies. In earlier studies, she found that the daughters of mothers exposed to the highest DDT levels while pregnant had elevated rates of breast cancer, hypertension and obesity.

Cohn's newest study, on the exposed women's grandchildren, documents the first evidence that DDT's health effects can persist for at least three generations. The study linked grandmothers' higher DDT exposure rates to granddaughters' higher body mass index (BMI) and earlier first menstruation, both of which can signal future health issues.

"This study changes everything," says Emory University reproductive epidemiologist Michele Marcus, who was not involved in the new research. "We don't know if [other human-made, long-lasting] chemicals like PFAS will have multigenerational impacts—but this study makes it imperative that we look." Only these long-term studies, Marcus says, can illuminate the full consequences of DDT and other biologically disruptive chemicals to help guide regulations.

In the late 1950s Jacob Yerushalmy, a biostatistician at the University of California, Berkeley, proposed an ambitious study to follow tens of thousands of pregnancies and measure how experiences during fetal development could affect health into adolescence and adulthood. The resulting Child Health and Development Study (CHDS) tracked more than 20,000 Bay Area pregnancies from 1959 to 1966. Yerushalmy's group took blood samples throughout pregnancy, at delivery and from newborns while gathering detailed sociological, demographic and clinical data from mothers and their growing children.

Cohn took the helm of the CHDS in 1997 and began to use data from the children, then approaching middle age, to investigate potential environmental factors behind an increase in breast cancer. One possibility was exposure in the womb to a group of chemicals classified as endocrine disruptors—including DDT.

Human endocrine glands secrete hormones and other chemical messengers that regulate crucial functions, from growth and reproduction to hunger and body temperature. An endocrine-disrupting chemical (EDC) interferes with this finely tuned system. Many pharmaceuticals (such as the antibiotic triclosan and the antimiscarriage drug diethylstilbestrol) act as EDCs, as do industrial chemicals like bisphenol A and polychlorinated biphenyls, and insecticides like DDT. "These chemicals hack our molecular signals," says Leonardo Trasande, director of the Center for the Investigation of Environmental Hazards at New York University, who was not involved in the study.

Thawing tens of thousands of CHDS samples from decades earlier, Cohn and her colleagues measured the DDT in each mother's blood to determine the amount of fetal exposure. In a series of studies, they connected this level to the children's midlife heart health and breast cancer rates.

Fetuses produce all their egg cells before birth, so Cohn suspected these children's prenatal DDT exposure might also affect their own future children (the CHDS group's grandchildren). With an average age of 26 this year, these grandchildren are young for breast cancer—but they might have other conditions known to increase risk of it striking later.

Using more than 200 mother-daughter-granddaughter triads, Cohn's team found that the granddaughters of those in the top third of DDT exposure during pregnancy had 2.6 times the odds of developing an unhealthy BMI. They were also more than twice as likely to have started their periods before age 11. Both factors, Cohn says, are known to raise the risk of later developing breast cancer and cardiovascular disease. These results, published in *Cancer Epidemiology, Biomarkers, and Prevention*, mark the first human evidence that DDT's health threats span three generations.

Akilah Shahib, 30, whose grandmother was in the CHDS study and who participated in the current work, says the results provide a stark reminder that current health problems may stem from long-ago exposures. "DDT was a chemical in the environment that my grandparents had no control over," she says. "And it wasn't the only one."

To Andrea Gore, a toxicologist at the University of Texas at Austin, the new results are nothing short of groundbreaking. "This is the first really robust study that shows these kinds of multigenerational outcomes," says Gore, who was not involved in the study.

Laboratory studies, including one by Cohn in 2019, have shown that DDT and other EDCs can lead to effects across generations via epigenetic changes, which alter how genes turn on and off. Cohn is also investigating the multigenerational effects of other endocrine disruptors, including BPA and polyfluorinated compounds.

Such research also highlights the need for long-term testing to determine a chemical's safety, N.Y.U.'s Trasande says. Gore agrees, arguing that regulators should require more rigorous testing for endocrine-disrupting effects; while scientists learn about the specific mechanisms by which EDCs influence health over multiple generations, she adds, they should routinely look for hallmarks of such influences in lab toxicology studies.

As Trasande puts it: "This study reinforces the need to make sure that this doesn't happen again." —*Carrie Arnold*

SPACE

When the Dust Settles

How much space dust lands on Earth every year?

Space debris has rained down on our planet throughout its history—and the celestial shower continues with each passing day. Sizable chunks of rock and metal are the most dramatic examples: they tear through the atmosphere in fiery streaks and occasionally reach the ground as meteorites. But most of what falls to Earth is submillimeter-sized dust particles, called micrometeorites, that are harder to track and quantify.

Now, in a study published in *Earth and Planetary Science Letters*, a team measuring micrometeorite accumulation in Antarctica has estimated that incoming extraterrestrial dust weighs in at around 5,200 metric tons annually.

Polar regions covered with ice year-round are hotspots for micrometeorite research because of their geographical isolation and stasis. Scant material from elsewhere on Earth reaches these places, so the icy terrain soaks up space dust with minimal earthly contamination. Plus, researchers can determine when micrometeorites fell if they find them in annual snow layers that persist year after year.

Both poles work for such research, but "the South Pole is by far the best because you are surrounded by oceans—you are completely isolated from mainlands," says Sorbonne University cosmochemist and study co-author Jean Duprat.

In three field seasons over the past two decades, Duprat and his colleagues collected micrometeorites near the French-Italian Concordia research station in Antarctica's Dome C region. Julien Rojas, a doctoral student at the University of Paris–Saclay and lead author of the study, says the area's sparse snowfall let the team gather decades of annual micrometeorite deposits in one spot without having to melt huge amounts of ice. To avoid human contamination from Concordia, the researchers used snow layers dating from before 1995—a year before research projects at Dome C took off.

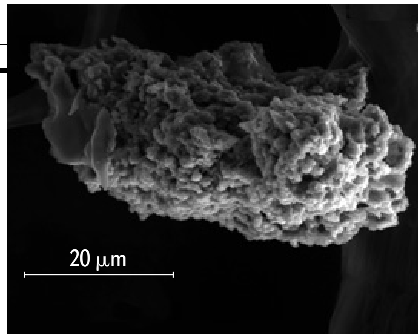
They ultimately isolated and analyzed more than 2,000 particles. Space dust motes usually have several telltale characteristics—for instance, a spherical shape (from melting during atmospheric entry) or a distinctly unearthly distribution of chemical isotopes. The researchers' analyses suggest that more than 60 percent of the space dust on Earth probably originated from "Jupiter family" comets, those that the giant planet's gravitational influence herds into orbital periods of less than 20 years. Another 20 percent of the dust most likely came from the asteroid belt between Mars and Jupiter. "The dust from comets is fluffier than from asteroids," Rojas says, adding that cometary material also tends to be richer in organic matter.

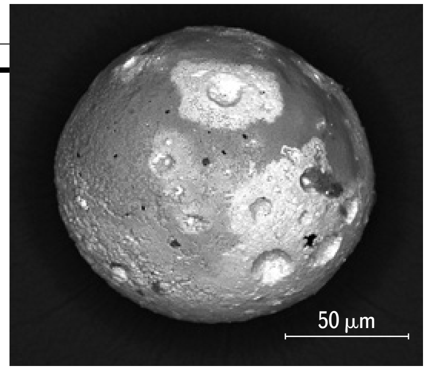
"Meteorites and cosmic dust are these really nice complimentary sets of astromaterials," says Marc Fries, a planetary scientist and curator of NASA's Cosmic Dust Collections, who was not involved in the study. He explains that asteroids tend to be cohesive, rocky bodies from which chunks and shards find their way to Earth's surface as meteorites, whereas comets' loose material easily disintegrates into cosmic dust.

Organic compounds from the latter "probably added a sizable contingent of the total amount of volatiles to Earth's surface: water, carbon and other materials that were important for prebiotic chemistry and for the rise of life," Fries says. "Understanding the full range of composition of these particles gives us a snapshot of the composition of the inner solar system—the small bodies in particular."

When calibrated against the calendar set by annual snowfall at Dome C and extrapolated to the entire planet, the dust's abundance suggested that 4,000 to 6,700 metric tons fall to Earth every year—their best estimate is 5,200. U.S. Naval Research Laboratory geologist Kate Burgess, who was not involved in the new study, is impressed by the work but cautions that this tally cannot be the final word. "Counting hundreds and hundreds of particles—it's just so much work to try to get enough particles to have good enough statistics to take away any kind of statistical error in that number," she notes. In particular, the amount of dust from transient sources such as comets fluctuates over time. Still, Burgess praises the study for putting tighter constraints than some earlier ones on how long the micrometeorites took to accumulate.

"From our perspective inside the community, this is a really good bit of work," Burgess says. Fries agrees, adding that "the scientific community has a long-standing desire for exactly the kind of samples that this team collected"—that is, samples that are fresh, clean and gathered with painstaking precision and care. —*Sarah Derouin*





Antarctic micrometeorites

1


2


3


4


1 Four members of a five-cheetah pack. Male cheetahs usually live alone or in groups of two or three, so this large coalition—known as the Tano Bora, which translates to "the Magnificent Five" in the local Maa language—defies expected behavior.

2 Male lion. As lions' native habitats fragment, national parks provide islands of protection. Or, rather, biologists had thought the parks were islands: in 2020 researchers reported lions moving between groups in three separate national parks, showing that corridors with human settlements can peacefully accommodate the predators.

3 Black rhino with an avian companion. Only about 5,600 of the horned giants are around today; conservationists work to counter poaching and to keep the rhinos mating.

4 Tim the elephant. Schmeisser was only six feet away when he took this shot of the animal, which had evaded poachers and entanglement long enough to have its continuously growing tusks reach nearly to the ground. Tim died of natural causes at age 50 in February 2020.

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JOACHIM SCHMEISSER

ECOLOGY

Science in Images

By Leslie Nemo

The wildlife that roams vast swaths of Africa faces an equally vast array of threats. Poachers collecting prized body parts, along with farmers protecting their crops and livestock, are steadily picking off lions, elephants, giraffes and cheetahs one by one. Agriculture increasingly chips away at savannas, depriving animals of space and contact with others of their kind. Meanwhile climate change is drying up grasses and water sources, increasing the odds that desperate animals will venture closer to humans and put themselves at even higher risk.

Conservationists push back on these pressures by cultivating protected areas such as southern Kenya's Amboseli National Park, whose wildlife inhabitants are documented by photographer Joachim Schmeisser in his new book *Last of Their Kind.*

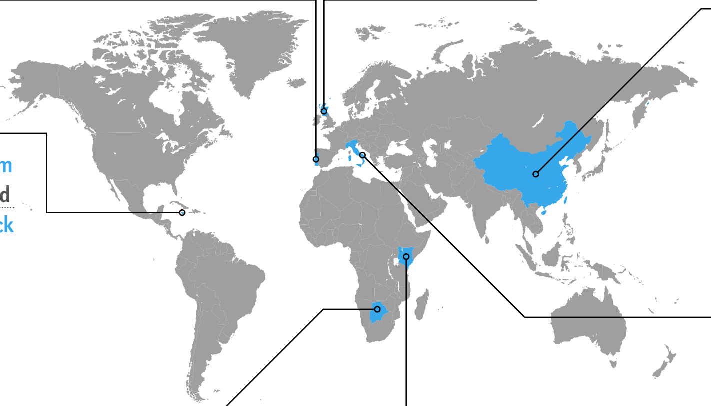
"Some of the largest and most wonderful creatures in Africa have become very dear to me over the years," Schmeisser writes. His book of portraits carries dual messages: "It [is] a homage and warning at the same time—a visual message with the aim of sharpening our clouded view of the one infinitely complex and vulnerable nature, and to recognize which treasures we are about to irretrievably lose."

IN THE NEWS

Quick Hits

By Sarah Lewin Frasier

For more details, visit www.ScientificAmerican.com/jul2021/advances



PORTUGAL

The town of Arouca has opened the world's longest pedestrian suspension bridge, stretching 516 meters across the Paiva River. The bridge is mostly metal with see-through mesh, hanging from steel cables; it was inspired by Incan bridges made from woven grass ropes.

SCOTLAND

A four-story shaft in Edinburgh acts as a huge gravity-powered battery, using grid power to hoist a 50-metric-ton weight—which can later be dropped to generate electricity again. The prototype is an alternative to large chemical batteries.

JAMAICA

Researchers used a core sample from a two-meter-tall pile of accumulated bat guano in a Jamaican cave to track the bats' food sources and how they adapted to changes in climate over 4,300 years.

CHINA

Scientists in northern China discovered a fossilized "monkeydactyl," which appears to be the only known pterosaur with thumbs. The little flying lizard probably used its three-fingered hands to hunt and climb.

ITALY

In Florence, researchers tested a new way to remove vandalism from street art: a thin foil sheet with a solvent-containing hydrogel. Placed for a few minutes on a painted-over work, it softens only the top layers of newer paint, which can then be wiped away.

BOTSWANA

Astronomers plotted a space rock's 22-million-year voyage from the asteroid Vesta to its explosion over the Kalahari Desert in 2018. They analyzed fragments and telescope images to determine its makeup, trajectory and speed—60,000 kilometers per hour just before it hit Earth's atmosphere.

KENYA

Using a specially built barge called the GiRaft, researchers successfully rescued nine critically endangered Rothschild's giraffes stranded on an island in Lake Baringo. The island—originally a peninsula—is vanishing as lake levels rise.

TECH

Too Much Information

AI writes troves of decoy docs

Hackers constantly improve at penetrating cyberdefenses to steal valuable documents. So some researchers propose using an artificial-intelligence algorithm to hopelessly confuse them, once they break in, by hiding the real deal amid a mountain of convincing fakes.

The algorithm, called Word Embedding-based Fake Online Repository Generation Engine (WE-FORGE), generates decoys of patents under development. But someday it could "create a lot of fake versions of every document that a company feels it needs to guard," says its developer, Dartmouth College cybersecurity researcher V. S. Subrahmanian.

If hackers were after, say, the formula for a new drug, they would have to find the relevant needle in a haystack of fakes. This could mean checking each formula in detail—and perhaps investing in a few dead-end recipes. "The name of the game here is, 'Make it harder,'" Subrahmanian explains. "'Inflict pain on those stealing from you.'"

Subrahmanian says he tackled this project after reading that companies are unaware of new kinds of cyberattacks for an average of 312 days after they begin. "The bad guy has almost a year to decamp with all our documents, all our intellectual property," he says. "Even if you're a Pfizer, that's enough time to steal almost everything. It's not just the crown jewels—it's the crown jewels, and the jewels of the maid, and the watch of the secretary!"

Counterfeit documents produced by WE-FORGE could also act as hidden "trip wires," says Rachel Tobac, CEO of cybersecurity consultancy SocialProof Security. For example, an enticing file might alert security when accessed. Companies have typically used human-created fakes for this strategy. "But now if this AI is able to do that for us, then we can create a lot of new documents that are believable for an attacker—without having to do more work," says Tobac, who was not involved in the project.

The system produces convincing decoys by searching through a document for keywords. For each one it finds, it calculates a list of related concepts and replaces the original term with one chosen at random. The process can produce dozens of documents that contain no proprietary information but still look plausible. Subrahmanian and his team asked computer science and chemistry graduate students to evaluate real and fake patents from their respective fields, and the humans found the WE-FORGE-generated documents highly believable. The results appeared in the Association for Computing Machinery's *Transactions on Management Information Systems*.

WE-FORGE might eventually expand its scope, but Subrahmanian notes that a document recommending a course of action, for instance, would be much more complex than a technical formula. Still, both he and Tobac think this research will attract commercial interest. "I could definitely see an organization leveraging this type of product," Tobac says. "If this ... creates believable decoys without releasing sensitive details within those decoys, then I think you've got a huge win there." *—Sophie Bushwick*

PLANETARY SCIENCE

New Moon

Young rocks from China's lunar mission have a story to tell

This summer Chinese scientists begin analyzing the first new samples brought back from the moon in 45 years—specimens that could reset the clock on not just lunar chronology but also planetary bodies' evolution across the solar system. And researchers around the world are eager to get a look.

China's Chang'e 5 mission, whose return capsule reached Earth last December, collected about 1.7 kilograms of rock and soil from Oceanus Procellarum (the Ocean of Storms) in the northwestern corner of the moon's near side. Orbital imagery suggests the crust there formed about 1.5 billion years ago. But that relative youth is at odds with computer models, which show that a small body like the moon should by then have lost the internal heat remaining from its formation—heat needed to drive volcanic resurfacing and crust development.

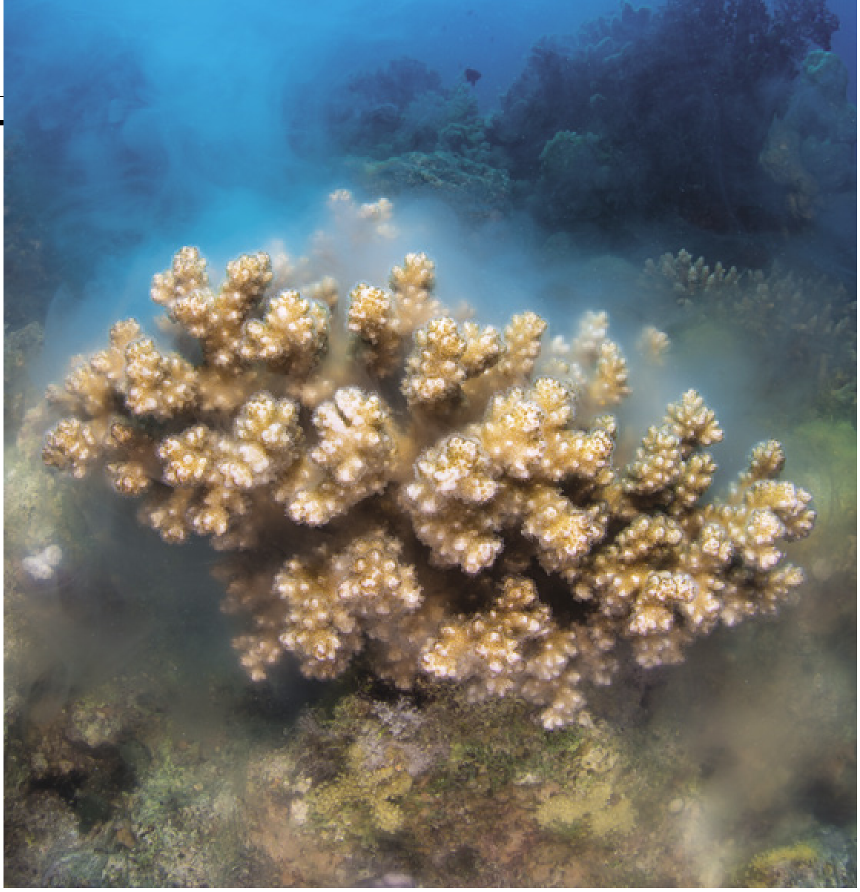
Lacking samples from this region, scientists had estimated its surface age by counting impact craters: older surfaces, they reasoned, would bear more such scars than younger ones would. This technique extends to any solid planetary body. Samples that U.S. and Soviet missions collected from the moon's equatorial, northeastern and northern regions between 1969 and 1976 indicate those surfaces are three billion to four billion years old. "The Apollo samples were like ground truth for the crater-counting models," says Julie Stopar, a geomorphologist at the Lunar and Planetary Institute in Houston. But the earlier samples cover only those older regions: "Anything that happened between roughly three to one billion years ago, we didn't have samples of."

If the new specimens prove younger than the crater-counting models suggest, "that means our whole chronology of the moon needs correcting. That's pretty fundamental," says Brown University planetary scientist Jim Head. Other measurements, such as radioactivity, could help explain lunar volcanoes' extended activity. Learning this history is not only key to lunar evolution; it also helps age-date Mercury, Mars, Earth and other bodies.

A six-month time frame for Chinese investigators to submit requests for samples will end in July or August—and China's policy is to open future allocations to international research teams, Head says. The decade-old Wolf Amendment effectively bans NASA-backed entities from working with China. But exceptions are possible, and other agencies (including the National Science Foundation) are not subject to the congressional rule.

Head, for one, would like to see the U.S. and China conduct an Apollo-Chang'e 5 sample swap. "I'm hopeful in the not too distant future," he says, "we will be able to have some of these kinds of exchanges." *—Irene Klotz*

Illustrations by Thomas Fuchs



ALEX MUSTARD *Nature Picture Library*

BIOLOGY

Coral Cultures

Growing coral cells in the lab could reveal keys to their health

Studying corals usually requires either observing them alive in the ocean or examining their dead tissue in a laboratory. But new research offers a way to keep all coral cell types alive in a lab culture for two weeks or longer, opening novel experimental possibilities.

The cells of cnidarians (a group that includes corals and sea anemones) are notoriously difficult to culture. These cells are easily damaged during extraction, and corals also have complex microbiomes that are tricky to eradicate with antibiotics—but if left alive, the microbes often take over cell cultures.

Many cnidarians are both endangered and critical for marine ecosystem health. "We need to do more than just document their death," says University of Miami marine biologist Nikki Traylor-Knowles, who is senior author on a new study in *Scientific Reports*. In it, her team details how to reduce a coral to its constituent cells and then grow them all together—like cultivating the animal on a plate.

The researchers tweaked a standard growth medium (made of seawater, chemicals and antibiotics) to reach optimal formulas for two different cnidarian species. These formulas let all the tested species' cell types grow at once, without microbes or extraneous tissues. The new methodology will bring unparalleled visibility into how cell types interact, Traylor-Knowles says, and it will allow for higher-volume experiments without raising or killing whole animals.

Scientists do not yet understand all cnidarian cell types, let alone their functions. These cultures could show how different cells respond to stressors, which types are most vulnerable to health failures—and possibly where cnidarians get their impressive regenerative abilities.

The study is groundbreaking, says molecular biologist Juris Grasis of the University of California, Merced, who was not involved with the paper but also studies cnidarians. He says he was "jealous as hell" when he saw the result. Some cell populations survived for as long as 30 days, he notes—which bodes well for the possibility of scaling up cell reproduction for future research. Next up, Grasis says: "How do we translate this back into the field and make corals healthy again?"

—Hannah Seo

ENVIRONMENT

Narwhal Record

Evidence of a warming Arctic caught in spiraling tusks

Narwhal tusks record decades of environmental information and clearly show a changing Arctic, researchers reported in *Current Biology*. Every year the spiraling tusks grow another layer, incorporating variants of carbon and nitrogen called isotopes and some of the mercury a narwhal consumes. The researchers bought 10 tusks from Inuit subsistence hunters in northwestern Greenland and found that the objects contained nearly 50 years' worth of information.

Having access to such a long stretch of data "was just an amazing step forward in our understanding of the factors that affect things like diet and mercury [levels]," says lead author and McGill University marine biologist Jean-Pierre Desforges.

The researchers sliced open the whale tusks (which are actually teeth, made of dentine), ground parts of them into powder and analyzed the samples' isotope content. The results indicate where and what a narwhal might have eaten, as well as its exposure to mercury—a potent toxin whose accumulation affects animals' immune and reproductive systems.

From the 1960s to the 1990s, when sea ice covered much of the narwhals' habitat, carbon and nitrogen isotopes suggest that the animals ate fish high on the food chain that swam near ice or near the seafloor, such as halibut. When sea-ice coverage plummeted after 1990, the carbon isotope profile began to change. It indicated a diet of fish from an ice-free ocean, including polar cod and capelin, species that are a few links lower on the chain and so typically contain less mercury. Yet the narwhals still ingested more of the toxic metal. The researchers say this could possibly result from climate change or increasing emissions, or a combination of the two.

Changing food sources affect narwhals' pollution exposure and access to nutrients, which could eventually alter population levels. More broadly, the research demonstrates narwhal tusks' potential for tracking how the region and its organisms react to climate change, says University of Manitoba marine biologist Cortney Watt, who studies the whales but was not involved in the new research. "I think they are a good sentinel for what's really being laid down in the environment," she says. "They're a good archive of history—and what's happening in the Arctic." —*Susan Cosier*

AGEFOTOSTOCK AND ALAMY STOCK PHOTO

Dictyostelium discoideum in its fruiting body stage

TYLER LARSEN (CC BY SA 4.0), HTTPS://COMMONS.WIKIMEDIA.ORG/WIKI/FILE:DICTYOSTELIUM_DISCOIDEUM_FB_2.JPG

GENETICS

Insights from Amoebas

Microscopic soil dwellers help to battle a killer lung disease

Chronic obstructive pulmonary disease (COPD), which includes emphysema, chronic bronchitis and other conditions, is among the top causes of death in the U.S. No current therapies can prevent or reverse COPD. But thanks to amoebas, a new study has identified genes that may help protect lung cells against such harm—and potentially reverse COPD symptoms.

"I see COPD patients, so this was something very important to me," says the study's lead author Corrine Kliment, a lung disease researcher and physician at the University of Pittsburgh. To search for potentially useful genes, Kliment and her team turned to the soil-dwelling amoeba *Dictyostelium discoideum.*

Amoebas have many genes that are also found in humans, but the microscopic creatures have much shorter life cycles—so scientists can use them to quickly spot genes of interest before studying mammalian models. "We often joke that humans are just amoebas with hair," says study senior author Douglas Robinson, a researcher at Johns Hopkins University.

About 75 percent of COPD deaths are linked to smoking cigarettes. So Robinson's laboratory (in four short weeks) screened 35,000 amoebas, whose genes were modified to overproduce a range of different proteins, to see if any of those proteins might protect the amoebas from smoke damage. When researchers exposed all the amoebas to cigarette smoke extract, they found the ones that fared best were overproducing certain proteins important for cellular metabolism.

Next they looked for those same proteins in human and mouse lung cells. They found that cells from smokers, COPD patients and mice with long-term smoke exposure produced less of one of those proteins in particular, called ANT2.

And the researchers were surprised to observe that ANT2 seemed to be playing another, nonmetabolic role as well. Looking at the lung cells under a microscope, Kliment saw ANT2 accumulating on their surfaces around hairlike projections called cilia, which sweep back and forth to clear mucus from lungs. In COPD, these cilia cannot move well; mucus then builds up and can cause respiratory failure. Kliment and her colleagues found that ANT2 boosted hydration, making it easier for cilia to sweep away mucus. Their study appeared in the *Journal of Cell Science.*

Kliment, Robinson and others now aim to create drugs and gene therapies that increase ANT2 production, which they hope could ease mucus buildup to reverse COPD symptoms. Robinson and some collaborators are working to start a company that will use amoebas to screen candidates for future therapies, including ones for COPD.

Gregg Duncan, a lung disease researcher at the University of Maryland, who was not involved in the study, says he is optimistic that this work may help those with COPD: "It's nice to see an opportunity to reverse the symptoms in a more durable, long-term way." *—Sam Jones*

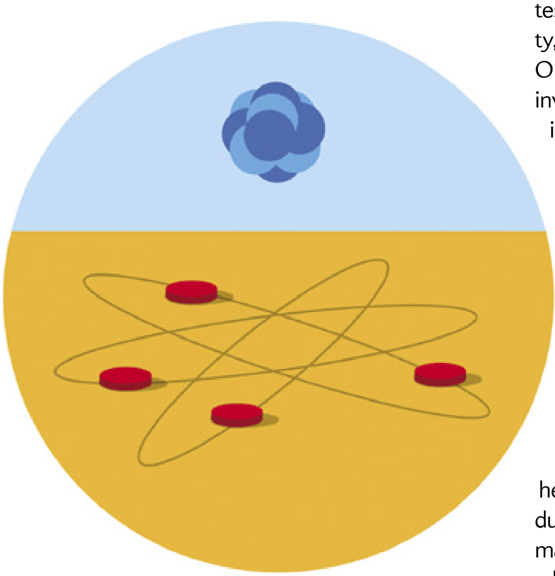
PHYSICS

Electrons in Flatland

Researchers spot 2-D behavior in a 3-D superconductor

The idea of hidden worlds ruled by odd laws of physics sounds like something out of science fiction. Recently, however, scientists observed a hidden, flattened world within a real material built to perfectly conduct electricity. In the *Proceedings of the National Academy of Sciences USA*, researchers reported that electrons in a three-dimensional material behaved as if only two dimensions of space exist.

Our lives happen along three spatial dimensions: depth, width and height. Scientists can engineer extremely thin materials to effectively eliminate



height, but this team, based at SLAC National Accelerator Laboratory, did not do so. While working on a new type of superconductor—a substance in which electrons flow without resistance, used in MRI machines, particle accelerators and some quantum computers—they found something unusual. Their sample, made from barium, lead, bismuth and oxygen, was fully three-dimensional. Yet examination with a powerful quantum microscope found that electrons within it disregarded the third dimension and formed perfectly flat stripes. "Superconducting electrons collapsed spontaneously into this two-dimensional system without any physical or chemical change or specific fabrication," says lead author Carolina Parra, a physicist at the Federico Santa Maria Technical University in Chile.

Physicists had previously speculated that this material might host two-dimensional electron behavior that they could not measure. The new study observed it directly. With the researchers' quantum microscope, "you get information about the physical parameters of the sample, down to the atomic level," says study co-author and SLAC physicist Hari Manoharan. The tool measured an effect called quantum tunneling: electrons from inside the microscope tried to sneak into the sample, revealing characteristics of single superconductor atoms and their electrons.

The electronic "flatlands" that these measurements uncovered are promising test beds for theories of superconductivity, says Nandini Trivedi, a physicist at the Ohio State University, who was not involved with the work. She studies instances in which electrons in extremely thin superconductors form lots of tight-knit islands of particles. Manoharan's team members observed their electrons self-organizing in the same way—and showing more of this distinctive behavior than seen in materials that scientists purposefully engineer as flat.

Pinpointing electrons' specific actions in a superconductor can also help push the development of superconducting materials forward. Most such materials currently known work only when cooled to hundreds of degrees below zero Fahrenheit. This requirement is impractical, but physicists do not yet know what alterations would make them conduct perfectly at room temperature, too, says study co-author and physicist Paula Giraldo-Gallo of the University of the Andes in Bogotá. Some of the tight-knit electron groups measured in this study appeared to superconduct when unexpectedly warm. "This material has the potential to be a higher-temperature superconductor," Giraldo-Gallo says. "What's driving that is an open question." The answer may lie in the new study's 2-D world. —*Karmela Padavic-Callaghan*

EPIDEMIOLOGY

Viral Countdown

New project predicts what animal viruses might cross to humans

Long before COVID-19, scientists had been working to identify animal viruses that could potentially jump to people. These efforts have led to a Web-based platform called SpillOver, which ranks the risk that various viruses will make the leap. Developers hope the new tool will help public health experts and policymakers avoid future outbreaks.

Jonna Mazet, an epidemiologist and disease ecologist at the University of California, Davis, has led this work for more than a decade. It began with the USAID PREDICT project, which sought to go beyond well-tracked influenza viruses and identify other emerging pathogens that pose a risk to humans. Thousands of scientists scoured more than 30 countries to locate and identify animal viruses, discovering many new ones in the process. But not every virus is equally threatening. So Mazet and her colleagues decided to create a framework to interpret their findings. "We wanted to move beyond scientific stamp collecting [simply finding viruses] to actual risk evaluation and reduction," she says.

The team was surprised to find very little existing research on categorizing threats from viruses that are currently found only in animals but are in viral families that can likely cause disease in people. So the researchers started from scratch, identifying 31 factors pertaining to animal viruses (such as how they are transmitted), to their hosts (such as how many and varied they are), and to the environment (human population density, frequency of interaction with hosts, and more). These are summed up in a risk score out of 155; the higher the score, the more likelihood of spillover.

Cornell University virologist Colin Parrish, who was not involved in the study, says the factors examined were important in previous spillovers. But he notes that other viruses' crossover risk may be heightened by unforeseeable factors that crop up later. "It's a bit like the stock market," he says.

The new study, published in the *Pro-*

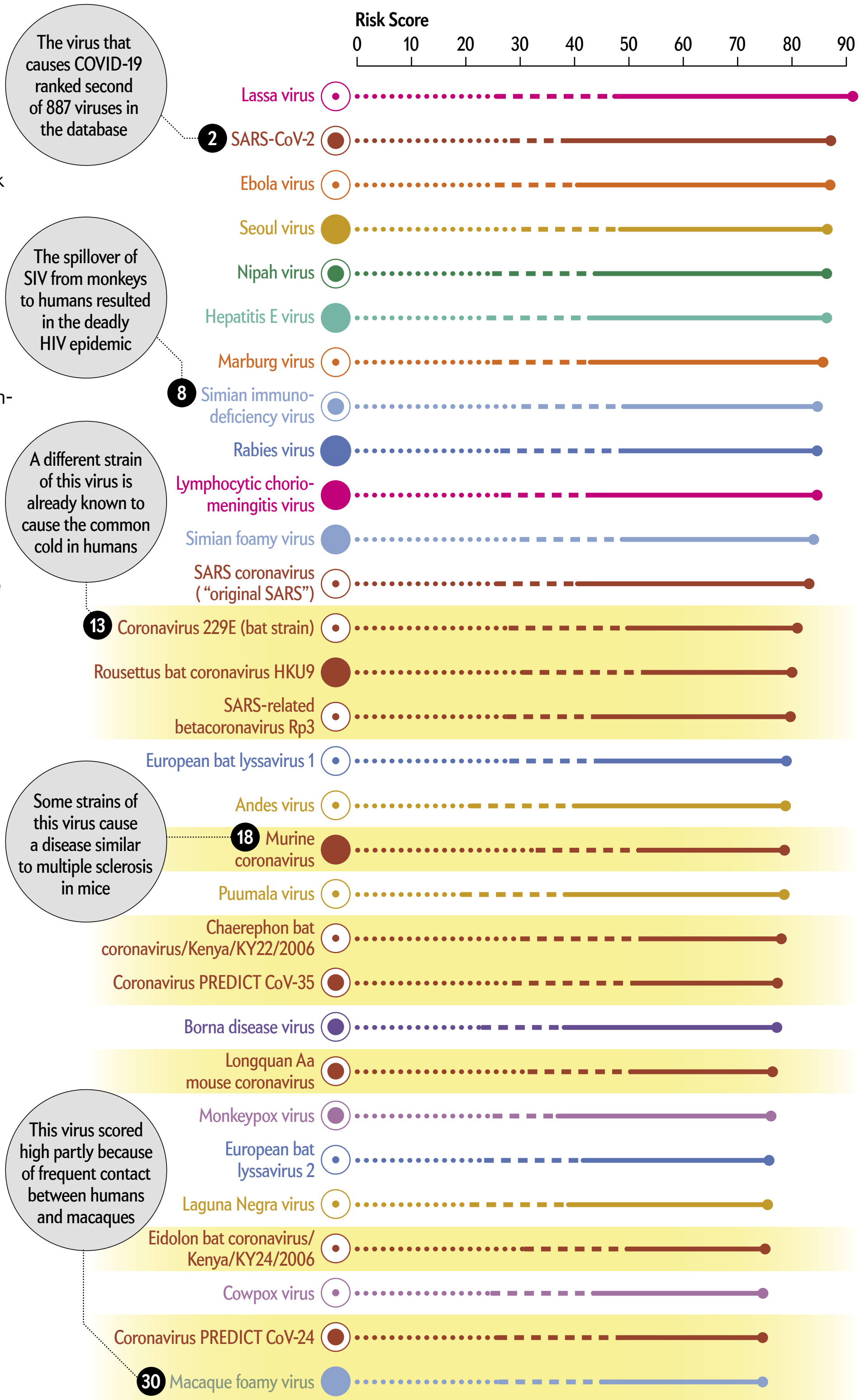
ceedings of the National Academy of Sciences USA, ranks 887 animal-borne viruses. Twelve known human pathogens scored at the top—with the virus that causes COVID-19 in second place, just under the rat-carried Lassa virus. (Influenza would have topped the list if included, Mazet says, but flu variants are already tracked elsewhere.) Parrish notes that the list also omits insect-borne viruses and those from domesticated animals. “This is a work in progress,” he says. “I’m sure it will be iterated into a more powerful tool as more information and data become available.”

SpillOver is publicly editable, and scientists around the world are already contributing their own findings. Mazet hopes it catches the attention of public health practitioners and leaders, too. With targeted action, Mazet says, “we can ensure that we don’t have these spillovers at all. Or if we do, we’re ready for them—because we’re watching.”

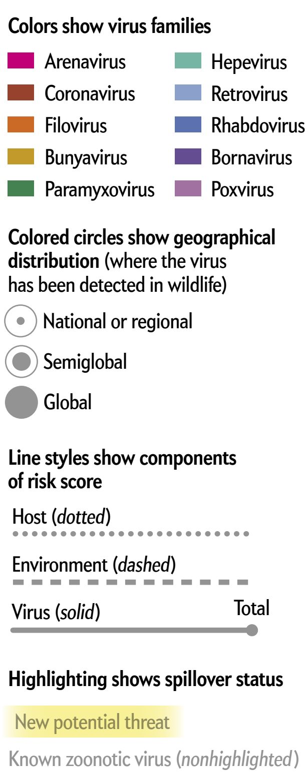
—Harini Barath

Top 30 Viruses by Spillover Risk Score

Scientists ranked each virus by its risk score—the sum of three values based on factors related to the virus itself, its host and its environment. Flu viruses were omitted from the ranking since their spillover potential is already closely studied.



HOW TO READ THE GRAPH



SOURCE: SPILLOVER (HTTPS://SPILLOVER.GLOBAL); DATA AS OF APRIL 7, 2021

Graphic by Amanda Montañez

Christina Olson's poetry collections include *Terminal Human Velocity* and *Before I Came Home Naked,* as well as the chapbooks *Weird Science* and *Rook & The M.E.* Her chapbook *The Last Mastodon* won a 2019 Rattle Chapbook Prize. She has drawn life lessons from a variety of animals and plants, both alive and fossilized.

Lesson from the West African Lungfish
(*Protopterus annectens*)

In a year of panic, envy
any creature who estivates
in the heat. Line a cavity
with mucus & hunker down.
A bunker hardens around you.
Watch the river shrivel
without worry. In the 1950s,
humans dug up backyards,
poured concrete, stocked
canned goods. The lungfish
feeds not off Spam but from
its own muscle, digests
itself into slime & vitamin.
When the rivers flood again,
emerge from your opposite
hibernation. Your legs don't walk,
but they taste. Masticate, mash,
gulp, slurp. Scientists say
you are in a constant state
of agitation, but they are just
jealous. They too want to touch
everything again. To pull
themselves from the muck
& mire. They watch you
gulp a goldfish. Exhale orange
flakes. Swim between stars
in this little galaxy, the one
you built wholly from yourself.

JOEL SARTORE *National Geographic Photo Ark*

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.*

Cancer Blood Tests Get Real

There is rapid progress on "liquid biopsies" for early detection

By Claudia Wallis

Imagine a simple blood test that could flag most kinds of cancers at the earliest, most curable stage. For decades that idea—the "liquid biopsy"—has been a holy grail of oncology. Liquid biopsies could, in theory, detect a tumor well before it could be found by touch, symptoms or imaging. Blood tests could obviate the need for surgeons to cut tissue samples from suspicious lumps and lesions and make it possible to reveal cancer lurking in places needles and scalpels cannot safely reach. They could also determine what type of cancer is taking root and what treatment might work best to squash it.

The grail is not yet in hand, because it is hard to find definitive cancer signals in a tube of blood, but progress in recent years has been impressive. Last year the journal *Science* published the first big prospective study of a liquid biopsy for DNA and proteins from multiple types of cancers, conducted in 10,000 healthy older women. Though far from perfect, the blood test called CancerSEEK, developed at Johns Hopkins University and licensed by diagnostics company Thrive, found 26 malignancies that had not been discovered with conventional screenings such as mammography and colonoscopy. An even larger study is getting underway in London with 25,000 adults who have a history of smoking, using a blood test from a company audaciously named Grail.

No multicancer blood test is close to being approved, but the U.S. Food and Drug Administration has signaled its enthusiasm by designating CancerSEEK as a "breakthrough device," due to its lifesaving potential. That status was also achieved this year by some more narrowly targeted blood tests, including one (from Bluestar Genomics) aimed at picking up pancreatic cancer in high-risk individuals and others that look for glimmers of recurrence in patients already treated for cancer. The breakthrough listing "accelerates the review process," explains Nickolas Papadopoulos, one of the Johns Hopkins scientists who developed CancerSEEK.

Liquid biopsies can rely on a variety of biomarkers in addition to tumor DNA and proteins, such as free-floating cancer cells themselves. "It's believed that there's a lot of turnover within a tumor," explains cancer biologist Ana Robles of the National Cancer Institute, "and as cells are dying, fragments are released into blood."

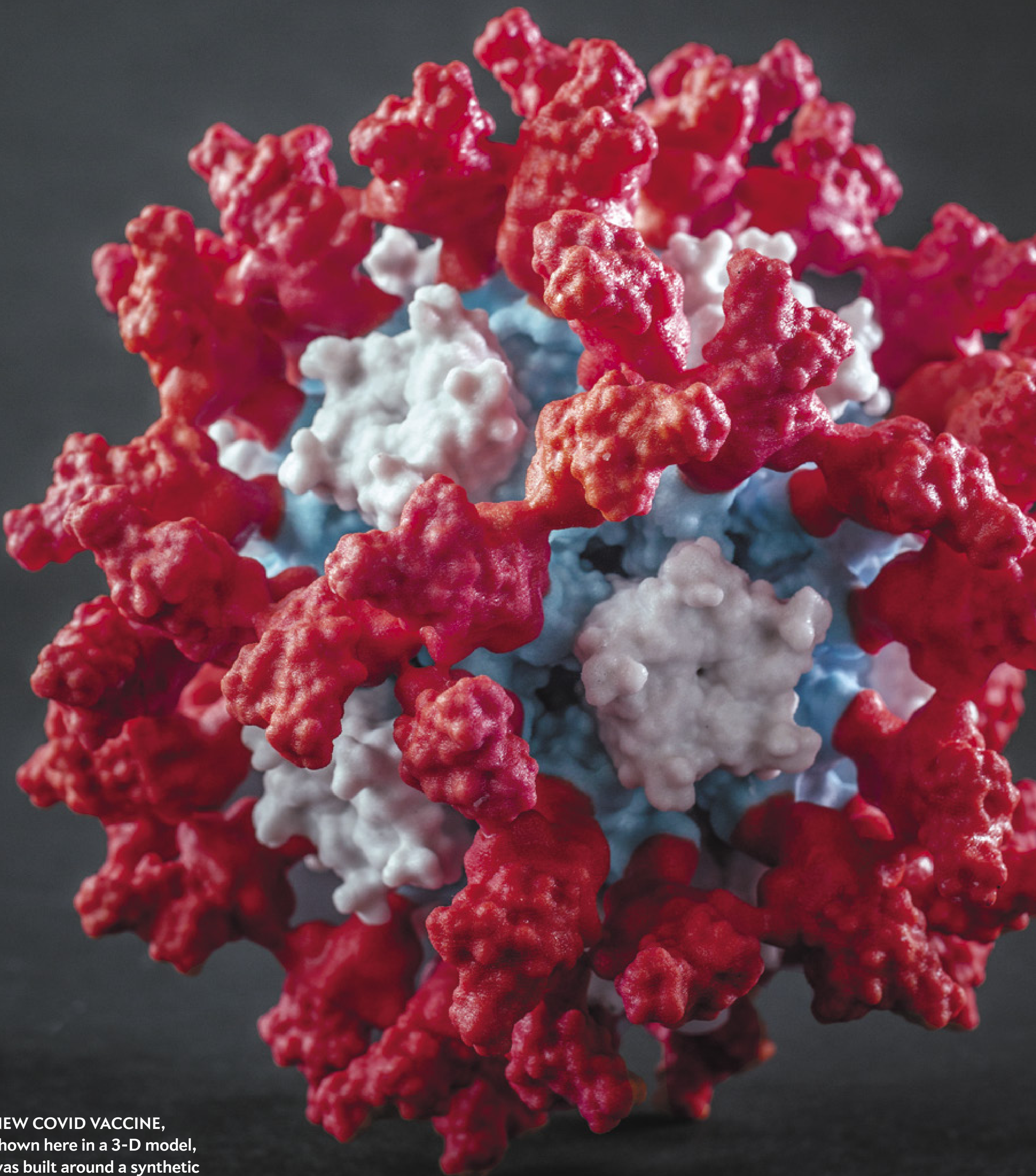
What makes the search difficult, Robles explains, is that "if you have an early-stage cancer or certain types of cancer, there might not be a lot of DNA being shed," and tests might miss it. The ideal blood test will be both very specific (uncovering a mutation or other signal that can only be cancer) and very sensitive so that even tiny tumors can be found. To tackle this challenge, CancerSEEK looks for cancer-specific mutations on 16 genes and for eight proteins that are linked to cancer and for which there are highly sensitive tests. In a study that used an updated version of the test, it detected more than 95 percent of ovary and liver tumors and about 70 percent of cancers of the stomach, pancreas and esophagus but only 33 percent of breast tumors and just 43 percent of stage 1 cancers. It will take further giant, costly studies for pan-cancer liquid biopsies to prove their efficacy for early detection.

And simple detection is not the only goal. An ideal liquid biopsy will also determine the likely location of the cancer so that it can be treated. "Mutations are often shared among different kinds of cancer, so if you find them in blood you don't know if that mutation is coming from a pancreatic cancer or lung cancer," says Anirban Maitra, a pancreatic cancer scientist at the M.D. Anderson Cancer Center in Houston. To solve that problem, some newer liquid biopsies look for changes in gene expression—whether they are turned on or off—as opposed to changes in the genes themselves. Such changes, Maitra notes, are "more organ-specific."

On the nearer horizon are liquid biopsies to help people already diagnosed with cancer. Last year the FDA approved the first two such tests, which scan for tumor DNA so doctors can select mutation-targeted drugs. Scientists are working on blood tests to detect the first signs of cancer recurrence in patients who have completed treatment. This work on "minimal residual disease" is moving fast, Papadopoulos says. "The question is: Does it save lives?"

That is the question companies such as Thrive and Grail must answer for their broadly ambitious screening tests. A high rate of false positives or negatives or a tendency to detect cancers that are slow-growing and trivial will not be useful. "These companies have to prove that they can detect early cancer and, more important, that the early detection can have an impact on cancer survival," Maitra observes. "That is the holy grail of the holy grail." SA

Illustration by Fatinha Ramos



NEW COVID VACCINE, shown here in a 3-D model, was built around a synthetic protein nanoparticle and designed to create powerful immune protection.

BIOCHEMISTRY

Life, New *and* Improved

Natural proteins do everything for us. Now scientists have learned to create artificial ones—a feat that has yielded a new COVID vaccine and could revolutionize biology

By Rowan Jacobsen

Photographs by Timothy Archibald

LATE ON A FRIDAY NIGHT IN APRIL 2020, LEXI WALLS WAS ALONE IN HER laboratory at the University of Washington, waiting nervously for the results of the most important experiment of her life. Walls, a young structural biologist with expertise in coronaviruses, had spent the past three months working day and night to develop a new kind of vaccine against the pathogen ravaging the world. She hoped that her approach, if successful, might not only tame COVID but also revolutionize the field of vaccinology, putting us on a path to defeat infectious diseases from flu to HIV. Unlike any vaccine used before, the vaccine Walls was developing was not derived from components found in nature. It consisted of artificial microscopic proteins drawn up on a computer, and their creation marked the beginning of an extraordinary leap in our ability to redesign biology.

Rowan Jacobsen is a journalist and author of several books, such as *Shadows on the Gulf* (Bloomsbury, 2011) and *Truffle Hound* (Bloomsbury, 2021). His many magazine articles include "The Invulnerable Cell" in *Scientific American's* July 2019 issue and "Ghost Flowers," published in February of that year. He was a 2017–2018 Knight Science Journalism Fellow at the Massachusetts Institute of Technology.

Proteins are intricate nanomachines that perform most tasks in living things by constantly interacting with one another. They digest food, fight invaders, repair damage, sense their surroundings, carry signals, exert force, help create thoughts, and replicate. They are made of long strings of simpler molecules called amino acids, and they twist and fold into enormously complex 3-D structures. Their origamilike shapes are governed by the order and number of the different aminos used to build them, which have distinct attractive and repellent forces. The complexity of those interactions is so great and the scale so small (the average cell contains 42 million proteins) that we have never been able to figure out the rules governing how they spontaneously and dependably contort from strings to things. Many experts assumed we never would.

But new insights and breakthroughs in artificial intelligence are coaxing, or forcing, proteins to give up their secrets. Scientists are now forging biochemical tools that could transform our world. With these tools, we can use proteins to build nanobots that can engage infectious diseases in single-particle combat, or send signals throughout the body, or dismantle toxic molecules like tiny repo units, or harvest light. We can create biology with purpose.

Walls is at the forefront of this research. She completed her doctorate in coronavirus structure in December 2019, making her a member of what was at the time a very small club. "For five years I'd been trying to convince people that coronaviruses were important," she says. "At my Ph.D. defense, I began by saying, 'I'm about to tell you why this family of viruses has the potential to cause a pandemic, and we are not prepared for that pandemic.' Unfortunately, that ended up coming true."

As soon as word of a mysterious new pneumonia trickled out of Wuhan, China, in late December 2019, Walls suspected a coronavirus. On January 10, 2020, the genetic sequence for SARS-CoV-2 was released to the world. Walls and biochemist David Veesler, the head of her lab at the University of Washington, stayed up all night analyzing it. Walls says she felt an overwhelming sense of focus: "It was like, 'Okay, we know what to do,'" she says. "'Let's go do it.'"

LIKE OTHER CORONAVIRUSES, SARS-CoV-2 resembles a ball covered in protein "spikes." Each spike ends in a cluster of amino acids—a section of the protein known as the receptor-binding domain, or RBD—whose alignment and atomic charges pair perfectly with a protein on the surface of human cells. The viral protein docks at the receptor like a spacecraft, and the virus uses this connection to slip inside the cell and replicate.

Because of its dangerous role, the RBD is the primary target of the immune system's antibodies. They, too, are proteins, created by the body to bind to the RBD and take it out of commission. But it takes a while for specialized cells to manufacture enough effective antibodies, and by that time the virus has often done considerable damage.

The first-generation COVID vaccines, including the mRNA vaccines that have been such lifesavers, work by introducing the virus's spike into the body, without a functional coronavirus attached, so the immune system can learn to recognize the RBD and rally its troops. But the RBD is periodically hidden by other parts of the spike protein, shielding the domain from antibodies looking to bind to it. This blunts the immune response. In addition, a free-floating spike protein does not resemble a natural virus and does not always trigger a strong reaction unless a large dose of vaccine is used. That big dose increases costs and can trigger strong side effects.

As successful as the COVID vaccines have been,

VACCINE DEVELOPERS Lexi Walls (*left*) and Brooke Fiala (*right*) used custom-crafted proteins to create a promising new COVID inoculation. It waves a vulnerable part of the SARS-CoV-2 virus in front of immune system cells, provoking a strong neutralizing response.

many experts see inoculations based on natural proteins as an interim technology. "It's becoming clear that just delivering natural or stabilized proteins is not sufficient," says Rino Rappuoli, chief scientist and head of vaccine development at U.K.-based pharmaceutical giant GlaxoSmithKline. Most current vaccines, from childhood inoculations to adult flu shots, involve such natural proteins, which vaccinologists call immunogens; GSK makes a lot of them. "We need to design immunogens that are better than natural molecules," Rappuoli says.

Walls and Veesler had an idea. What if, instead of a whole spike, the immune system were presented with just the RBD tip, which would not have any shield to hide behind? "We wanted to put the key component on display," Walls says, "to say, 'Hey, immune system, this is where you want to react!' "

The immediate trouble with that notion was that biology does not make isolated RBDs, and the segment on its own would be too small and unfamiliar to get the immune system's attention. But Walls and Veesler knew some people who could help them solve that problem. Just up the street from them was the Bell Labs of protein invention, the University of Washington's Institute for Protein Design (IPD). The institute had learned enough about protein folding to design and build a few hundred very simple, small proteins—unlike any that have ever been found in a living organism—that would fold into consistent shapes with predictable functions.

In 2019 a group in the IPD led by biochemist Neil King had designed two tiny proteins with complementary interfaces that, when mixed together in solution, would snap together and self-assemble into nanoparticles. These balls were about the size of a virus and were completely customizable through a simple change to their genetic code. When the scientists festooned the particles with 20 protein spikes from the respiratory syncytial virus, the second-leading cause of infant mortality worldwide, they triggered an impressive immune response in early tests.

Why not try a similar nanoparticle core for a SARS-CoV-2 vaccine, Walls and Veesler thought, using just the RBD instead of an entire spike? As a bonus, the protein-based nanoparticle would be cheap and fast to produce compared with vaccines that use killed or weakened virus. It would also be stable at room temperature and easy to deliver to people, unlike fragile mRNA vaccines that must be kept in a deep freeze.

Walls reached out to the IPD and collaborated with nanoparticle specialist Brooke Fiala, who worked with King, on a prototype—a nanoparticle sphere displaying 60 copies of the RBD. The scientists also tried something radical: Instead of fusing the RBDs directly to the surface of the nanoparticle, they tethered them with short strings of amino acids, like kites. Giving the RBDs a little bit of play could allow the immune system to get a better look at every angle and produce antibodies that would attack many different spots.

But nobody knew whether that would really happen. So on that April Friday last year, as Walls waited for results, she had her fingers crossed. Three weeks earlier she and her colleagues had injected some mice with the nanoparticle vaccine. Other mice got the plain spike that other vaccines were using. Now the researchers had drawn blood from the mice and mixed it with a SARS-CoV-2 pseudovirus, an artificial, nonreplicating version of the virus that is safer to use in labs. The idea was to see whether any vaccinated mice had developed antibodies that would home in on and neutralize the pseudovirus.

It takes a while for antibodies to do their thing, which is why Walls had to wait until late that Friday night. No way was she going home to be kept in suspense all weekend. Her colleagues had wished her good luck as they headed out the door. Before Veesler cut out, he asked her to contact him as soon as she had results.

Now it was dark outside, and the lab was ghostly quiet. It was finally time to look. Walls fired up a lab instrument that could detect and count antibodies attached to virus particles, took a deep breath and peeked at the numbers.

Some mice had been given a low dose of the plain spike, and that was a total failure: zero effect on the pseudoviruses. Mice given a high dose of the spike showed antibodies with a moderate neutralizing effect, similar to what some other vaccines had produced. But in mice that got the nanoparticle vaccine, the pseudovirus was completely outmatched. Antibodies smothered it and had 10 times the neutralizing effect of the large-dose spike preparation. That magnitude held even when only a minuscule dose was used. Walls was looking at something that could be a low-cost, shelf-stable, ultrapotent vaccine.

Walls fired off an all-caps text message to Veesler: "THEY'RE NEUTRALIZING!"

Veesler wrote right back: "The next generation of coronavirus vaccines is in your hands!"

That was only the first of several tests the vaccine had to pass. From there they would have to prove the vaccine could offer protection from the live virus in mice, nonhuman primates and, finally, people. The nanoparticles entered that last testing phase early in 2021. But at that moment, as an emblem of the power of protein design, it was already a success—the clearest sign yet that a technology long beyond our grasp had suddenly arrived. We were learning to sculpt the living clay from which we are all made.

AS TRANSFORMATIONAL as the genetics revolution of the past decades has been, at its heart has always been a mystery: proteins. A gene is simply the code for making a single protein. In that gene, a set of three DNA nucleotides, represented by letters, yields one amino acid, and another triplet codes for a different amino acid. There are 20 amino acids that a cell can use as protein-building blocks, and each one has a unique shape and function. Some are more flexible than others. Some are positively charged, some negative. Some are attracted to water; others are repelled by it.

All day long our cells churn out new proteins in the exact order of amino acids dictated by our genetic code, and the proteins spontaneously snap into shape. That shape, along with the charges of the atoms on the exposed bits, determines the function: what they respond to, what they attach to, what they can do. When we say, "He has the gene for red hair," it means he has the blueprint for proteins that lead to a particular kind of pigment. When we say, "She has a gene that causes breast cancer," it means she has a mutation in a gene that causes its protein to be made with an incorrect amino acid, which screws up its function in a way that can lead to cancer.

Understanding the mechanics of protein folding would allow us to design new classes of drugs that could hobble or replace proteins gone wrong and to probe the etiology of diseases such as Alzheimer's, Parkinson's, Huntington's and cystic fibrosis, which are linked to misshapen proteins.

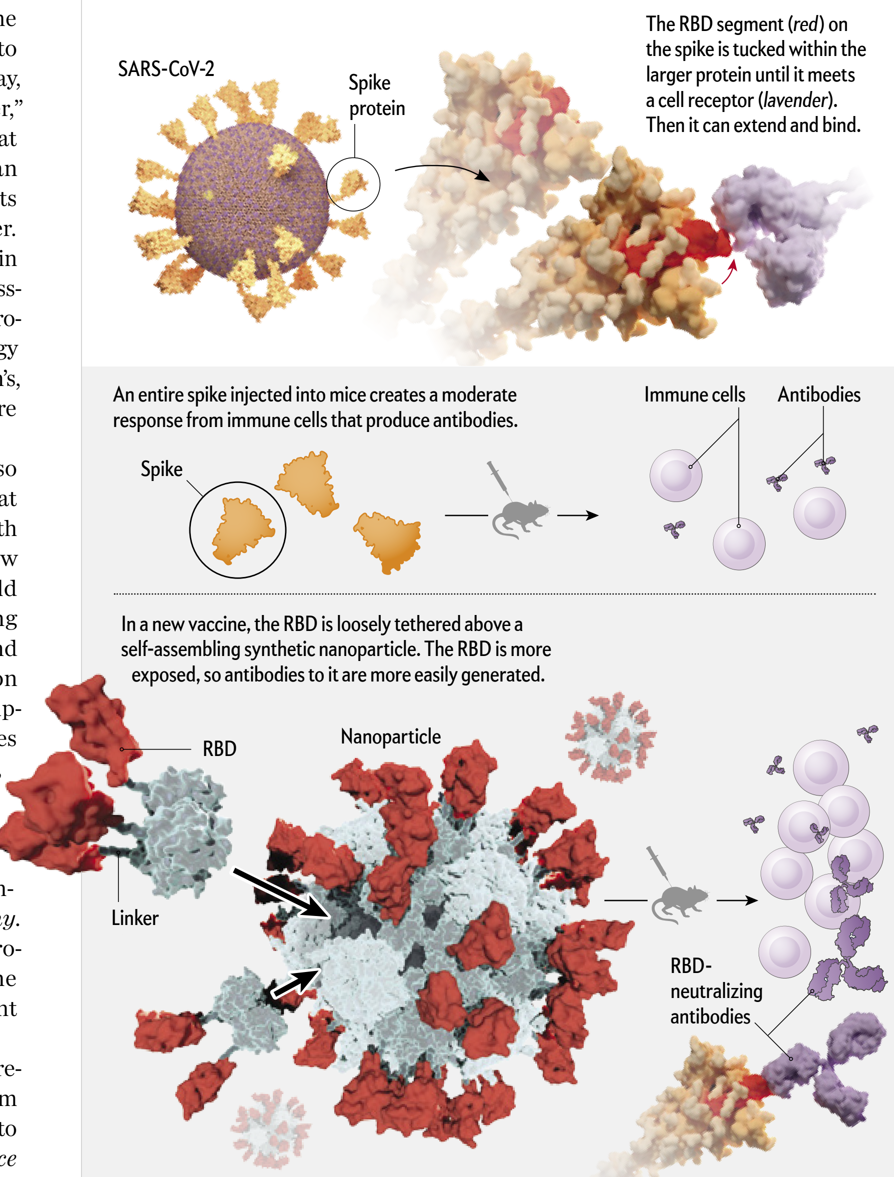
Unfortunately, because proteins are so small, it is almost impossible to tell what is happening in this nanoworld, even with powerful microscopes. We do not know precisely how all of these proteins fold correctly, much less what goes wrong when they misfold. It can take a year and $120,000 to produce a high-resolution image of one protein on specialized equipment. We currently know the structures of just 0.1 percent of them. For the rest, we guess. That is why there is a mystery at the center of the genetics revolution: Certain genetic sequences are associated with physical and mental effects, but often we cannot tell *why*. We have lacked the Rosetta stone of protein structure to translate between the starting point of genes and the end point of bodily functions.

In theory, it should be possible to predict the final structure of a protein from its genetic sequence—a task so essential to our understanding that in 2005 *Science* magazine included it in its 125th-anniversary issue's list of the most important unanswered questions in science. But in reality, it has been possible for only a very few extremely simple proteins. For example, scientists know that if they want to build a straight helix (a common Slinky-like structure in proteins that provides stability), they can use amino acids such as leucine, alanine and glutamate, which have the right curve and complementarity to form regular spirals and bond tightly to the amino acids on the coil above or below them. If scientists want a kink in their Slinky, they can add a proline, which does not form a bond and allows the rest of the helix to bend away from it.

Structural biologists such as David Baker, who

Exposing a Viral Weakness

The SARS-CoV-2 virus cloaks its vulnerabilities. Current vaccines introduce a free-floating version of the viral spike protein into the body, aiming to trigger antibodies. But the crucial part of the spike, the receptor-binding domain (RBD) that attaches to cells, is often hidden within folds of the larger protein. This makes it hard for the immune system to spot the RBD and develop antibodies against it. Now vaccine designers have isolated the RBD and linked it to a synthetic nanoparticle. This appears to generate a powerful antibody response.



TO BLOCK A VIRUS, Longxing Cao of the Institute for Protein Design developed small synthetic proteins called mini binders. They glom on to the part of a coronavirus that attaches to cells, stopping it. Mini binders could be sprayed up the nose to prevent infections.

founded the IPD—where Walls and Veesler went to get their nanoparticles—have been able to deduce a few of these basic rules. Baker's group has incorporated these rubrics into a structure-predicting computer program called Rosetta and used them to make a number of small proteins, typically a few dozen amino acids in size. Some of their successes have shown the great potential of the field: microscopic "nanocages" that could be used to package drugs and transport them into the body and molecular detectors that go off when they encounter cells with specific combinations of amino acids on their surface, indicating such cells are cancerous.

But most important proteins in living things are much bigger than these examples and contain thousands of amino acids, each of which interacts with up to a dozen neighbors, some forming bonds as strong as those in a diamond, some pushing others away. All those relationships morph depending on proximity. So the possibilities quickly become astronomical, and the formulas for figuring out the final structures have long eluded our best minds and supercomputers.

Frustrated by this problem back in 1994, a group of computational biologists decided that a little friendly competition might spur some progress. Led by John Moult of the University of Maryland, they launched CASP, the Critical Assessment of Structure Prediction contest. Moult obtained detailed specs of proteins whose structure had been recently identified but not released. He sent the genetic sequence for the proteins to various teams from different research labs, which then submitted their best ideas about what the finished protein looked like.

Those predictions were scored on their similarity to the actual structure based on the percentage of molecules in the right place. Getting the basic architecture right might score a 50, getting the angles and links between the main parts might be good for a 70, and nailing the tiny molecular threads that sprout off proteins like hairs would merit a 90-plus.

Moult has been running the contest every two years since then. For a long time not even the best teams could do much better than guesswork. In 2012, the year Baker's protein design institute started up, the very best CASP teams were averaging scores in the low 20s, and there had been no improvement for a decade. "There were moments after some CASPs where I'd see the results and despair," Moult says. "I'd think, 'This is all a joke. Why are we even doing this?'" Some new insights led to a rise at CASP11, with the best scores averaging nearly 30, and another slight bump to around 40 at CASP12.

Then came CASP13 in 2018. The best teams, led by Baker's institute, improved again, averaging nearly 50, but they were bested by a surprise entrant: Google's DeepMind, whose artificial-intelligence system had trounced the world's best Go player in 2017. The AI averaged a score of about 57 per protein.

That result rocked the world's protein-engineering labs, but it turned out to be just a dress rehearsal for 2020. In that year DeepMind's predictions were spot-on. "I thought, 'This can't be right. Let's wait for the next one,'" Moult says. "And they just kept coming."

DeepMind averaged a 92 for all proteins. On the easier ones, it had virtually every atom in the right place. But its most impressive results were on some exceedingly difficult proteins that completely stymied most teams. On one molecule, no group scored higher than the 20s—DeepMind scored in the high 80s.

Moult was stunned by the results. "I spent a lot of my career on this," he says. "I never thought we'd get this level of atomic accuracy." Most impressive, he says, is the indication that DeepMind has picked up on previously unknown fundamentals. "It's not just pattern recognition. In some alien way, the machine 'understands' the physics and can calculate how the atoms in a unique arrangement of amino acids are going to arrange themselves."

"It was shocking," agrees structural biologist and CASP competitor Mohammed AlQuraishi of Columbia University. "Never in my life had I expected to see a scientific advance so rapid." AlQuraishi expects the breakthrough to transform the biological sciences.

The DeepMind team is expected to publish its methods paper, with details about how it worked, later this year. Some aspects may remain inscrutable—the AI picks up on faint relationships that cannot easily be explained with rules—but at the moment, scientists do have the general outlines.

To predict amino acids' effects on one another, the machine's programmers invoked a technique called attention that has been responsible for recent leaps forward in accurate language translation by AIs. Like proteins, language is a seemingly linear string of information that folds back on itself to produce meaning. A word such as "it" might draw its significance from a word used in an entirely different sentence. ("For the longest time, AI made no sense to me. And then, after much reading, I finally understood it.") When we communicate, we are constantly moving backward and forward along this linear string, paying attention to one local cluster of words to understand what a different word means in context. Once we have that meaning resolved, we can move to another, related passage and understand those words in light of the new information.

DeepMind does something like this for proteins, focusing its attention on one local cluster of amino acids, understanding as much as it can about their relation to one another. Some pairs of aminos, for example, appear to have coevolved, indicating a bond between them and limiting their possible positions in the protein. DeepMind uses this information to leap to a different part of the protein and analyze that section in light of what it knows about the first cluster. It carries out multiple iterations across all parts of the protein string and eventually uses this information to build a 3-D cloud of points that represents the relations among all the atomic constituents of every amino. It basically treats protein folding like a new, alien language to be deciphered.

As other labs incorporate DeepMind's techniques and on-point protein prediction becomes ubiquitous, AlQuraishi says, the lengthy trial-and-error period of getting a real-world protein to fold like you thought it would will become much faster. "It will percolate everywhere," he says. "It's going to make protein design much more effective."

But the DeepMind team is not in the business of applied science, so the AI will not spend its time churning out blueprints for complicated protein construction on demand. Its big contribution will be indirect. "Their work shines light on the power of proteins and the bright future of engineering new ones," says California Institute of Technology biochemist Frances Arnold, who won the Nobel Prize in Chemistry in 2018 for improving the performance of natural proteins through a method called directed evolution. "But they have not solved the problem of designing or engineering proteins to solve problems for people."

That work will fall to the Arnolds and Bakers of the world, who are trying to use DeepMind's techniques to supercharge their labs' abilities to sculpt proteins. "It's a big breakthrough," says Baker, whose team again finished a distant second in the competition. "I think it will make what's already working well work even better."

A vaccine that is easy to produce, that protects against mutant viruses that may emerge, may be exactly the solution the world needs.

Right now there is an enormous problem for people, to use Arnold's phrase, that is wracking the world. That problem is COVID. When it hit, Baker and others in his lab looked to proteins for solutions. They plugged the genetic sequence for the coronavirus into Rosetta, their protein-structure-prediction computer program, to produce a 3-D model, then pored over it for weaknesses like Rebel pilots plotting an assault on the Death Star. As Walls did, they zeroed in on the spike's RBD. But instead of making a vaccine to trigger antibody production, Baker wanted to build a better antibody. He wanted a protein whose sole purpose was to ensnare the RBD like microscopic Velcro.

Amazing as they are, antibodies are not perfect. The body cannot custom-design an antibody in advance for a pathogen it has never seen, so it makes a lot of different versions. When a new invader shows up, immune system cells make many copies of whatever antibody binds best, but the fit is not always tight enough to stop the pathogen. Natural antibodies are also relatively big proteins that are not always able to get their business end snug against a virus's RBD.

Enter the "mini binders," as Baker calls them. These are small synthetic proteins that can be designed amino acid by amino acid to fit precisely against a virus's RBD. With no extraneous bits, they bind more tightly. And they are small and lightweight enough to be administered through a spritz up the nose rather than an injection into the arm. No needles!

Baker's dream was to create a medication rather than a vaccine: a nasal spray that could be used at the first sign of infection—or beforehand as daily prevention—to flood the nose with a mist of mini binders that would coat the RBDs of virus particles before they could attach to anything. It would have the long shelf life of a bag of dried lentils, and it could be quickly reformulated for any new pathogen and rushed into the hands of health-care workers, teachers and anyone else on the front lines—a kind of designer-driven immune system for civilization.

To engineer the mini binder, Longxing Cao, a postdoc in Baker's lab who headed the project, scouted the virus RBD's structure, comparing it with the library of tiny proteins the institute had previously designed and looking for complementary shapes. Like a rock climber on a challenging face, the mini binder needed to be small enough to wriggle into the cleft where the RBD lay, and it needed to be shaped so that it could get firm handholds and toeholds in the right places. Cao cataloged where the RBD's amino acids made patches of positive electrical charges, patches of negative charges and hydrophobic (water-hating) patches, then tailored mini binders to have as many complementary patches as possible. He tested millions of possibilities on Rosetta.

The best designs were made of three helixes connected like sausage links by short strings of amino acids. Each mini binder was about 60 amino acids long in total—less than a tenth the size of an antibody and a twentieth the size of a coronavirus spike.

Then, of course, Cao had to take his protein from Rosetta to the real world. Amazingly, that process has become trivially easy. DNA—the As, Cs, Gs and Ts of the genetic code—can be printed for pennies on devices that resemble inkjet printers. Cao printed DNA strands with the sequence for his mini binder and inserted them into yeast, which, like programmable livestock, pumped out those tiny proteins along with their normal ones. He then harvested the proteins and tested them.

The top mini binder bound the virus six times more effectively than the best antibodies known—better than any molecule on the planet, in fact, forming dozens of strong bonds with the RBD. It was extraordinarily stable, and it sprayed easily out of a nozzle. Hamsters given a snootful became immune to COVID. "I was definitely excited," Cao says, "but not totally surprised." Researchers expect clinical trials for mini binders to start later in 2021, and a number of labs around the world are now exploring other ways that mini proteins might help the body function or ward off illness.

Although there is great optimism about the technology, some biosecurity researchers have expressed concerns about proteins that could be designed for nefarious purposes. Prions, for example, which are responsible for "mad cow" and other neurodegenerative diseases, are misfolded proteins that cause other proteins to misfold in turn, triggering deadly chain reactions that are transmissible; they could be delivered by aerosol. The Biological Weapons Convention, which virtually all nations have signed, effectively bans the development or use of pathogen-based bioweapons, but no one ever thought to extend it to address proteins that were never part of an organism.

"This is a real concern," says biosecurity expert Filippa Lentzos of King's College London, "because potential future biological weapons won't necessarily make us sick using pathogens." Synthetic mini proteins may or may not fall under the control of the convention, she says, "so legal status is an important issue."

But engineered mini proteins are also an extremely unlikely threat, Lentzos says, and quite low on her list of worries: "If you want to cause harm, why would you turn to something as sophisticated and complicated as protein design? There are plenty of more accessible things in nature you could use." Naturally occurring toxins and pathogens are ready-made and all over the place. If you really want to hurt people, there are easier ways.

AT THIS MOMENT, the helpful types of de novo proteins are attracting an increasing amount of scientific energy and expertise, and the molecules may be coming to a clinic near you. As most of the world's nearly eight billion people await a COVID vaccine, Walls's nanoparticle is looking like a promising candidate.

After successfully neutralizing the pseudovirus in mouse cells, the vaccine's next big test was against the real coronavirus. For that, Walls had to ship her mice to the University of North Carolina lab of Ralph S. Baric, one of the world's foremost coronavirus researchers. The facility has the biosecurity level required to work with the live virus. Baric and his colleagues see many vaccine candidates, so in June 2020 Walls was pleased to get an encouraging e-mail from them: the neutralizing power of the nanoparticle vaccine was off the charts—higher than anything they had tested.

"Everything worked better than we'd hoped!" Walls says. When exposed to the real virus, the mice did well. "Completely protected. No sign of illness." (Later Walls found that she could reduce the already low dose an additional ninefold, add a booster and get equally good results.) In January of this year the vaccine began early clinical trials in Washington State and South Korea.

Yet even as those trials were progressing, the virus was spawning a new wave of variants with the ability to evade some of the antibodies triggered by the first generation of vaccines. So Walls went back to work, designing a new and improved nanoparticle. Instead of copies of just the SARS-CoV-2 RBD, this version had a mosaic of four different RBDs: some from SARS-CoV-2, some from the original SARS virus from the early 2000s and some from two other coronaviruses. This broad spectrum of RBDs elicited a robust antibody response against all coronaviruses tested, including the most elusive of the variants.

A vaccine that is effective in tiny doses, that is easy and inexpensive to produce, that does not require refrigeration and that protects against a bunch of mutant viruses, including ones that may emerge in the future, could be exactly the solution the world needs. These advantages have drawn the attention of the world's vaccine heavyweights, including GSK's Rappuoli. "There is no question that our immune system likes nanoparticles," he says. "These represent the best option we have." In a recent commentary in the journal *Cell,* Rappuoli predicted that such designer molecules will usher in a new era of vaccines: "From here, the sky is the limit."

And the capability will not end with vaccines. In this new Amino Age, the ability to intelligently design nanomachines at an atomic scale could turn fighting every disease into an engineering exercise. "When we tackle problems involving any sort of protein, we need to have this in mind," Walls says. "We need to look at the protein and know that we can engineer solutions. Every day there are new successes coming."

Some of those successes will come in areas other than medicine, such as materials science. The IPD has invented proteins that self-assemble into microscopic honeycomb grids that attract mineral deposition, a new way to produce efficient superconductors and batteries. Another project is crafting proteins that harvest light, as do photosynthetic proteins in plants, and convert that energy into electricity and fuel.

As the Amino Age tool kit grows, the natural proteins we now use for help—insulin for people with diabetes, for instance—may come to seem as archaic as the sharpened rocks our Stone Age ancestors once used. By the same token, our current designer proteins, as exciting as they are, are just sundials and wagon wheels. The features of a future landscape filled with bespoke molecules are beyond conception. But like the new proteins themselves, those features will, eventually and elegantly, fold into shape. SA

FROM OUR ARCHIVES

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

scientificamerican.com/magazine/sa

BIOLOGY

The Hum

Water has been a driving force in our history

By Asher Y. Rosinger

an Thirst

Asher Y. Rosinger is a human biologist at Pennsylvania State University. He studies human variation in water intake and how this relates to environmental resources and health and disease risk.

WE TREKKED THROUGH THE BOLIVIAN AMAZON, DRENCHED IN sweat. Draped head to toe in bug repellent gear, we stayed just ahead of the clouds of mosquitoes as we sidestepped roots, vines and giant ants. My local research assistant Dino Nate, my partner Kelly Rosinger and I were following Julio, one of my Tsimane' friends and our guide on this day. Tsimane' are a group of forager-horticulturalists who live in this hot, humid region. Just behind us, Julio's three-year-old son floated happily through the jungle, unfazed by the heat and insects despite his lack of protective clothing, putting my perspiration-soaked efforts to shame.

We stopped in front of what looked like a small tree but turned out to be a large vine. Julio told us Tsimane' use it when they are in the old-growth forest and need water. He began whacking at the vine from all sides with his machete, sending chips of bark flying with each stroke. Within two minutes he had cut off a meter-long section. Water started to pour out of it. He held it over his mouth, drinking from it for a few seconds to quench his thirst, then offered it to me. I put my water bottle under the vine and collected a cup. It tasted pretty good: light, a little chalky, almost carbonated.

As part of my field research, I was asking Julio and other Tsimane' people how they obtain the drinking water they need in different places—in their homes, in the fields, on the river or in the forest. He told me only two types of vines are used for water; the rest don't work or make you sick. But when he pointed to those other vines, I could hardly tell a difference. The vines are a hidden source of water. Julio's observations raise a fundamental question of human adaptation: How did our evolutionary history shape the strategies we use to meet our water needs, particularly in environments without ready access to clean water?

Here in the forest we were in a relatively water-rich environment, but as we moved away from streams, Julio still knew exactly where and how to get water. Humans are not alone in keeping close track of natural water sources—many animals make mental maps of their surroundings to remember where important resources are found, and some even alter their environments for water. But we are unique in taking much more extreme measures.

Throughout history people have drastically engineered their environments to ensure access to water. Take the historic Roman city of Caesarea in modern-day Israel. Back when it was built, more than 2,000 years ago, the region did not have enough naturally occurring freshwater to sustain a city. Because of its geographic importance to their colonial rule, the Romans, through extractive slave labor, built a series of aqueducts to transport water from springs as far as 16 kilometers away. This arrangement provided up to 50,000 people with approximately 145 liters of water per capita a day.

Today cities use vast distribution networks to provide potable water to people, which has led to remarkable improvements in public health. When we have plenty of water, we forget how critical it truly is. But when water is precious, it is all we think about. All it takes is news of a shutoff or contamination event for worries about water insecurity to take hold.

Without enough water, our physical and cognitive functions decline. Without any, we die within a matter of days. In this way, humans are more dependent on water than many other mammals are. Recent research has illuminated the origins of our water needs—and how we adapted to quench that thirst. It turns out that much as food has shaped human evolution, so, too, has water.

PRECEDING PAGES: I AM A PHOTOGRAPHER AND AN ARTIST *Getty Images* their ability to dissipate heat, making them more water-efficient.

Other key adaptations accompanied this shift in body plan. As climate change replaced forests with grasslands, and early hominins became more proficient at traveling on two legs in open environments, they lost their body hair and developed more sweat glands. These adaptations increased our ancestors' ability to unload excess heat and thus maintain a safe body temperature while moving, as work by Nina Jablonski of Pennsylvania State University and Peter Wheeler of Liverpool John Moores University in England has shown.

Sweat glands are a crucial part of our story. Mammals have three types of sweat glands: apocrine, sebaceous and eccrine. The eccrine glands mobilize the water and electrolytes inside cells to produce sweat. Humans have more eccrine sweat glands than any other primate. A recent study by Daniel Aldea of the University of Pennsylvania and his colleagues found that repeated mutations of a gene called *Engrailed 1* may have led to this abundance of eccrine sweat glands. In relatively dry environments akin to the ones early hominins evolved in, the evaporation of sweat cools the skin and blood vessels, which, in turn, cools the body's core.

Armed with this powerful cooling system, early humans could afford to be more active than other primates. In fact, some researchers think that persistence hunting—running an animal down until it overheats—may have been an important foraging strategy for our ancestors, one they could not have pursued if they did not have a means to avoid overheating.

This enhanced sweating ability has a downside, however: it elevates our risk of dehydration. Martin Hora of Charles University in Prague and his collaborators recently demonstrated that *Homo erectus* would have been able to persistence hunt for approximately five hours in the hot savanna before losing 10 percent of its body mass. In humans, 10 percent body mass loss from dehydration is generally the cutoff before serious risk of physiological and cognitive problems or even death occurs. Beyond that point, drinking becomes difficult, and intravenous fluids are needed for rehydration.

Our vulnerability to dehydration means that we are more reliant on external sources of water than our primate cousins and far more than desert-adapted animals such as sheep, camels and goats, which can lose 20 to 40 percent of their body water with-

TSIMANE' TEENAGER drinks water from a vine in the Bolivian Amazon.

MATTHIEU PALEY

BREAKING A SWEAT

TO UNDERSTAND HOW WATER has influenced the course of human evolution, we need to page back to a pivotal chapter of our prehistory. Between around three million and two million years ago, the climate in Africa, where hominins (members of the human family) first evolved, became drier. During this interval, the early hominin genus *Australopithecus* gave way to our own genus, *Homo*. In the course of this transition, body proportions changed: whereas australopithecines were short and stocky, *Homo* had a taller, slimmer build with more surface area. These changes reduced our ancestors' exposure to solar radiation while allowing for greater exposure to wind, which increased out risking death. These animals have an extra compartment in the gut called the forestomach that can store water as an internal buffer against dehydration.

In fact, desert-dwelling mammals have a range of adaptations to water scarcity. Some of these traits have to do with the functioning of the kidneys, which maintain the body's water and salt balance. Mammals vary in the size and shape of their kidneys and thus the extent to which they can concentrate urine and thereby conserve body water. The desert pocket mouse, for example, can live without water for months, in part because of the extreme extent to which its kidneys can concentrate urine. Humans can do this to a degree. When we lose copious amounts of water from sweating, a complex network of hormones and neural circuitry directs our kidneys to conserve water by concentrating urine. But our limited ability to do so means we cannot go without freshwater for nearly so long as the pocket mouse.

DESERT MAMMALS such as camels have a range of adaptations to water scarcity.

MLENNY *Getty Images*

Neither can we preload our bodies with water. The desert camel can drink and store enough water to draw on for weeks. But if humans drink too much fluid, our urine output quickly increases. Our gut size and the rate at which our stomach empties limit how fast we can rehydrate. Worse, if we drink too much water too fast, we can throw off our electrolyte balance and develop hyponatremia—abnormally low levels of sodium in the blood—which is just as deadly if not more so than dehydration.

Even under favorable conditions, with food and water readily available, people generally do not recover all of their water losses from heavy exercise for at least 24 hours. And so we must be careful to strike a balance in how we lose and replenish the water in our bodies.

QUENCHING OUR THIRST

THERE WAS A REASON I WAS ASKING Julio about "hidden" sources of water, such as vines, that Tsimane' consumed. One evening after dinner a few weeks into my first bout of fieldwork in Bolivia in 2009, the combination of thirst and hunger led me to devour a large papaya. The juices ran down my chin as I ate the ripe fruit. I didn't think much of it at the moment, but soon after I got into my mosquito net for the night, my error revealed itself.

In the Bolivian Amazon, the humidity reaches up to 100 percent at night. Every evening before going to bed I stripped down to my boxers, then rolled my clothes up tightly and put them into large resealable plastic bags so they wouldn't be soaked the next morning. After about an hour of lying in my mosquito net praying for a gust of wind to cool me off, a dreaded sensation set in: I needed to urinate. Knowing the amount of work it would take to get dressed, relieve myself, and then refold and stow my clothes, I cursed my decision to eat the papaya. And I had to repeat the process again later that night. I started thinking about how much water was in that fruit—the equivalent of three cups, it turns out. No wonder I had to pee.

Our dietary flexibility is perhaps our best defense against dehydration. As I learned the hard way on that sweltering night, the amount of water present in food contributes to total water intake. In the U.S., around 20 percent of the water people ingest comes from food, yet my work among Tsimane' found that foods, including fruits, contribute up to 50 percent of their total water intake. Adults in Japan, who typically drink less water than adults in the U.S., also get around half their water from the foods they eat. Other populations employ different dietary strategies to meet their water needs. Daasanach pastoralists in northern Kenya consume a great deal of milk, which is 87 percent water. They also chew on water-laden roots.

Chimpanzees, our closest living primate relatives, also exhibit dietary and behavioral adaptations to obtaining water. They lick wet rocks and use leaves as sponges to collect water. Primatologist Jill Pruetz of Texas State University has found that in very hot environments, such as the savannas at Fongoli in Senegal, chimps seek shelter in cool caves and forage at night rather than during the day to minimize heat stress and conserve body water. But overall nonhuman primates get most of their water from fruits, leaves and other foods.

Humans have evolved to use less water than chimps and other apes, despite our greater sweating ability, as new research by Herman Pontzer of Duke University and his colleagues has shown. Yet our greater reliance on plain water as opposed to water from food means that we must work hard to stay hydrated. Exactly how much water is healthy differs between populations and even from person to person, however. Currently there are two different recommendations for water intake, which includes water from food. The first, from the U.S. National Academy of Medicine, recommends 3.7 liters of water a day for men and 2.7 liters for women, while advising pregnant and lactating women to increase their intake by 300 and 700 milliliters, respectively. The second, from the European Food Safety Authority, recommends 2.5 and 2.0 liters a day for men and women, respectively, with the same increases for pregnant and lactating women. Men need more water than women do because their bodies are larger and have more muscle on average.

These are not hard-and-fast recommendations. They were calculated from population averages based on surveys and studies of people in specific regions. They are intended to fulfill the majority of water needs for moderately active, healthy people living in temperate and often climate-controlled environments. Some people may need more or less water depending on factors that include life habits, climate, activity level and age.

In fact, water intake varies widely even in relatively water-secure locations such as the U.S. Most men consume between 1.2 and 6.3 liters on a given day and women between 1.0 and 5.1 liters. Throughout human evolution our ancestors' water intake probably also varied substantially based on activity level, temperature, and exposure to wind and solar radiation, along with body size and water availability.

AQUEDUCTS brought water from distant springs to the ancient city of Caesarea.

MARIE LISS *Getty Images*

Yet it is also the case that two people of similar age and physical condition living in the same environment can consume drastically different amounts of water and both be healthy, at least in the short term. Such variation may relate to early life experiences. Humans undergo a sensitive period during fetal development that influences many physiological functions, among them how our bodies balance water. We receive cues about our nutritional environment while in the womb and during nursing. This information may shape the offspring's water needs.

Experimental studies have demonstrated that water restriction among pregnant rats and sheep leads to critical changes in how their offspring detect bodily dehydration. Offspring born to such water-deprived mothers will be more dehydrated (that is, their urine and blood will be more concentrated) than offspring born to nondeprived mothers before they become thirsty and seek out water. These findings indicate that the dehydration-sensitivity set point is established in the womb.

Thus, the hydration cues received during development may determine when people perceive thirst, as well as how much water they drink later in life. In a sense, these early experiences prepare offspring for the amount of water present in their environment. If a pregnant woman is dealing with a water-scarce environment and is chronically dehydrated, it may lead to her child consistently drinking less water later in life—a trait that is adaptive in places where water is hard to come by. Much more work is needed to test this theory, however.

KEEPING IT CLEAN

ALTHOUGH EARLY LIFE EXPERIENCES may determine how much water we drink without our being aware of it, locating safe sources of water is something we actively learn to do. In contrast to my accidental discovery of the hydrating effects of the papaya, Tsimane' deliberately seek out water-rich foods. In an environment without clean water, eating instead of drinking more water may protect against exposures to pathogens. Indeed, my study found that those Tsimane' who consumed more of their water from foods and fruit, such as papayas, were less likely to experience diarrhea.

Many societies have developed dietary traditions that incorporate low-alcohol, fermented beverages, which can be essential sources of hydration because fermentation kills bacteria. (Beverages containing higher percentages of alcohol, on the other hand, increase urine production and thereby deplete the body's water stores.) Like other Amazonian populations, Tsimane' drink a fermented beverage called chicha that is made from yuca or cassava. For Tsimane' men, consuming fermented chicha was associated with lower odds of becoming dehydrated.

Getting enough water is one of humanity's oldest and most pressing challenges. Perhaps it is not surprising, then, that we map the locations of water sources in our minds, whether it is a highway rest stop, desert spring or jungle plant. As I watched Julio cut the vine down, his son was also watching, learning where this critical water source was. I glimpsed how this process plays out across generations. In so doing, I realized that being covered in sweat and finding ways to replace that lost water is a big part of what makes us human. SA

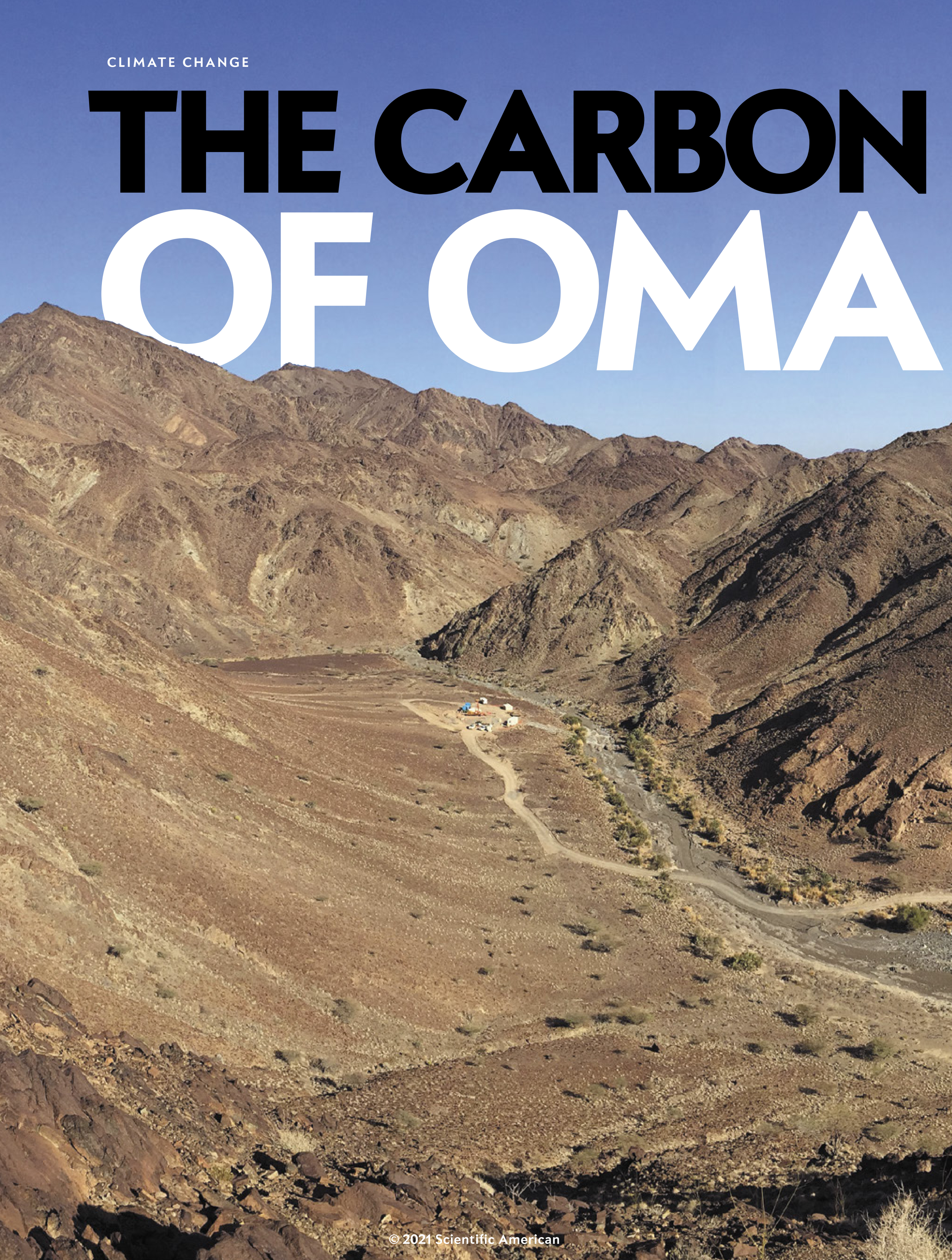
FROM OUR ARCHIVES

The Naked Truth. Nina Jablonski; February 2010.

scientificamerican.com/magazine/sa

CLIMATE CHANGE

THE CARBON OF OMA



ROCKS
N

Could an unusual outcropping of Earth's interior solve the world's climate problem?

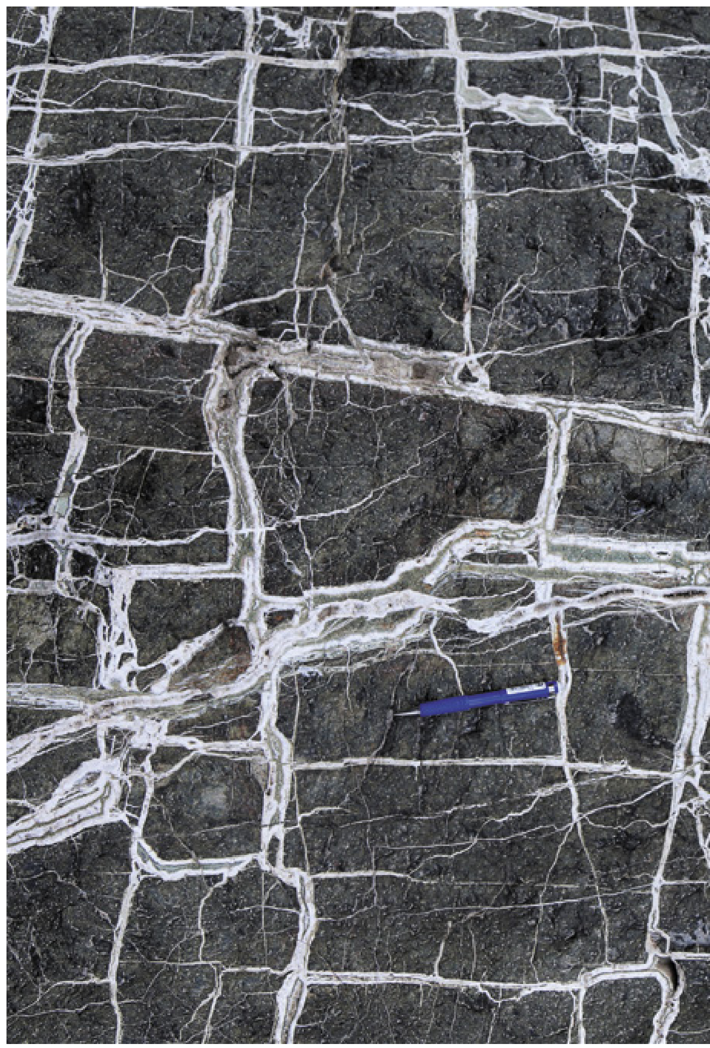
By Douglas Fox

MOUNTAINS of mantle rocks that are usually many kilometers belowground are exposed across Oman and interact with the air, turning carbon dioxide into stone.

Douglas Fox writes about climate science, geology and biology from California. He wrote our 2020 article "Extreme Survivor," about tiny, buglike life in Antarctica.

WADI LAWAYNI IS A REMOTE DESERT VALLEY IN THE INTERIOR AL-HAJAR Mountains of Oman, east of Saudi Arabia. A visitor gets there by following a lonely dirt road that dwindles to tire tracks running through a gravelly wash. Groundwater in this region occasionally surfaces in small pools that have a bluish tint—saturated with alkaline salts and sometimes so full of hydrogen gas that the liquid fizzes like champagne when it's raised out of a well.

The valley, sparsely dotted with thorny shrubs, is ringed by worn pinnacles of faded brown stone that rise hundreds of meters into the air. The rock is an anomaly of minerals that are chemically unstable on Earth's surface. It may have formed dozens of kilometers below the surface, within the mantle—the middle layer of our planet, which humans have never directly seen—far deeper than any oil well or diamond mine. The rock was shoved to the surface through an accident of plate tectonics around 80 million years ago, and now that it is exposed to the elements, it is undergoing a smoldering, flatulent geochemical decay.



Peter Kelemen thinks this geologic oddity might help humans change the course of the climate emergency. He introduced this vision to me one afternoon in January 2018 as we sat in camp chairs in Wadi Lawayni in the tattered shade of a scraggly acacia tree. A hundred meters away, under a canopy, was a makeshift outdoor laboratory with tables, chemicals and a specialized scanner for examining rock samples. Now 65, Kelemen is a geologist at the Lamont-Doherty Earth Observatory at Columbia University, with cropped gray hair and skin tanned by decades of working outside. Leathery dollops of camel dung were strewn in the gravel at our feet. Kelemen motioned to the wall of rock behind us, made of brownish, weathered mantle rock called peridotite. When rain percolates through cracks in the rock, it brings dissolved oxygen and carbon dioxide from the air. The water and gases react with the rock, forming solid veins of new minerals that dig, like tree roots, ever deeper into the stone. The rock was crisscrossed with these creamy-white veins. Kelemen pointed to one a centimeter across composed of magnesium carbonate. "That's about 50 percent CO_2," he said. When I tapped it with a pebble, it emitted a glassy clang.

Kelemen and his colleagues estimate that Oman's exposed mantle rocks are absorbing and petrifying up to 100,000 metric tons of CO_2 every year. That's roughly one gram of the greenhouse gas per cubic meter of stone. "If you [enhance] that by a factor of a million"—something Kelemen thinks is doable with a bit of engineering—"then you end up with a billion tons of CO_2 per cubic kilometer of rock per year," he says. And Oman, with about 15,000 cubic kilometers of the rock, has plenty of capacity. Kelemen's plan involves accelerating the natural reactions by drilling several kilometers down, to where the rocks are hotter, and pumping in seawater saturated with CO_2 drawn from the air.

Similar outcrops emerge from Earth's surface in Alaska, Canada, California, New Zealand, Japan, and other places. Kelemen estimates the worldwide storage capacity of these rocks, including Oman's, as 60 trillion to 600 trillion tons of CO_2—roughly 25 to 250 times the amount that humans have added to the atmosphere since 1850. Kelemen says exploiting that stony repository could have a huge impact. A 2019 report by the Intergovernmental Panel on Climate Change concluded that global warming cannot be limited to 1.5 degrees Celsius—a level generally thought to avoid catastrophic impacts—unless humans somehow remove between 100 billion and one trillion tons of CO_2 from the atmosphere by 2100. If the process started by 2050, that would mean drawing down two billion to 20 billion tons of CO_2 every year.

For this vision to materialize, humans would have to build an extensive, global infrastructure of machines that pull CO_2 from the atmosphere and inject it down wells drilled into mantle rock—a kind of mirror image of the infrastructure that currently extracts fossil fuels, which when burned send CO_2 into the air. Kelemen sees Oman as a bustling center of this vast new industry.

Whether this counterinfrastructure could work will depend on investigations unfolding in Oman. While we chatted under the tree, Kelemen's team of scientists was getting ready to drill down into Wadi Lawayni's floor and extract 400 meters of rock core to study the chemical reactions happening below our feet. A backhoe rumbled in the distance, excavating a pit in preparation for drilling.

The findings, published in 2019 and 2020, revealed a clear path for how humans could enhance the reactions. In late May of this year a new team of workers was scheduled to arrive in Wadi Lawayni to conduct the world's first test of injecting and mineralizing CO_2 deep in mantle rock. If that experiment succeeds, it could be the first step toward transforming Oman, or even the greater Arabian Peninsula, into a major industrial center for managing the climate emergency.

FAST REACTIONS

SCIENTISTS HAVE SPOKEN for decades about counterbalancing greenhouse gas emissions by capturing airborne CO_2 and pumping it into the ground. But an increasing number of studies now indicate that the need for such "negative carbon emissions" has become urgent. Scientists have proposed various strategies. Replanting forests or fertilizing the ocean would, respectively, increase the growth of trees or phytoplankton that naturally absorb CO_2 through photosynthesis. Improved farmland management would allow more of the CO_2 absorbed by crops to remain in the soil after the plants are harvested. "Carbon capture" equipment could filter CO_2 from the smokestacks of power plants or factories, and thousands of "direct-air capture" machines around the world could pull it from the atmosphere night and day.

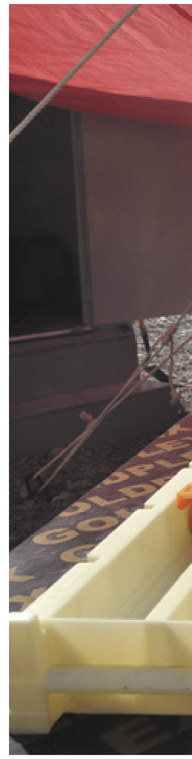
Captured CO_2 has to be permanently sealed away. A few operations have tried. At the Sleipner gas field off Norway's coast, CO_2 that comes up with the natural gas is injected back into sedimentary rocks—grainy deposits such as sandstone—in the reservoir a kilometer below the seafloor. This project, begun in 1996, stores roughly a million tons of CO_2 a year. The issue with such operations is that the CO_2 barely reacts with sedimentary rocks. It mostly percolates amid the rock's pores, leading some scientists to worry that it could gradually leak back out.

Kelemen spent the 1990s pursuing a different line of scientific research, camping for weeks in Oman's remote valleys, called wadis, mapping fossilized vents that once carried magma from deeper, hotter layers of the mantle up toward the surface, where it solidified into rock known as basalt—a hard, dense, dark stone that also forms much of the ocean's crust. But when Kelemen moved in 2004 from the Woods Hole Oceanographic Institution in Massachusetts to Lamont-Doherty, he met geochemist Juerg M. Matter (now at the University of Southampton in England) and physicist Klaus S. Lackner (now director of the Center for Negative Carbon Emissions at Arizona State University). Lackner and Matter were exploring whether CO_2 could be injected into rocks high in magnesium and calcium, which are more chemically reactive than sedimentary rocks and would readily convert the gas into solid minerals—a process called mineral carbonation.

Oman's mantle peridotite rocks contain high levels of magne-

PRECEDING PAGES: JUERG M. MATTER; THIS PAGE: PETER KELEMEN

DARK PERIDOTITE is widespread in mantle rock. It reacts with airborne carbon dioxide dissolved in rainwater that percolates through cracks, forming white veins of carbonate minerals.



sium and calcium in two abundant minerals: olivine and pyroxene. These rocks are shot through with carbonate veins, so they have clearly absorbed CO_2 in the past. But some researchers had assumed it happened over millions of years. Kelemen had never thought much about carbon disposal, yet he was skeptical about the reactions being so slow. While working in Oman, he had often walked past an alkaline spring in a valley called Khafifah, where water burbling from the ground was so saturated in calcium that it continuously reacted with CO_2 in the air, forming a smooth, pearly, paper-thin coat of the carbonate mineral calcite on the surface of the pools. Kelemen noticed that when the calcite film was shattered by wind or rain, it was replaced by a new film within 24 hours. "For a geologist, a thing that happens in a day—that's supersonic," he says.

This fast reaction at the surface made Kelemen wonder whether veins might also be forming underground more quickly than people thought. When he traveled again to Oman in 2007, he and his students collected chunks of carbonate veins. Back home, they had the minerals dated. "I thought those veins would be 90 million years old," Kelemen admits. "They were all less than 50,000 years." Some were only 6,000 years old. Oman's mantle rocks had not just absorbed CO_2 in the distant past; they were still doing it now, perhaps 10,000 times faster than Kelemen had imagined.

During another trip, in 2008, Kelemen and Matter calculated that the minerals accounted for about 1 percent of the rock volume near the surface. That would mean the entire region was naturally solidifying 10,000 to 100,000 tons of CO_2 a year—roughly equal to the annual emissions of 2,000 to 20,000 American automobiles. This amount wouldn't make a dent in climate change, but it caused them to consider whether they could accelerate the process enough to make a worldwide difference.

The two researchers returned to Oman every year for the next four years. They sampled water from wells to trace the chemical reactions that occur as it travels underground. The results suggested that as rain soaks into cracks in the ground, CO_2 dissolved in the rainwater pairs up with magnesium atoms, forming magnesium carbonate veins, until the small amount of gas in the water quickly runs out. Meanwhile calcium from the same mantle peridotite rock dissolves and accumulates in the water as it migrates. They thought that this calcium-rich water eventually reemerged

Map by Mapping Specialists

HOLLOW DRILL slowly bores into mantle rock (*left*), creating a cylindrical core. Researchers lay out sections from the top down (*right*) to see how deeply water penetrates and how much CO_2 is mineralized.

at springs such as the one in Khafifah. There it reacts with CO_2 in the air to form the calcite films that Kelemen had seen, as well as forming vast stepping-stone terraces of a calcite rock called travertine, which are scattered across the region.

Kelemen and Matter still didn't know how much humans could speed up this process. It would depend on how deeply and quickly the water circulated. To answer that question, they needed to get below the surface.

DEEP WATER

ON A WARM, CLOUDLESS AFTERNOON in January 2018, I watched as Kelemen and Matter got a crucial look inside the rocks of Wadi Lawayni. Eight camels chewing on shrubs paid no attention to the grinding roar of the drill mounted on the back of a bulky work vehicle, spinning as it bored into the valley floor.

A cable had already hoisted nine meters of core out of the hole. The core sections, each a couple of meters long and as wide as a baseball bat, were laid out in order on folding tables as half a dozen scientists inspected them. "There's a lot of action in the first few meters," Kelemen said as he moved with purpose from table to table. The color of the rock changed notably with even these relatively small changes in depth.

When the mantle rocks were still deep underground, they would have been dark green because of the magnesium- and calcium-rich minerals olivine and pyroxene formed at temperatures above 1,300 degrees C, in the complete absence of oxygen, water and CO_2. But by the time tectonics and erosion brought the rocks to the surface, the minerals had undergone waves of chemical reactions. The top several meters of rock were tinged in shades of orange, showing that in the layers closest to the surface, oxygen, carried by water, had bonded with iron in the minerals, essentially rusting the rock.

A few meters down those colors disappeared, meaning the dissolved oxygen had been exhausted in the water that had percolated that deep. By this point, the gray rock was perfused with countless, hair-thin turquoise-colored veins—a mineral called serpentine, which forms as water molecules attach to magnesium and iron atoms. (The process produces the hydrogen gas that fizzes from groundwater.)

Crisscrossing that background were white carbonate veins, which had formed as CO_2 latched on to magnesium and calcium. Those veins started out about finger width, but by 10 meters down they were rare and thin, indicating that water had also lost its CO_2 as it seeped downward.

As drilling continued over the coming days, workers packed the cores into crates to make way for dozens of new segments that crowded the tables, creating a veritable flea market of stone cylinders. The rocks from 400 meters deep were still permeated with fine serpentine veins, confirming that water had percolated at least that far down.

Analysis continued at the scientists' labs over the next three years to determine how quickly the rocks were reacting with CO_2 and water. In 2020 and early 2021 I spoke several times with Matter, and he was struck by one pattern seen in all the cores: "You find absolutely no carbonate minerals in veins or fractures below a maximum of 100 meters," he said. For whatever reason, CO_2 was not getting any deeper into the rocks.

Recent analyses published by the team suggest why this may be. In a 2019 paper, Kelemen and his colleagues, including Matter and Matter's former student Amelia Paukert Vankeuren, now at California State University, Sacramento, estimated that groundwater in the upper 50 meters of the boreholes had been there for four to 40 years; it had seeped in from rainfall. But water in the rocks below that had been underground for at least 20,000 years. For a paper published in 2020, Matter and his collaborator Gérard Lods of the University of Montpellier in France measured how readily water moves through the rock by pumping water between two deep boreholes 15 meters apart. They found that water moved relatively easily at spots in the upper 100 meters, but below that the permeability dropped 1,000-fold.

Taken together, these observations show that the rate of mineral carbonation in Oman is limited by a major bottleneck: rainwater simply does not go deeper than about 100 meters. And Oman's mantle rocks are, on average, about three kilometers thick. "It tells us that there's huge potential for carbonation deeper down," Matter says—if water can somehow get down there and circulate rapidly through the rocks so that it provides a steady supply of CO_2.

To overcome this bottleneck, direct-air capture machines,

OPPOSITE PAGE: DOUGLAS FOX; THIS PAGE: JUERG M. MATTER which have fans that pull air through chemical absorbents, would remove CO_2 from the air and concentrate it. Other equipment would pressurize the gas and send it down a borehole. At 1,000 to 3,000 meters down, the gas would be mixed with water (injected through a separate pipe), and the water with dissolved CO_2 would be released into the surrounding mantle rocks. The water would seep through the rock's pores, eventually reaching a second hole as much as 1,000 meters away that would act as a return chimney. The water, depleted of CO_2, would rise back to the surface, where more gas could be concentrated in it again.

Rock temperatures three kilometers down are about 100 degrees C. That heat would accelerate the reactions. Additional heat generated by the reactions themselves would help drive the circulation of warmed water back up the chimneys.

In 2020 Kelemen and Paukert Vankeuren published calculations suggesting that pumping water containing mildly elevated concentrations of CO_2 down to three kilometers could accelerate mineralization by many thousands of times. At that rate a single injection well could capture up to 50,000 tons of CO_2 a year—similar to the amount of the gas being absorbed naturally in all of Oman—under an area of ground about the size of nine soccer fields. Over 10 years that well could capture half a million tons of CO_2.

The scientists extracting cores in Wadi Lawayni did not attempt to inject CO_2 into mantle rocks. But a few years earlier scientists in Iceland had tried injecting CO_2 into a different type of rock that is chemically similar to the mantle. That successful project set the stage for what is now about to happen in Oman.

FRACK FACTOR

HUNDREDS OF KILOMETERS UNDERNEATH the North Atlantic Ocean, between Greenland and Norway, lies a hotspot in the mantle. Heat rising from Earth's core softens the rock. This "partial melt" magma rises buoyantly through cracks up to the seafloor. For 50 million years this magma solidified into basalt—a rock that is derived from the mantle and is one of the major components of our planet's crust. This plateau of basalt rose higher and higher above the seafloor until it emerged from the ocean, forming modern-day Iceland. The gray-black rock is dense, peppered with tiny bubbles. It contains less magnesium and calcium than its parent rock but still more than most rocks on Earth's surface.

By 2005 Matter, Lackner and Wallace Broecker of Lamont-Doherty were convinced that these basalts provided a good opportunity for mineralizing CO_2. Broecker (who died in 2019) collaborated with Reykjavik Energy to initiate a CO_2-injection experiment called Carbfix at Iceland's Hellisheidi geothermal power plant. Starting in 2012, machines separated CO_2 and hydrogen sulfide gas—natural products of the geothermal sites—from the plant's exhaust and injected them through wells 400 to 800 meters back down into the basalt.

Over eight months engineers injected about 250 tons of CO_2. Monitoring at nearby wells showed that 95 percent of it was locked into carbonate minerals within two years. The project has operated ever since, storing roughly 10,000 tons of CO_2 per year. In 2019 Carbfix was spun off as an independent company with the goal of locking a billion tons of CO_2 into basalt by 2030.

Matter, who helped to lead the experiment, sees its results as a major validation. At the beginning, he says, "the carbon capture community thought we were crazy" because basalts were not thought to be porous enough to circulate water through. Since then, another team at Pacific Northwest National Laboratory in Richland, Wash., has also mineralized CO_2 in basaltic rocks—the Wallula Basalt Pilot Demonstration.

Mantle rocks could be more potent than basalts because they contain three times as much reactive magnesium and calcium. One ton of mantle peridotite could solidify up to 500 kilograms of CO_2, compared with about 170 kilograms for a ton of basalt.

But not everyone thinks that mantle rocks, or even basalts, are the perfect solution. Christopher Zahasky, a hydrogeologist at the University of Wisconsin–Madison, says that even though CO_2 injected into sedimentary rocks can migrate, its storage is still secure because powerful capillary forces trap it in the tiny spaces between mineral grains. Even if rock above fractures, the gas is unlikely to leak out.

Zahasky still sees an important advantage to storing CO_2 in basalts and mantle rocks, though. "It's just easier to sell and explain to people," he says—an important consideration given that large-scale projects are unlikely to happen without strong public support. And in some regions such as Oman, India and the U.S. Pacific Northwest, basalts or mantle rocks may be more plentiful than suitable sedimentary deposits. To solve the carbon problem, Zahasky notes, "we really need to throw everything at the wall."

The challenge with mantle rocks, Zahasky says, is that they have far less pore space than sedimentary rocks. "You need more wells to distribute fluids within the subsurface more evenly," he says. Kele-

JUERG MATTER (*left*) analyzes groundwater so saturated in calcium that it reacts with CO_2 in the air, forming pearly white films of calcite on the surface (*above*). Calcite can also accumulate on rock surfaces.

OPPOSITE PAGE: PETER KELEMEN; THIS PAGE: JUERG M. MATTER

men has gnawed on this problem for years. He thinks there's a solution: if injection is done correctly, the chemical reactions themselves could fracture the rocks, allowing water to move through.

When I was in Oman, Kelemen led me down a narrow wash. We stopped beside a rounded hunk of rock the size of a car, riddled with carbonate veins. Brick-sized blocks of rock that once fit snugly together were now tilted and pushed haphazardly apart by the intervening veins—like a ruined building in which the mortar between the bricks has expanded out of proportion. "When I look at this outcrop, I can almost hear it exploding," Kelemen said.

This figurative "explosion" happened in slow motion while the rocks were still underground. When CO_2 attaches to magnesium or calcium to form carbonate minerals, it adds mass. The new material occupies 20 to 60 percent more volume than the prior minerals did. Kelemen's modeling suggests that these carbonate minerals can exert up to 2,900 atmospheres of pressure on the surrounding rock as they grow, pushing the rock apart. The chemical conversion of mantle rocks, Kelemen says, should naturally fracture them—driving cracks ever deeper and wider, exposing new reactive surfaces and allowing more water and CO_2 to trickle in.

Matter and Robert Sohn, a geophysicist at Woods Hole, uncovered evidence of this fracking during two trips to Wadi Lawayni in 2019 and 2020. They lowered hydrophones into several water-filled boreholes that remained after drilling and placed seismometers around the holes. Over the course of a month, they recorded hundreds of microearthquakes that were far fainter than anything a person could feel. "If you have this reaction-driven cracking, it's going to generate these very distinctive signals," Sohn says. The data, he says, "were full of those signals." He cautions that the results are consistent with reaction-driven cracking but don't yet prove it.

Even if engineers could figure out how to harness expansion and cracking to their advantage, they would need to consider unintended consequences. Ballpark estimates suggest that trapping a billion tons of CO_2 in carbonate minerals could potentially increase the volume of the rock by up to a tenth of a cubic kilometer, equal to about 35 Empire State Buildings. If that expansion were distributed in the rocks underlying 300 square kilometers of land—as it would be in one of Kelemen's scenarios—then mineralizing a billion tons of CO_2 a year could conceivably cause the ground to rise by up to 30 centimeters a year.

Injecting just a million tons of CO_2 a year over 300 square kilometers would lead to less than a millimeter of ground rise a year—less than what naturally occurs in many areas from tectonic forces. The expansion becomes problematic only at truly vast scales of injection. Kelemen thinks that to reckon with the issue, any gigaton-scale injection in Oman should occur near the shores of the Gulf of Oman, where engineers could drill diagonally into mantle rocks that sit below the shallow seafloor. Any bulging would probably occur on the seafloor, where it would likely be benign. And the site would obviously provide plentiful

LARGE PORT serves Muscat, Oman's capital. Capturing billions of tons of atmospheric CO_2, and concentrating it in water that is pumped belowground, where it mineralizes, would require extensive industrial infrastructure.

seawater to carry concentrated CO_2, important because groundwater tends to be scarce in this desert nation.

Clearly, questions need to be answered before mantle rocks can start making a dent in CO_2 emissions. A trial to address those questions is beginning.

CONQUERING COST

AN OMAN-BASED COMPANY named 44.01 (after the average molecular weight of CO_2) has received government approval to run the world's first pilot test of mineral carbonation in mantle rocks. The company was to begin moving equipment into Wadi Lawayni in May or June 2021. A few weeks later 44.01 would start injecting freshwater containing CO_2 and an inert tracer chemical into a borehole a short distance from the one I observed in 2018. Researchers would monitor the levels of tracer, CO_2 and dissolved minerals in a second borehole around 100 meters away to determine how quickly water is traveling through the intervening rock and how much CO_2 is being stripped from it. Kelemen and Matter are advising the company. If this experiment shows that CO_2 is mineralizing quickly—which 44.01's founder, Talal Hasan, should know within about four months—the company plans to begin its first commercial injection operation in 2022. It would use freshwater or possibly treated wastewater to carry 10,000 tons of the gas a year down a single well, with hopes of eventually expanding to 100,000 tons a year. The company also plans to initiate a second pilot test closer to the coast, using seawater.

Hasan, an entrepreneur, envisions 44.01 as a mineral carbonation company that will sell its services to firms such as Switzerland-based Climeworks or British Columbia–based Carbon Engineering, which would run their direct-air capture machines in Oman. Carbon dioxide emitted into the air from anywhere on Earth wafts around the planet, so the gas can be captured and disposed of wherever it's convenient. Oman could become a major global center.

Hasan thinks 44.01 could one day mineralize 1.3 billion tons of CO_2 annually in Oman's mantle formation. That quantity would make a meaningful dent in the two billion to 20 billion tons of CO_2 that humans need to remove from the air every year to stay within 1.5 degrees C of warming. Currently 44.01 is the only company trying to inject CO_2 into mantle rocks, but a 2019 report by the National Academy of Sciences suggests that similar mantle formations around the world could lock away upward of 10 billion tons a year. Operations in basalt, such as the one by Carbfix, would add further capacity.

Sequestering a billion tons of CO_2 a year in Oman would require massive infrastructure. Kelemen has calculated that if the gas were concentrated to 440 times what naturally occurs in seawater—which can readily be done by today's air-capture machines—5,000 injection wells would be needed. Together they would pump a combined 23 cubic kilometers of water a year—about 4 percent of the flow of the Mississippi River. The scale of such an operation might sound shocking, but the climate emergency requires a tremendous intervention. And this operation would still be quite small compared with the infrastructure that

VINCENT FOURNIER

extracts fossil fuels. There are more than a million oil and gas wells in the U.S. alone. Of course, it would be up to humanity to use the opportunity to switch to renewable energy rather than as a license to emit even more carbon.

Cost will be pivotal. Carbfix in Iceland is mineralizing CO_2 for about $25 a ton (44.01 is not releasing any official cost estimates). That falls within the price ranges of strategies such as reforestation and crop soil management, which store carbon less permanently, according to a 2018 report by an international group of scientists, published in *Environmental Research Letters*.

The real challenge is capturing and concentrating the CO_2 before it's injected. Kelemen's collaborator Jennifer Wilcox, who is serving as the U.S. principal deputy assistant secretary for fossil energy, and her Ph.D. student Noah McQueen of the University of Pennsylvania have developed a framework for estimating the combined cost of capturing and compressing CO_2, including workers' salaries and expenses for building and maintaining the hardware over 20 years. Their numbers suggest that the cost would be roughly $120 to $220 per ton of CO_2 removed from the atmosphere. Direct-air capture requires a lot of energy, and "if you choose to use fossil [fuels]," Wilcox says, "you have to think about the cost of managing the additional carbon" produced. The technology is still young, says Ajay Gambhir, a climate economist at Imperial College London, and innovation could bring its costs down. If the machinery follows the same trajectory that wind turbines have over the past decade, it could cost about a quarter of the rate today. But "we don't really know until it's scaled up," Gambhir says.

It is unlikely that many emitters will pay for air capture and mineral carbonation until governments place a price on greenhouse gas emissions. Gregory Nemet, an energy policy researcher at the University of Wisconsin–Madison, says that although current carbon taxes imposed by industrialized countries are generally under $50 per ton of CO_2, a carbon fuel standard in California is prompting companies to spend up to $200 a ton on carbon credits, with prices likely to increase over time. That figure provides an opening for a mineralization company such as 44.01 working in partnership with a direct-air capture company to start a small joint operation. As more governments institute carbon pricing, the demand for these services could grow. "They don't have to be doing gigatons [of CO_2] by 2025," Nemet says. "What they need is a sequence of increasingly large facilities they learn from and improve to get the cost down over time."

Oman is an attractive location for more than its rocks; the country's big fossil-fuel industry has expertise handling pressurized gases, and sunlight is intense year-round. An operation capturing a billion tons of gas a year would require 700 billion to 1.3 trillion kilowatt-hours of energy, according to McQueen's calculations. This power could come from 300 to 600 square kilometers of solar arrays, occupying no more than 0.2 percent of Oman's territory, according to standard formulas based on sunlight intensity.

Oman is also known for its dramatic coastlines, canyons, medieval fortresses and mosques, which attract millions of tourists every year. And it is home to a traditional Bedouin population that migrates seasonally. This fragile heritage must be protected, but the country, and the Arabian Peninsula as a whole, has an abundance of empty, arid land that could host a burgeoning negative-emissions industry.

Scientists have other visions about how to use mantle rocks. Some suggest, for example, that they be mined, crushed to increase their surface area, and spread across thousands of square kilometers of desert, where they would naturally absorb CO_2. Every year they could be gathered and baked to drive out the CO_2, then spread again. The CO_2 would have to be disposed of—likely by injection into other rock formations—or used as a raw material for plastics or synthetic fuels. Alternatively, the rock could be spread on croplands and left there, where it would absorb CO_2 and potentially improve the soil quality. Either way, mining, crushing and transporting the stone could scar the landscape and consume loads of energy. In Oman, at least, Kelemen's modest proposal to drill 5,000 injection wells may seem less extreme. Wells could be located along parts of the coastline that already host industrial operations, producing no more visual disturbance than a coastal wind farm would. Solar arrays could be placed in carefully selected parcels farther inland.

For now, Kelemen says he is glad simply to see a first step: the field test in Wadi Lawayni. His journey has been a long one, from aloof curiosity in the early 2000s to outright excitement today. He is already thinking ahead about how the physical footprint of mineral carbonation could be reduced. One evening in 2018 he led me scrambling up a canyon. In the dimming light of dusk, he stopped and pointed to a reddish pinnacle to our right. "In this mountain there are a billion tons of CO_2 " he declared. Across Oman carbonate veins account for only 1 percent of the surface rock volume, but in this little mountain, Kelemen said, "every single magnesium atom and every single calcium atom are combined with CO_2 to form carbonate."

These rocks started out with the same mantle minerals found everywhere else. But they reacted with CO_2 and water longer ago, while they were still deeply buried and therefore very hot. (The water and CO_2 came from a deep subduction zone nearby, where ocean sediments were being pressure-cooked as they sank into the mantle.) Based on geochemical analyses published in 2020, Kelemen thinks the rocks were as hot as 250 degrees C when they mineralized the CO_2—hot enough to push reaction-driven cracking to completion—so every bit of rock could react.

Plenty of Oman's mantle rocks are that hot today, but they are five to six kilometers below the surface. Reaching them would require more sophisticated drilling, which could make economic sense if pilot studies prove out, Hasan says.

After all, the negative-emissions industry is still in its infancy, at the same stage oil drilling was at in the mid-1800s, when it was dwarfed by a mighty whale-oil industry. The first oil wells were only a few meters deep. Companies gradually pursued bigger prizes deeper in the earth. What allowed that to happen was better drilling technology; a burgeoning global infrastructure for capturing, transporting and selling the valued product; and a growing desperation for more. These same forces might one day drive humans to delve ever deeper in search of another resource: hot rocks to solidify CO_2. Oman, a country that has earned billions of dollars by selling buried hydrocarbons to the world, could make the ingenious transition to earning billions more to bury that same carbon back in the ground. SA

FROM OUR ARCHIVES

Washing Carbon Out of the Air. Klaus S. Lackner; June 2010.

scientificamerican.com/magazine/sa

NEW WAYS TO SMASH PARTICLES

To reach the next frontier of fundamental physics, scientists must design the most powerful particle accelerators yet

By Chandrashekhar Joshi

Illustration by Peter and Maria Hoey

AT THE START OF THE 20TH CENTURY SCIENTISTS HAD little knowledge of the building blocks that form our physical world. By the end of the century they had discovered not just all the elements that are the basis of all observed matter but a slew of even more fundamental particles that make up our cosmos, our planet and ourselves. The tool responsible for this revolution was the particle accelerator.

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The pinnacle achievement of particle accelerators came in 2012, when the Large Hadron Collider (LHC) uncovered the long-sought Higgs boson particle. The LHC is a 27-kilometer accelerating ring that collides two beams of protons with seven trillion electron volts (TeV) of energy each at CERN near Geneva. It is the biggest, most complex and arguably the most expensive scientific device ever built. The Higgs boson was the latest piece in the reigning theory of particle physics called the Standard Model. Yet in the almost 10 years since that discovery, no additional particles have emerged from this machine or any other accelerator.

Have we found all the particles there are to find? Doubtful. The Standard Model of particle physics does not account for dark matter—particles that are plentiful yet invisible in the universe. A popular extension of the Standard Model called supersymmetry predicts many more particles out there than the ones we know about. And physicists have other profound unanswered questions such as: Are there extra dimensions of space? And why is there a great matter-antimatter imbalance in the observable universe? To solve these riddles, we will likely need a particle collider more powerful than those we have today.

Many scientists support a plan to build the International Linear Collider (ILC), a straight-line-shaped accelerator that will produce collision energies of 250 billion (giga) electron volts (GeV). Though not as powerful as the LHC, the ILC would collide electrons with their antimatter counterparts, positrons—both fundamental particles that are expected to produce much cleaner data than the proton-proton collisions in the LHC. Unfortunately, the design of the ILC calls for a facility about 20 kilometers long and is expected to cost more than $10 billion—a price so high that no country has so far committed to host it.

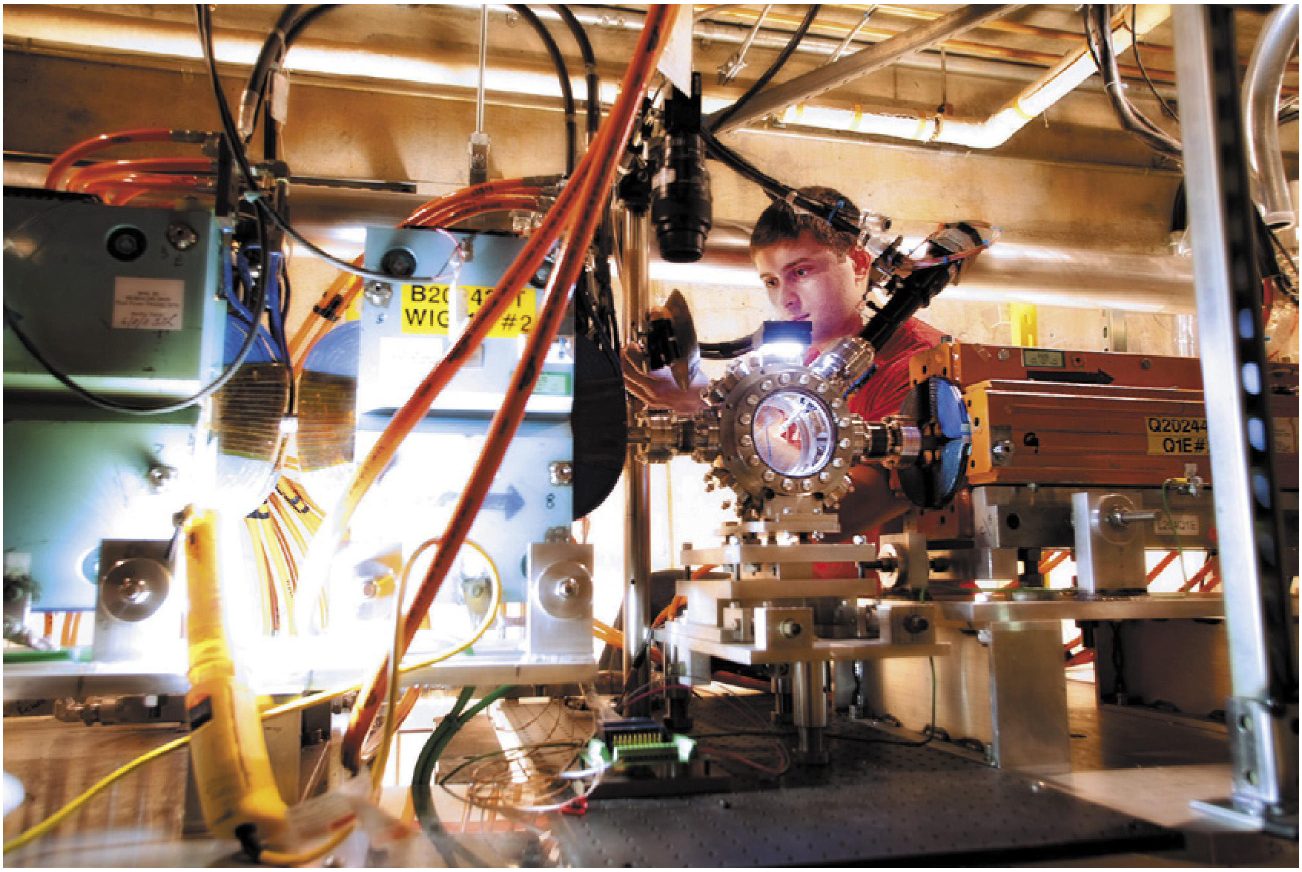
In the meantime, there are plans to upgrade the energy of the LHC to 27 TeV in the existing tunnel by increasing the strength of the superconducting magnets used to bend the protons. Beyond that, CERN is proposing a 100-kilometer-circumference electron-positron and proton-proton collider called the Future Circular Collider. Such a machine could reach the unprecedented energy of 100 TeV in proton-proton collisions. Yet the cost of this project will likely match or surpass the ILC. Even if it is built, work on it cannot begin until the LHC stops operation after 2035.

But these gargantuan and costly machines are not the only options. Since the 1980s physicists have been developing alternative concepts for colliders. Among them is one known as a plasma-based accelerator, which shows great promise for delivering a TeV-scale collider that may be more compact and much cheaper than machines based on the present technology.

THE PARTICLE ZOO

THE STORY OF PARTICLE ACCELERATORS began in 1897 at the Cavendish physics laboratory at the University of Cambridge. There J. J. Thomson created the earliest version of a particle accelerator using a tabletop cathode-ray tube like the ones used in most television sets before flat screens. He discovered a negatively charged particle—the electron.

Soon physicists identified the other two atomic ingredients—protons and neutrons—using radioactive particles as projectiles to bombard atoms. And in the 1930s came the first circular particle accelerator—a palm-size device invented by Ernest Lawrence called the cyclotron, which could accelerate protons to about 80 kilovolts. Thereafter accelerator technology evolved



SCIENTIST tests a prototype plasma accelerator at the Facility for Advanced Accelerator Experimental Tests (FACET) at the SLAC National Accelerator Laboratory in California.

BRAD PLUMMER AND SLAC NATIONAL ACCELERATOR LABORATORY

rapidly, and scientists were able to increase the energy of accelerated charged particles to probe the atomic nucleus. These advances led to the discovery of a zoo of hundreds of subnuclear particles, launching the era of accelerator-based high-energy physics. As the energy of accelerator beams rapidly increased in the final quarter of the past century, the zoo particles were shown to be built from just 17 fundamental particles predicted by the Standard Model. All of these, except the Higgs boson, had been discovered in accelerator experiments by the late 1990s. The Higgs's eventual appearance at the LHC made the Standard Model the crowning achievement of modern particle physics.

Aside from being some of the most successful instruments of scientific discovery in history, accelerators have found a multitude of applications in medicine and in our daily lives. They are used in CT scanners, for x-rays of bones and for radiotherapy of malignant tumors. They are vital in food sterilization and for generating radioactive isotopes for myriad medical tests and treatments. They are the basis of x-ray free-electron lasers, which are being used by thousands of scientists and engineers to do cutting-edge research in physical, life and biological sciences.

ACCELERATOR BASICS

ACCELERATORS COME IN TWO SHAPES: circular (synchrotron) or linear (linac). All are powered by radio waves or microwaves that can accelerate particles to near light speed. At the LHC, for instance, two proton beams running in opposite directions repeatedly pass through sections of so-called radio-frequency cavities spaced along the ring. Radio waves inside these cavities create electric fields that oscillate between positive and negative to ensure that the positively charged protons always feel a pull forward. This pull speeds up the protons and transfers energy to them. Once the particles have gained enough energy, magnetic lenses focus the proton beams to several very precise collision points along the ring. When they crash, they produce extremely high energy densities, leading to the birth of new, higher-mass particles.

When charged particles are bent in a circle, however, they emit "synchrotron radiation." For any given radius of the ring, this energy loss is far less for heavier particles such as protons, which is why the LHC is a proton collider. But for electrons the loss is too great, particularly as their energy increases, so future accelerators that aim to collide electrons and positrons must either be linear colliders or have very large radii that minimize the curvature and thus the radiation the electrons emit.

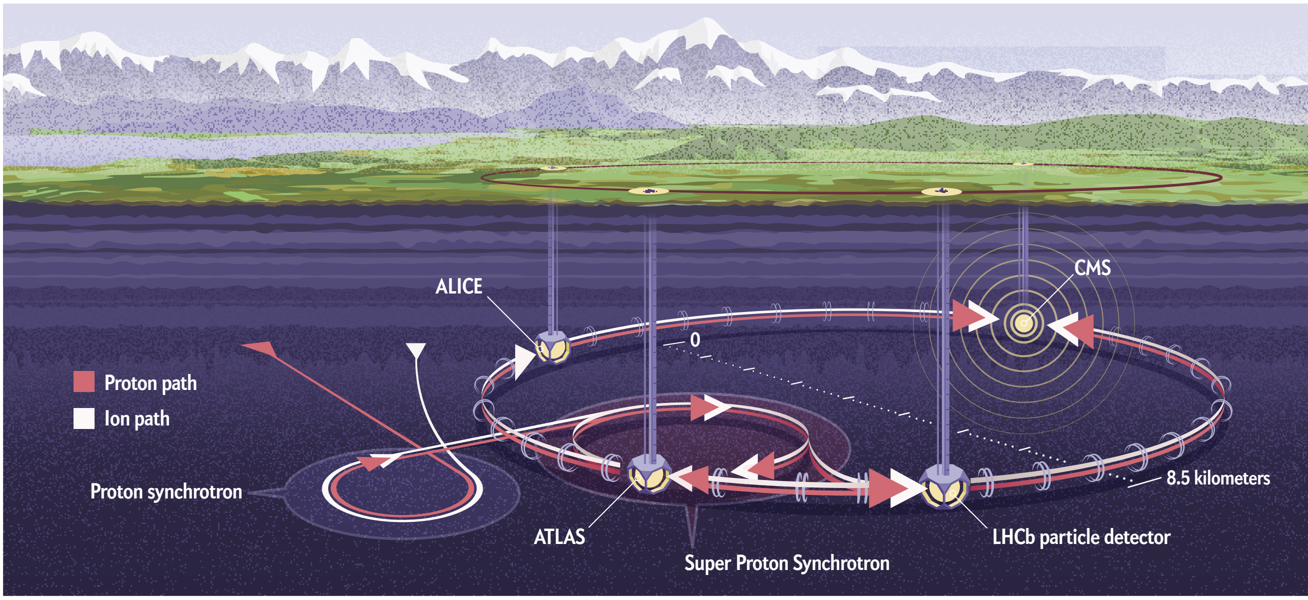
The size of an accelerator complex for a given beam energy ultimately depends on how much radio-frequency power can be pumped into the accelerating structure before the structure suffers electrical break-

Next-Generation Particle Accelerators

Most particle accelerators built to date use radio waves or microwaves to create electric fields that accelerate charged particles and then crash them together, forming blasts of energy that can give rise to novel particles. The most advanced machine of this kind is the Large Hadron Collider at CERN, and some physicists have proposed a follow-up device called the International Linear Collider. This plan may be prohibitively large and expensive, however. To achieve the energy levels required for new discoveries, scientists may need to turn to exotic technology, such as a concept called plasma wakefield acceleration.

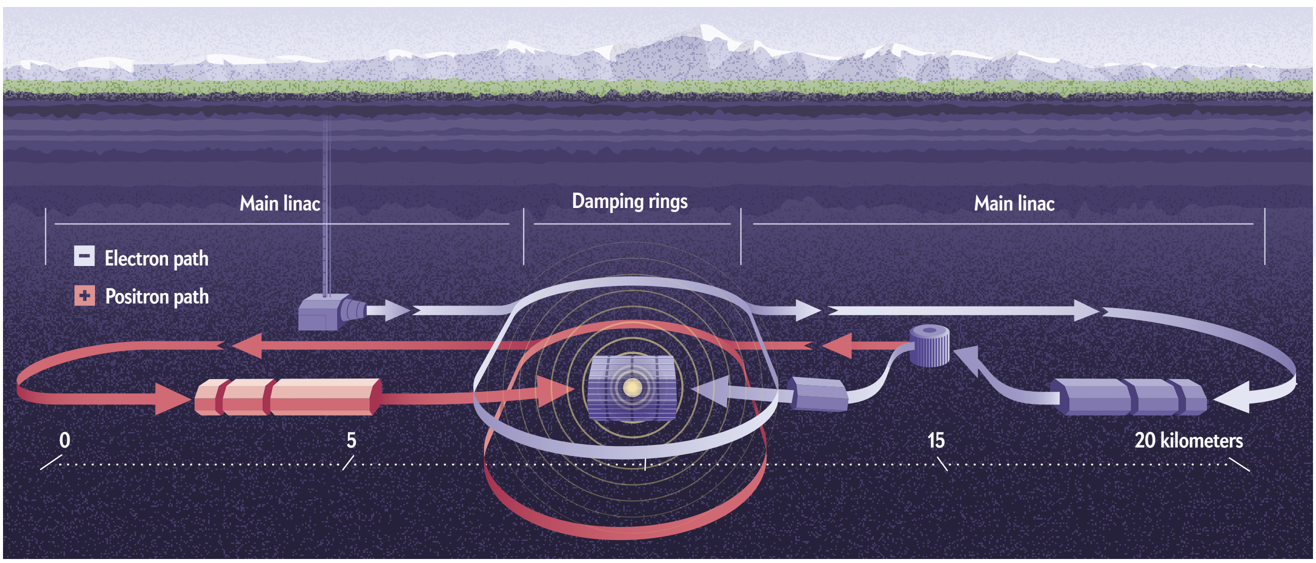
CURRENT LEADER: LARGE HADRON COLLIDER (LHC)

This 27-kilometer-ring, the largest and most powerful particle accelerator ever built, collides protons at energies of up to 14 trillion electron volts (TeV). Located underground near Geneva, the $4.75-billion device hosts four experiments at different collision sites. The LHC's crowning achievement was the revelation of the Higgs boson particle in 2012. To enable further discoveries, some scientists would like to upgrade the energy of the LHC to 27 TeV by increasing the strength of its superconducting magnets.

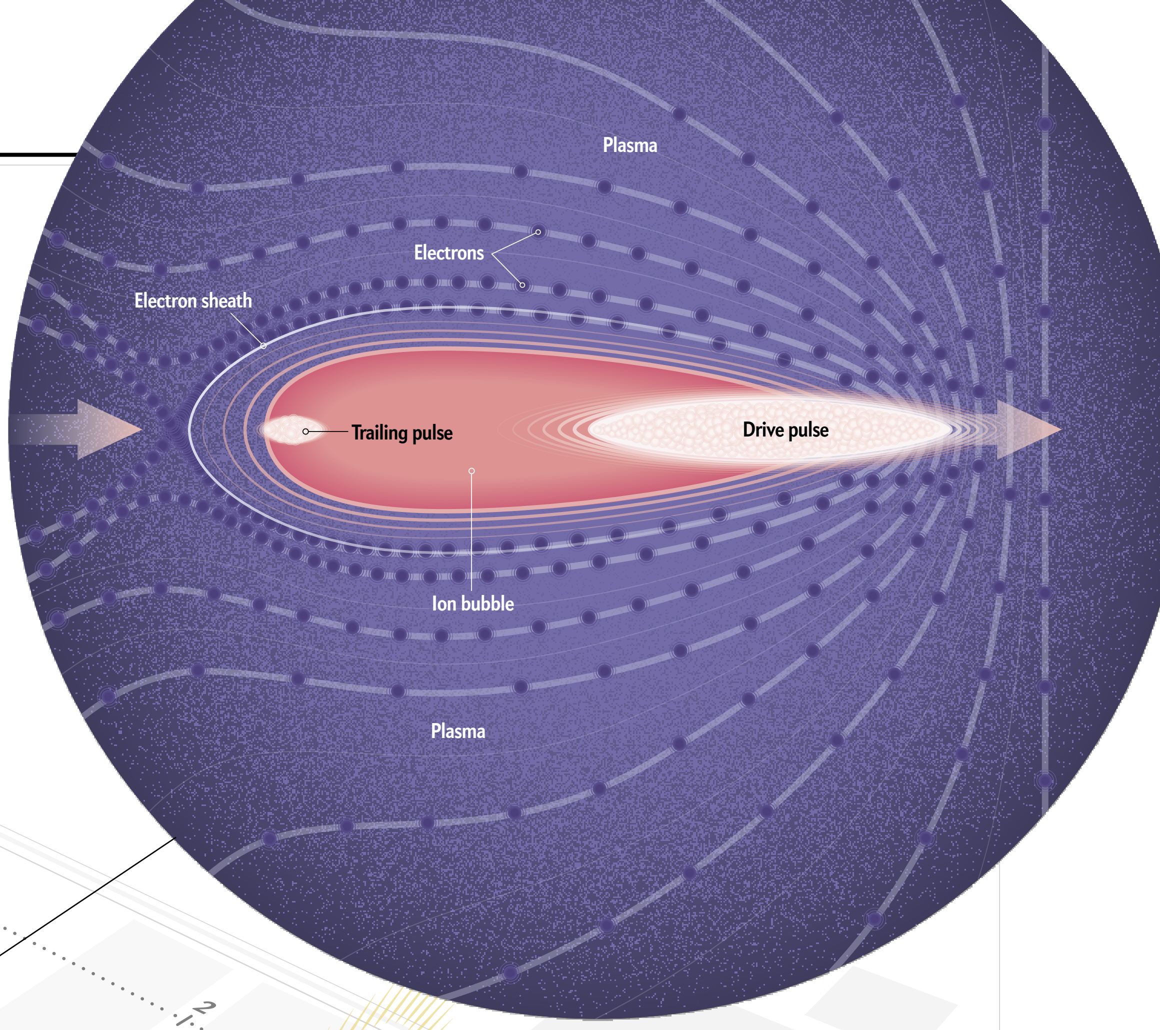


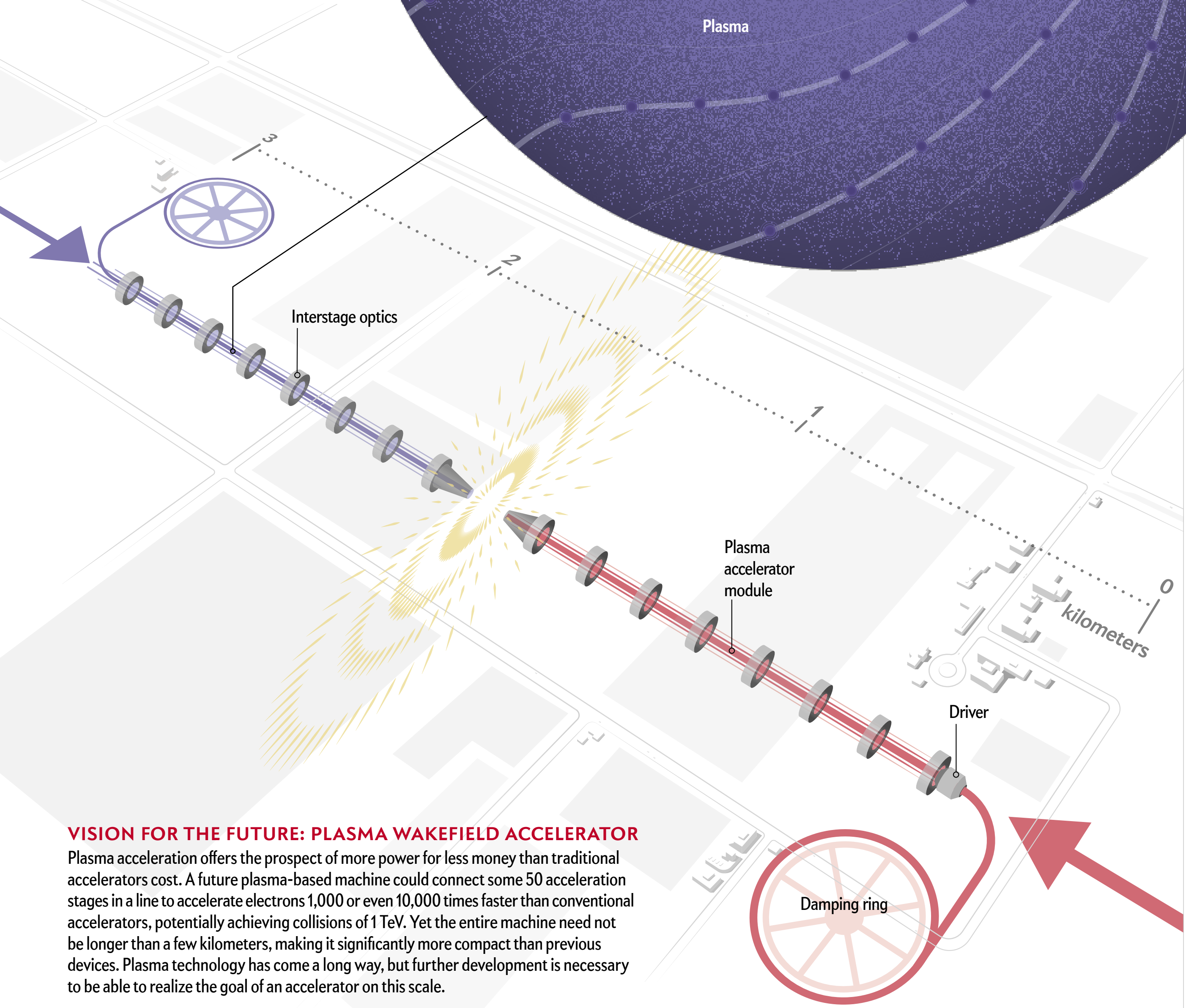
ON DECK: THE INTERNATIONAL LINEAR COLLIDER (ILC)

This proposed linear accelerator would collide electrons with their antimatter counterparts, positrons. The 20-kilometer-long machine would operate at a lower energy level (250 giga electron volts) than the LHC but would produce cleaner data. Yet its cost has been estimated to be around $10 billion, and no country has agreed to host it to date.



As an initial "drive" pulse of lasers or electrons travels through a plasma, it forces plasma electrons outward. When the drive pulse moves on, the plasma, now devoid of electrons, is positively charged and pulls the displaced electrons back toward it. As they rush in toward the axis, they overshoot and then are pulled backward again, creating an oscillating electric field in the wake. When a second "trailing" electron bunch then travels through the plasma, the electric field will accelerate it.

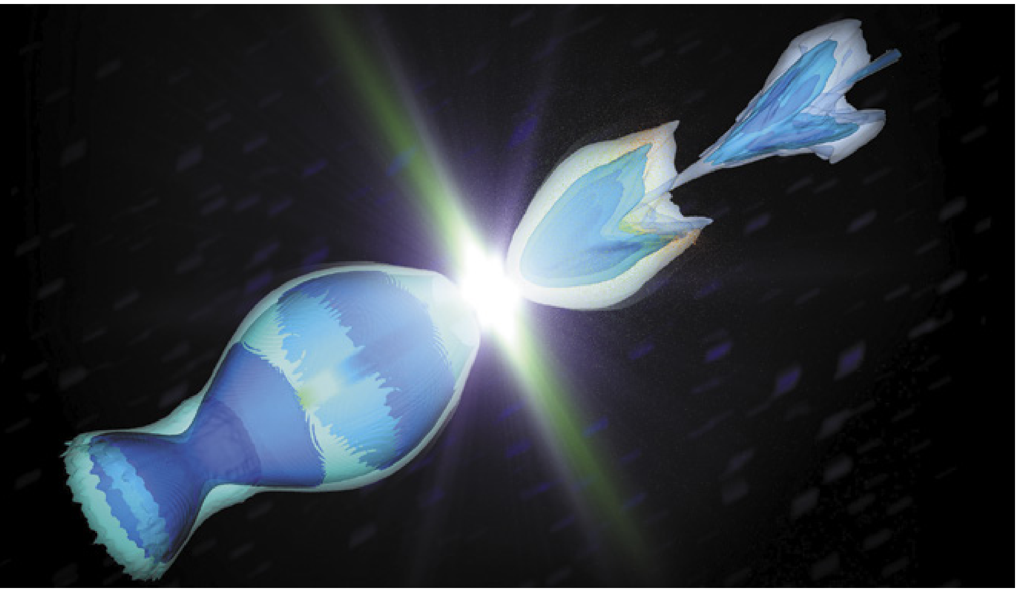




VISION FOR THE FUTURE: PLASMA WAKEFIELD ACCELERATOR

Plasma acceleration offers the prospect of more power for less money than traditional accelerators cost. A future plasma-based machine could connect some 50 acceleration stages in a line to accelerate electrons 1,000 or even 10,000 times faster than conventional accelerators, potentially achieving collisions of 1 TeV. Yet the entire machine need not be longer than a few kilometers, making it significantly more compact than previous devices. Plasma technology has come a long way, but further development is necessary to be able to realize the goal of an accelerator on this scale.

Illustration by Nick Bockelman



ELECTRONS and positrons accelerated by plasma collide in this computer simulation of the advanced acceleration scheme.

F. TSUNG, W. AN/U.C.L.A. AND SLAC NATIONAL ACCELERATOR LABORATORY

down. Traditional accelerators have used copper to build this accelerating structure, and the breakdown threshold has meant that the maximum energy that can be added per meter is between 20 million and 50 million electron volts (MeV). Accelerator scientists have experimented with new types of accelerating structures that work at higher frequencies, thereby increasing the electrical breakdown threshold. They have also been working on improving the strength of the accelerating fields within superconducting cavities that are now routinely used in both synchrotrons and linacs. These advances are important and will almost certainly be implemented before any paradigm-changing concepts disrupt the highly successful conventional accelerator technologies.

Eventually other strategies may be necessary. In 1982 the U.S. Department of Energy's program on high-energy physics started a modest initiative to investigate entirely new ways to accelerate charged particles. This program generated many ideas; three among them look particularly promising.

The first is called two-beam acceleration. This scheme uses a relatively cheap but very high-charge electron pulse to create high-frequency radiation in a cavity and then transfers this radiation to a second cavity to accelerate a secondary electron pulse. This concept is being tested at CERN on a machine called the Compact Linear Collider (CLIC).

Another idea is to collide muons, which are much heavier cousins to electrons. Their larger mass means they can be accelerated in a circle without losing as much energy to synchrotron radiation as electrons do. The downside is that muons are unstable particles, with a lifetime of two millionths of a second. They are produced during the decay of particles called pions, which themselves must be produced by colliding an intense proton beam with a special target. No one has ever built a muon accelerator, but there are die-hard proponents of the idea among accelerator scientists.

Finally, there is plasma-based acceleration. The notion originated in the 1970s with John M. Dawson of the University of California, Los Angeles, who proposed using a plasma wake produced by an intense laser pulse or a bunch of electrons to accelerate a second bunch of particles 1,000 or even 10,000 times faster than conventional accelerators can. This concept came to be known as the plasma wakefield accelerator. It generated a lot of excitement by raising the prospect of miniaturizing these gigantic machines, much like the integrated circuit miniaturized electronics starting in the 1960s.

THE FOURTH STATE OF MATTER

MOST PEOPLE ARE FAMILIAR with three states of matter: solid, liquid and gas. Plasma is often called the fourth state of matter. Though relatively uncommon in our everyday experience, it is the most common state of matter in our universe. By some estimates more than 99 percent of all visible matter in the cosmos is in the plasma state—stars, for instance, are made of plasma. A plasma is basically an ionized gas with equal densities of electrons and ions. Scientists can easily form plasma in laboratories by passing electricity through a gas as in a common fluorescent tube.

A plasma wakefield accelerator takes advantage of the kind of wake you can find trailing a motorboat or a jet plane. As a boat moves forward, it displaces water, which moves out behind the boat to form a wake. Similarly, a tightly focused but ultraintense laser pulse moving through a plasma at the speed of light can generate a relativistic wake (that is, a wake also propagating nearly at light speed) by exerting radiation pressure and displacing the plasma electrons out of its way. If, instead of a laser pulse, a high-energy, high-current electron bunch is sent through the plasma, the negative charge of these electrons can expel all the plasma electrons, which feel a repulsive force. The heavier plasma ions, which are positively charged, remain stationary. After the pulse passes by, the expelled electrons are attracted back toward the ions by the force between their negative and positive charges. The electrons move so quickly they overshoot the ions and then again feel a backward pull, setting up an oscillating wake. Because of the separation of the plasma electrons from the plasma ions, there is an electric field inside this wake.

If a second "trailing" electron bunch follows the first "drive" pulse, the electrons in this trailing bunch can gain energy from the wake much in the same way an electron bunch is accelerated by the radio-frequency wave in a conventional accelerator. If there are enough electrons in the trailing bunch, they can absorb sufficient energy from the wake so as to dampen the electric field. Now all the electrons in the trailing bunch see a constant accelerating field and gain energy at the same rate, thereby reducing the energy spread of the beam.

The main advantage of a plasma accelerator over other schemes is that electric fields in a plasma wake can easily be 1,000 times stronger than those in traditional radio-frequency cavities. Plus, a very significant fraction of the energy that the driver beam transfers to the wake can be extracted by the trailing bunch. These effects make a plasma wakefield-based collider potentially both more compact and cheaper than conventional colliders.

THE FUTURE OF PLASMA

BOTH LASER- AND ELECTRON-DRIVEN PLASMA wakefield accelerators have made tremendous progress in the past two decades. My own team at U.C.L.A. has carried out prototype experiments with SLAC National Accelerator Laboratory physicists at their Facility for Advanced Accelerator Experimental Tests (FACET) in Menlo Park, Calif. We injected both drive and trailing electron bunches with an initial energy of 20 GeV and found that the trailing electrons gained up to 9 GeV after traveling through a 1.3-meter-long plasma. We also achieved a gain of 4 GeV in a positron bunch using just a one-meter-long plasma in a proof-of-concept experiment. Several other labs around the world have used laser-driven wakes to produce multi-GeV energy gains in electron bunches.

Plasma accelerator scientists' ultimate goal is to realize a linear accelerator that collides tightly focused electron and positron, or electron and electron, beams with a total energy exceeding 1 TeV. To accomplish this feat, we would likely need to connect around 50 individual plasma accelerator stages in series, with each stage adding an energy of 10 GeV.

Yet aligning and synchronizing the drive and the trailing beams through so many plasma accelerator stages to collide with the desired accuracy presents a huge challenge. The typical radius of the wake is less than one millimeter, and scientists must inject the trailing electron bunch with submicron accuracy. They must synchronize timing between the drive pulse and the trailing beam to less than a hundredth of a trillionth of one second. Any misalignment would lead to a degradation of the beam quality and a loss of energy as well as charge caused by oscillation of the electrons about the plasma wake axis. This loss shows up in the form of hard x-ray emission, known as betatron emission, and places a finite limit on how much energy we can obtain from a plasma accelerator.

Other technical hurdles also stand in the way of immediately turning this idea into a collider. For instance, the primary figure of merit for a particle collider is the luminosity—basically a measure of how many particles you can squeeze through a given space in a given time. The luminosity multiplied by the cross section—or the chances that two particles will collide—tells you how many collisions of a particular kind per second you are likely to observe at a given energy. The desired luminosity for a 1-TeV electron-positron linear collider is 10^{34} $cm^{-2}s^{-1}$. Achieving this luminosity would require the colliding beams to have an average power of 20 megawatts each—10^{10} particles per bunch at a repetition rate of 10 kilohertz and a beam size at the collision point of tens of a billionth of a meter. To illustrate how difficult this is, let us focus on the average power requirement. Even if you could transfer energy from the drive beam to the accelerating beam with 50 percent efficiency, 20 megawatts of power will be left behind in the two thin plasma columns. Ideally we could partially recover this power, but it is far from a straightforward task.

And although scientists have made substantial progress on the technology needed for the electron arm of a plasma-based linear collider, positron acceleration is still in its infancy. A decade of concerted basic science research will most likely be needed to bring positrons to the same point we have reached with electrons. Alternatively, we could collide electrons with electrons or even with protons, where one or both electron arms are based on a plasma wakefield accelerator. Another concept that scientists are exploring at CERN is modulating a many-centimeters-long proton bunch by sending it through a plasma column and using the accompanying plasma wake to accelerate an electron bunch.

The future for plasma-based accelerators is uncertain but exciting. It seems possible that within a decade we could build 10-GeV plasma accelerators on a large tabletop for various scientific and commercial applications using existing laser and electron beam facilities. But this achievement would still put us a long way from realizing a plasma-based linear collider for new physics discoveries. Even though we have made spectacular experimental progress in plasma accelerator research, the beam parameters achieved to date are not yet what we would need for just the electron arm of a future electron-positron collider that operates at the energy frontier. Yet with the prospects for the International Linear Collider and the Future Circular Collider uncertain, our best bet may be to persist with perfecting an exotic technology that offers size and cost savings. Developing plasma technology is a scientific and engineering grand challenge for this century, and it offers researchers wonderful opportunities for taking risks, being creative, solving fascinating problems—and the tantalizing possibility of discovering new fundamental pieces of nature. SA

FROM OUR ARCHIVES

Plasma Accelerators. Chandrashekhar Joshi; February 2006.

scientificamerican.com/magazine/sa

SUSTAINABILITY

How Dirt Could Help Save the Planet

Farming practices that retain carbon in the soil, or return it there, would limit both erosion and climate change

By Jo Handelsman

Illustration by Chiara Vercesi

Jo Handelsman is director of the Wisconsin Institute for Discovery at the University of Wisconsin–Madison and a former science adviser to President Barack Obama. She is author of the book *A World Without Soil,* forthcoming from Yale University Press.

THE AMERICAN DUST BOWL OF THE 1930S demonstrated the ruinous consequences of soil degradation. Decades of farming practices had stripped the Great Plains of their fertile heritage, making them vulnerable to severe drought. Ravaging winds lifted plumes of soil from the land and left in their wake air choked with dust and a barren landscape. Thousands died of starvation or lung disease; others migrated west in search of food, jobs and clean air.

Today we again face the potential for extreme soil erosion, but this time the threat is intensified by climate change. Together they create an unprecedented dual hazard for the food supply and the health of the planet. Farmers, however, can be key partners in averting the catastrophic consequences. By using readily available practices, both erosion and climate change can be mitigated by incorporating more carbon into soil.

Photosynthetic carbon fixation removes carbon dioxide from the air, anchoring it in plant material that can be sequestered in soil. This process reduces atmospheric greenhouse gases and reduces soil erosion by enriching soil with carbon that feeds hungry microbes that produce sticky substances, which in turn bind soil particles into clumps that are less vulnerable to movement by wind and water. The Biden administration has the opportunity to avert both crises through domestic policy for U.S. agriculture and international policy that would restore U.S. leadership in the battle against climate change. Reducing greenhouse gas emissions is the central feature of most plans to slow the climate emergency at hand. Much less attention has focused on sequestering atmospheric carbon in soil.

Soil, which stores three times more carbon than the entire atmosphere, is the largest terrestrial carbon sink, offering a vast repository with immense, untapped capacity. Since the beginning of agriculture, food production has removed about half, or 133 gigatons, of the carbon once stored in agricultural soil, and the rate of loss has increased dramatically in the past two centuries, creating a large void to be filled. Restoring this carbon stockpile would sequester the equivalent of almost one fifth of atmospheric carbon, bringing greenhouse gas concentrations nearly to pre–industrial revolution levels and making soil less vulnerable to erosion. Realistically, we're not going to restore 133 gigatons of carbon any time soon. But working toward this goal could be a centerpiece of a multifaceted plan to address both erosion and climate change.

Farmers know that soil is no longer a renewable resource. Many farms are simply running out of it. A 2018 inventory from the U.S. Department of Agriculture reports that the U.S. loses soil on average 10 times faster than it is generated; in states such as Iowa, New Mexico and Nevada, erosion is much more rapid. In parts of Africa and Asia, soil erosion outstrips replenishment as much as 100-fold.

And it's getting worse. Heavy rainstorms are a key cause of erosion, driving loosened soil particles into streams and rivers. Many parts of the world, including the U.S. Midwest, have experienced a dramatic rise in the frequency and power of rainstorms, a trend likely to accelerate as climate change worsens. At current rates of erosion, some of the world's most productive farmland will lose most of its topsoil over the next few decades, rendering it worthless for food production just as Earth's population reaches nine billion. In fact, even the well-endowed soil of Iowa has been so ravaged that subsoil is revealed at the land surface at locations across the state. But there is a general principle worthy of attention: erosion is reduced by accumulation of soil carbon.

Carbon sequestration in agricultural soils was the goal of the "4 per 1000" proposal for food security and climate that was introduced by France during the 2015 Paris climate talks. The proposal contended that increasing the carbon content of soils worldwide by 0.4 percent annually would offset future emissions. Only 29 countries signed the agreement, and the U.S. was not among them. The proposal encompassed all soil on Earth, giving it an aspirational and unattainable nature that put off many potential signatories. So 4 per 1000 should be reformulated to pass a reality test, focusing only on agricultural soil for starters. As President Joe Biden reestablishes U.S. leadership in global climate policy, achieving broad ratification of a proposal to increase soil carbon should be high on his agenda.

To meet such soil carbon goals, the U.S. would need to adopt different farming practices. One important step is to reduce plowing, which causes erosion by breaking up large clods and destroying the soil structure that prevents detachment and movement of particles. The alternative—no-till planting—involves drilling seed directly into the stubble of the previous crop rather than plowing the field after harvest and again before planting and dropping seeds into plowed furrows. Although no-till methods were shown to substantially reduce erosion in the 1970s, they have been adopted on only one third of U.S. cropland. Another highly effective practice is growing cover crops—plant species that enrich the soil between fall harvest and spring planting of the main crop. Cover crops anchor soil and prevent winter winds and spring rainstorms from removing fertile topsoil.

Cropland soil can be stabilized by interspersing strips of perennial prairie plants, the very species that generated the expanses of Midwestern soils that have produced abundant food since European-Americans migrated to the center of the country in the 19th century. These perennials have massive root systems that feed the soil. Switchgrass roots, for example, can grow 14 feet deep and account for half of the plant's biomass at the end of the season, a reservoir that enables the plant to resprout in the spring. Corn, in contrast, has shallow roots and by the end of the growing season a negligible amount of root biomass remains after the plant has shuttled its carbon to the seeds. Replacing just 10 percent of a corn crop with strategically placed prairie plants reduces erosion 95 percent! Similarly, reforestation reduces erosion with large tree roots that anchor and enrich soil. All these soil-protective practices accelerate carbon sequestration, reducing greenhouse gas accumulation.

Another way to boost carbon sequestration is a method for pasturing cattle that stimulates plant growth. Intensive regenerative grazing replicates the effects of the herds of bison that once roamed the American plains, contributing to formation of some of Earth's most fertile soils. Regimes involve moving cattle frequently—sometimes several times in a single day—to new pasture, thereby preventing the animals from cropping the vegetation close to the ground. The remaining plants recover and start growing again more quickly than those that have been reduced to nubs, enabling them to be more photosynthetically active over the growing season and accumulate more carbon. Some researchers estimate that regenerative grazing boosts carbon fixation through photosynthesis enough to cancel out most of the greenhouse gases released by beef production.

BRANDING CLIMATE-FRIENDLY SOIL

EVENTUALLY SOIL WILL REACH its carbon-holding capacity. But that would be a good problem to confront—it would mean that soil was packed with carbon and was therefore healthy and resistant to erosion. By the time carbon capacity is reached in soils worldwide, strategies to reduce carbon emissions will likely be more advanced.

Critics of 4 per 1000 argue that the benefits of incorporating carbon into soil would be canceled out by the increased needs for nitrogen fertilizers, which are produced by a fossil-fuel-intensive process. But carbon sequestration can be accompanied by retention of nitrogen in plant material, reducing nitrogen needs of future crops. Moreover, nitrogen needs could be satisfied by biological nitrogen fixation, which is conducted by soil bacteria that need no fossil fuels to make nitrogen fertilizer.

We have the means to halt soil loss and mitigate greenhouse gas emissions, but we need policies that enable farmers to adopt new practices. Most farms survive with a fragile profit margin. Although Americans enjoy one of the cheapest, safest and most abundant food supplies in the world, farmers receive only 15 cents of every dollar spent on food, and between 2013 and 2018 net farm income dropped nearly 50 percent. The USDA forecast that half of U.S. farms would lose money in 2020. Many farms persist only because a family member provides income from off-farm employment. And financial hardship drives many farms out of business, which is evident in the loss of half of U.S. dairy farms between 2001 and 2019.

Intensive regenerative grazing replicates the effects of the herds of bison that once roamed the American plains, contributing to formation of some of Earth's most fertile soils.

To improve the profitability of farming and reduce both soil erosion and net carbon emissions, the Biden administration could restructure crop insurance to reduce premiums on land that is managed in a carbon-friendly manner. This strategy would pay for itself within a few years because even small increases in soil carbon reduce vulnerability to droughts and floods and, consequently, the likelihood of insurance payouts. The administration could build an alliance of key stakeholders—farmers, food retailers, consumers, Indigenous communities, agribusiness and environmental groups—to design certification and marketing strategies for food sold with a label indicating it had been produced under conditions that sequester carbon.

The label might read "Produced by Carbon Heroes" to recognize the heroism of farmers who make it possible for millions to eat and would now add protecting the planet to their list of contributions. Multinational retailers could demand such practices from their producers as they have already done with other practices friendly to animals and the environment. Current agricultural subsidies could be redirected to pay for both the food and the carbon sequestered during its production.

The U.S. experienced the impacts of extreme soil degradation during the Dust Bowl. We could avert a similar devastation of U.S. farmland by changing farming practices, which would generate ancillary benefits for climate. The stakes are too high to ignore the soil. SA

FROM OUR ARCHIVES

No-Till: The Quiet Revolution. David R. Huggins and John P. Reganold; July 2008.

scientificamerican.com/magazine/sa

PUBLIC HEALTH

MOMENT OF HOPE

After a year of sickness and death, lives changed at a COVID mass vaccination clinic

Photographs by Grant Delin
Text by Robin Lloyd

PEOPLE GET READY for their COVID vaccines at a large site in Newark, N.J. The facility was designed to accommodate up to 6,000 recipients a day.


NJIT
HIGHLANDERS
98,134
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ON AN OVERCAST LATE APRIL DAY IN NEWARK, N.J., after more than a year of pandemic suffering, some 2,000 people queued up at a public college campus to start healing. Inside a hangar-style tennis facility at the New Jersey Institute of Technology that had been converted into a mass vaccination site, they came face to face with one of the most remarkable biomedical achievements in history: a safe and highly effective COVID vaccine designed and tested in a 10-month sprint in 2020. During that same period, while scientists were racing to develop this virus blocker, more than 300,000 Americans and nearly two million people worldwide died of COVID.

Grant Delin is an award-winning photographer based in New York City who studied under photography masters Richard Avedon and Mary Ellen Mark. His clients include the Smithsonian Institution, the *Atlantic,* the *Washington Post Magazine* and *Popular Mechanics.*

Journalist **Robin Lloyd,** a contributing editor at *Scientific American,* publishes the "Smart, Useful, Science Stuff about COVID-19" newsletter. She is an adjunct professor at New York University's Science, Health and Environmental Reporting Program.

Although the two-dose vaccine made by Pfizer-BioNTech and given in Newark was configured rapidly for the SARS-CoV-2 virus—along with a similar inoculation from biotech firm Moderna—both are the careful culmination of decades of research into technology known as synthetic messenger RNA (mRNA). The shots gave the world its first real sign that humanity could break free of the pandemic.

Research into vaccines made from mRNA, conducted at the National Institutes of Health, the Department of Defense and several academic laboratories, yielded a way to use this compound to get the body's own cells to make a viral protein that provokes a strong immune response. Two different clinical trials, involving more than 70,000 people, were reviewed by vaccine and safety experts at the Food and Drug Administration and the Centers for Disease Control and Prevention, as well as outside advisory panels; the tests showed that the shots are healthy and extremely effective and led to vaccine authorization.

But the shots have not reached everyone equally. In the U.S., social and material barriers confront many people of color, including lack of transportation to clinics and computer access for making appointments and no paid time off, and the obstacles have meant that white people receive a disproportionate share of vaccine doses. The Newark site was created to address this problem. It is a joint state and federal effort that is managed by the Federal Emergency Management Agency (FEMA) and the Department of Defense. The site is located near train stations and bus stops. People who show up without appointments get booked for an upcoming date or even accommodated that day if supplies allow. Messages and instructions are available for visitors more comfortable in one of more than 50 languages, and some staffers are fluent in Portuguese, Spanish, and more. A video is available for people who communicate in American Sign Language. On April 30, a month after it opened, the site vaccinated its 150,000th person.

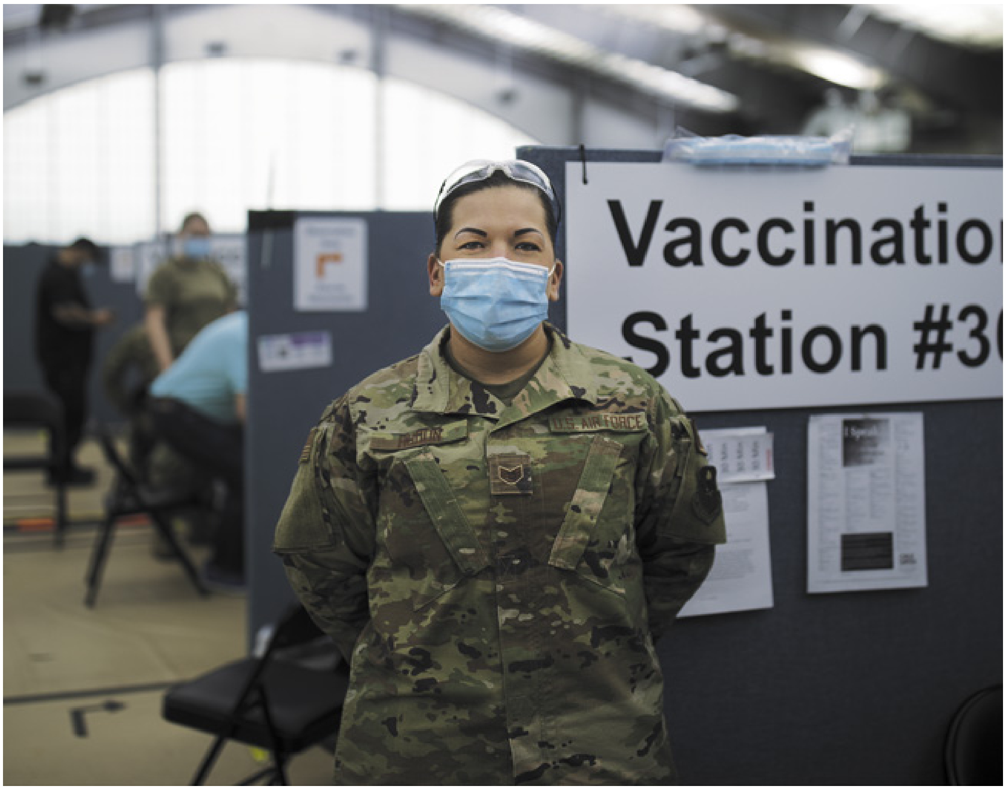
People arriving at the facility moved between rows of folding tables. After registering at one of 36 intake stations with Plexiglas barriers between patients and seated workers, patients walked down an improvised corridor toward one of 50 vaccination stations staffed by members of the military in fatigues. Tall partitions covered in steel-blue fabric maintained a sense of privacy. A military medic explained the two-dose regimen for the vaccine and the protection it provides, then asked if patients had any concerns.

These sites cannot reverse the huge missteps of the pandemic's first year or fix the web of health disadvantages spun by structural inequalities. And what has been done in the wealthy U.S. is still beyond the reach of much of the planet; large areas continue to suffer. But these photographs, taken on April 20, show encounters between people and the vaccines that can save them after a tragic year. They reveal the human side of the progress that is possible when societies use science—and compassion—to tackle the biggest problems.

CARMITA ANDRADE, 51 (*center*), thought she might die when she had COVID last year in April. She could hardly breathe. Her trauma, which included a week-long hospitalization, helped to inspire her son, Christopher, and her daughter, Nicole, to join her in getting vaccinated this spring. "I'm a survivor here," she says. "My biggest concern was to go to the hospital because you didn't know if you were coming back again. A lot of people who passed away because of COVID, they couldn't say goodbye to their families. But I've been very blessed to be back again with my family."

LAYLA SAYED, 17, an aspiring lawyer working at a Thai rolled ice cream shop, says she got vaccinated in part to protect her mom, with whom she lives. Getting the vaccine also brought to mind the risks facing her family members living in Egypt. "They don't have the kind of precautions we have," she says. "They don't have the vaccinations. They don't have the tests. Some of them don't even have masks, or they don't have the money to get one. So having the privilege to be able to get something like this, it was really important to me."

ALEX APPIAH FRIMPONG, 50, a former life insurance agent who is now studying for an M.B.A., chose to get vaccinated after the pastor at his Pentecostal Church counseled his congregation to get inoculated. "There are rumors out there that people are dying because of the shot, and I don't really believe it," Frimpong says. "The first shot, I didn't feel anything. And this is the second shot. I'm okay right now. So I'm good."



MARY BREANNA HUDON, 30, a military medic and U.S. Air Force staff sergeant, injects people with vaccines. She typically gives more than 200 shots daily, working two or three days in a row, at times in 11-hour shifts. She remembers vaccinating a 9/11 survivor in his 60s who mentioned that his toxic exposures at the World Trade Center site led to kidney cancer. "So I thanked him because at that time, they were there for us," she says. "I let him know: 'Thank you. We appreciate you. It's time for us to have your back.'"

CECILIA SESSIONS, 46, a physician and the site's chief medical officer and a U.S. Air Force colonel, begged to be deployed to Newark. She desperately wanted to help, in part because New Jersey had one of the highest COVID mortality rates among U.S. states. "Many of the people who come in talk to us about how they've personally been affected and the people that they've lost during the pandemic. So there's definitely a need. We had a deaf patient a couple of days ago, and I used my phone to ask for a sign language interpreter. And when the patient finished, when he got his vaccine, he just shouted, 'Thank you, God. Thank you, everyone.' He was so overcome with emotion. He was crying."

MEDICS PREPARE VACCINES ahead of time, often prepping for several patients at once. Each setup typically contains one alcohol wipe, one prefilled syringe and one adhesive bandage. Out of public view, medical technicians thaw trays of frozen vaccine vials to start the process of reconstituting up to 6,000 vaccine doses a day. Six doses are drawn from each vial into syringes. A U.S. Public Health Service pharmacist or a Veterans Administration nurse checks the quality of each step in this process, including a final check of every loaded syringe.

KAJAL NEGANDHI, 39, who works in patient safety for a drug company, says she lost a dear friend in India to the pandemic last October. After getting her second dose in Newark, Negandhi thought of her friend as well as her child and her community: "I have a little one at home. I would want her teachers to be vaccinated, so why not us? Save them, save the kids, save everybody all around."

YOULANDA LEE-CLENDENEN, 56, says she got vaccinated because she knows that people her age and those like her with underlying medical conditions are at higher risk for severe COVID. She wants to spend time with her six grandchildren and to travel. She also felt a sense of duty to get vaccinated to reduce the spread of the virus and a responsibility to provide accurate information about the vaccine to reluctant relatives in St. Vincent in the Caribbean. "They are ignorant to not take the vaccine," she says. "But I tell them, it's your life. If you want to go ahead and put your life at risk, that's on you. But I'm going to protect myself."

HODAN BULHAN, 39, who works as a legal assistant at a law firm, has several family members and friends who got severe COVID. They have recovered, she says, but "this [vaccination] would have been helpful if it was available at the time." The pandemic has been a frightening experience for her. "Anything that we can do to prevent ourselves from getting ill or hospitalized is important. I believe in vaccinations. I'm a child of the 80s, and I was vaccinated and I turned out okay. So I think this will work out."

FROM OUR ARCHIVES

The Vaccine Quest. Charles Schmidt; June 2020.

scientificamerican.com/magazine/sa

SHORT STORIES

Exploring Black Sci-Fi

A roving anthology of new and classic voices energizes the genre of speculative fiction

Review by Gabrielle Bellot

In a 1970s essay with the provocative title of "Why Blacks Don't Read Science Fiction," the late African-American writer Charles R. Saunders reflected bitterly on the prevalence of anti-Blackness in the genre. Although white American science-fiction writers "were capable of stretching their imaginations to the point of conceptualizing aliens with sympathetic qualities," he mused, "a black man or woman in a spacesuit was an image beyond the limits of [their] imaginations.… If blacks appeared at all in the pages of the science fiction pulp magazines, they were presented as offensive 'darkie' stereotypes." The genre, as Saunders memorably put it, was "as white as a Ku Klux Klan meeting."

In the years since Saunders's acerbic observations, Black writers have undoubtedly become more prominent in speculative fiction. But given white men's continual dominance of the genre, nonwhite authors are all too frequently still overlooked. A new collection, *Black Sci-Fi Short Stories,* aims to correct this, presenting readers with a wide range of short stories—and novellas—from 20th- and 21st-century writers, a number of which have never before been published. A roving set of introductory essays attempts to situate the book in the larger history of Black sci-fi and fantasy from around the globe.

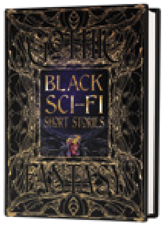
The book's selection seems uneven, offering ample space to never before published short stories and to lesser-known early-20th-century novellas yet curiously lacking work by well-known writers in the genre such as Octavia Butler, Nalo Hopkinson, Nnedi Okorafor or N. K. Jemisin, even though the introduction quotes a number of these luminaries. And although the collection gestures to the global presence of Black sci-fi and fantasy by alluding, for instance, to a number of African writers, the table of contents ultimately feels a bit Americentric.

Still, the anthology contains a thrilling group of memorable, moving tales that often examine the intersections of race, gender, grief, tech and the fantastical. W.E.B. Du Bois's 1920 short story "The Comet," for instance, imagines what would happen if a catastrophic celestial event left only a working-class Black man and a wealthy white woman alive. In "Elan Vital" (2009), a deeply poignant story from writer, speculative-fiction critic and teacher K. Tempest Bradford, we glimpse a world in which the dead can be scientifically resuscitated for hours at a time but only for the price of a fragment of someone else's life; to speak again to her late mother, the protagonist must shorten her own life. Nigerian writer Wole Talabi's "The Regression Test" blends transhumanism and the Turing test, proffering an intentionally unsettling look at what it means for a computer program to attempt to replace someone you've lost.

Other stories focus more on comedy or satire to make larger points about power, social responsibility and racism. One curious tale is the diary of a girl who unexpectedly gains superpowers, then must learn how to wield them to save her town; it rehashes tropes, but its structure as a diary and its escalating seriousness make it surprisingly memorable. Another story, "e-race," acidly satirizes the idea of racial color blindness, conjuring up an alarming yet eerily recognizable world in which people line up at a high-tech center to "end racism" by altering their brains to no longer see skin color. If such a premise seems absurd, it is meant to be, calling to mind the grim satire of George S. Schuyler's 1931 *Black No More.*

Perhaps the anthology's most fundamental argument is that racism and anti-Blackness seem inescapable. No matter how different the worlds imagined, racist sentiment—anti-Blackness most of all—persists in all of them, a cruel reminder that it is perhaps easier to fly to another planet or technologically revive the dead than it is to mend the scars of white supremacy. This is true even in the 1904 novella *Light Ahead for the Negro,* by Edward A. Johnson, who imagines a white abolitionist-minded man from 1906 transported, through dubious science, into 2006, where he finds, to his joy, that Black Americans have achieved significantly more sociopolitical equality. Still, in Johnson's perhaps unnecessarily long tale, which critics have described as "utopian," there is a clear sense of demarcation between racial groups, and a "Negro problem" appears to exist, even as its characters speak as though all is now well for Black citizens.

Overall, the collection is at once exciting and head-scratching. With its omissions of certain authors, *Black Sci-Fi Short Stories* isn't a definitive introduction to Black speculative fiction—and perhaps it doesn't seek to be, giving readers instead an intriguing range of new and lesser-known voices that seek to defy Saunders's bleak recollections of a genre that, for so long, excluded Black authors. It thus works best as a complement to other essential collections of short Black speculative fiction, such as Butler's *Bloodchild and Other Stories* (1995), Hopkinson's *Skin Folk* (2001) and Helen Oyeyemi's *What Is Not Yours Is Not Yours* (2016).

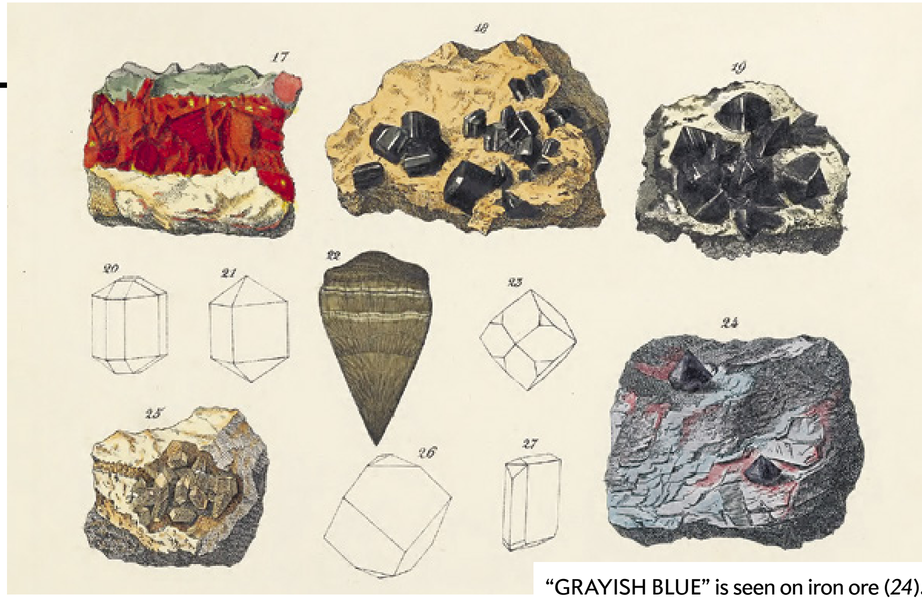


Black Sci-Fi Short Stories
edited by Tia Ross. Flame Tree Gothic series. Flame Tree, 2021 ($30)

Illustration by London Ladd

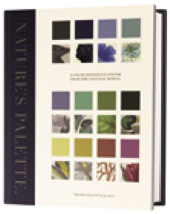
ILLUSTRATED NONFICTION

Learning through Color



"GRAYISH BLUE" is seen on iron ore (*24*).

For many people, pandemic lockdowns have led to a deeper acquaintance with their local natural environments. Bursts of color that may have previously gone unnoticed (violets amid the lawn; indigo buntings in a field) are now sources of solace. *Nature's Palette* is an extension of these connections between color and environment and how they orient us in a complex world. This richly illustrated reference guide, punctuated by essays from botanists and ecologists, is based on mineralogist Abraham Gottlob Werner's 19th-century *Nomenclature of Colours.* It was the first textbook that "presented a method of identifying rocks and minerals by their external characteristics as perceived by the five senses" and influenced the creation of standardized color systems that were used for scientific taxonomy from entomology to medicine. Designers and artists will appreciate the contemporary reference guide, as will anyone seeking to repaint their bedroom. Unlike parsing paint chips at a hardware store, exploring color through animals, plants and minerals illuminates its many tools and signals while providing context for why we find certain colors so appealing.



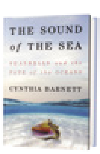
Nature's Palette:
A Color Reference System from the Natural World
Introduction by Patrick Baty.
Princeton University Press, 2021 ($39.95)

Beauty, of course, often leads to curiosity and knowledge, and interest in natural color seems to be on the rise. In *Braiding Sweetgrass* (Milkweed, 2013), botanist Robin Wall Kimmerer wondered why yellow goldenrod and purple aster, which often grow side by side, look more beautiful together than in isolation. It's a question rooted in her Indigenous heritage: "why the most ordinary scrap of meadow can rock us back on our heels." A handful of recent books and other media capture these sensory experiences, often through tactile practices. *The Art and Science of Natural Dyes: Principles, Experiments, and Results* (Schiffer, 2019) is dense with techniques, whereas *Make Ink* (Abrams, 2018) is a guide to foraging for color that includes city sidewalks and compost bins among its sources.

Soil scientists Karen Vaughan and Yamina Pressler recently began making and selling soil-based watercolors. "It's our sneaky way of doing science communication, of pushing our agenda for caring about soil formation," Vaughan says. By using minerals to create art pigments, she wants to show people that "soil is so much more than brown." Although *Nature's Palette* is more encyclopedic than experiential, it will help readers develop a language for observing nature through the lens of color—to look at a handful of soil and see hematite, ochre or ash. —*Jen Schwartz*

IN BRIEF

The Sound of the Sea:
Seashells and the Fate of the Oceans
by Cynthia Barnett. W. W. Norton, 2021 ($27.95)

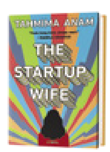


This natural and cultural history of seashells by award-winning environmental journalist Barnett brims with both wonder and dread. It opens with how the first seashells evolved, later explores how Neandertals turned them into jewelry, then illuminates how by the 14th century a Maldivian queen harvested and sold shells as currency, thus launching one of the world's first international trades. Climate change and human development now threaten the future of shells and our oceans, even as scientists and collectors rally to save them. Part ode to the natural world and part warning call, this deeply researched book reveals that shells really do "hold wisdom from the sea." —*Amy Brady*

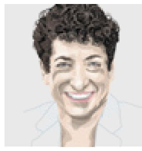
After Cooling:
On Freon, Global Warming, and the Terrible Cost of Comfort
by Eric Dean Wilson. Simon & Schuster, 2021 ($28)

Wilson, an essayist and poet, explores the unintended consequences of technological progress through the rise and fall of ozone-destroying chlorofluorocarbons. The book alternates between ride alongs with a friend who collects illicit Freon for safe destruction and digressive chapters on the cultural history of refrigeration—a story of narrowly averted disaster. "That we're turning toward more ecologically responsible refrigerants ... hardly comforts me," he writes. "We still fail to consider the stakes of our personal comfort, how and why we arrived here, and how our thinking might lead us into further danger." —*Seth Fletcher*

The Startup Wife:
A Novel
by Tahmima Anam. Scribner, 2021 ($26)



Asha, a late bloomer working at a neuroscience lab, runs into her high school crush, Cyrus, at a funeral. He creates customs for the faithless; she's trying to model empathy in the brain. They quickly marry, then launch a platform that supplants religion with an algorithmic ritual generator. As Cyrus becomes a literal god of social media, Asha (who has quit her Ph.D. program) convinces herself that she is content to lead from the shadow of her enigmatic husband—even after her voice is silenced. *The Startup Wife* is a zippy novel full of familiar satire (the techno optimists are secretly prepping for end times) that deepens into a reckoning with self-delusion. —*J.S.*



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).

Is Science Actually "Right"?

It doesn't deliver absolute truth, but it contains useful elements of truth

By Naomi Oreskes

The COVID crisis has led many scientists to take up arms (or at least keyboards) to defend their enterprise—and to be sure, science needs defenders these days. But in their zeal to fight back against vaccine rejection and other forms of science denial, some scientists say things that just aren't true—and you can't build trust if the things you are saying are not trustworthy.

One popular move is to insist that science is *right*—full stop—and that once we discover the truth about the world, we are done. Anyone who denies such truths (they suggest) is stupid, ignorant or fatuous. Or, as Nobel Prize–winning physicist Steven Weinberg said, "Even though a scientific theory is in a sense a social consensus, it is unlike any other sort of consensus in that it is culture-free and permanent." Well, no. Even a modest familiarity with the history of science offers many examples of matters that scientists thought they had resolved, only to discover that they needed to be reconsidered. Some familiar examples are Earth as the center of the universe, the absolute nature of time and space, the stability of continents, and the cause of infectious disease.

Science is a *process* of learning and discovery, and sometimes we learn that what we thought was right is wrong. Science can also be understood as an institution (or better, a set of institutions) that facilitates this work. To say that science is "true" or "permanent" is like saying that "marriage is permanent." At best, it's a bit off-key. Marriage today is very different from what it was in the 16th or 18th century, and so are most of our "laws" of nature.

Some conclusions are so well established we may feel confident we won't be revisiting them. I can't think of anyone I know who thinks we will be questioning the laws of thermodynamics any time soon. But physicists at the start of the 20th century, just before the discovery of quantum mechanics and relativity, didn't think they were about to rethink their field's foundations, either.

Another popular move is to say scientific findings are true because scientists use "the scientific method." But we can never actually agree on what that method is. Some will say it is empiricism: observation and description of the world. Others will say it is the experimental method: the use of experience and experiment to test hypotheses. (This is cast sometimes as the hypothetico-deductive method, in which the experiment must be framed as a deduction from theory, and sometimes as falsification, where the point of observation and experiment is to refute theories, not to confirm them.) Recently a prominent scientist claimed the scientific method was to avoid fooling oneself into thinking something is true that is not, and vice versa.

Each of these views has its merits, but if the claim is that any one of these is *the* scientific method, then they all fail. History and philosophy have shown that the idea of a singular scientific method is, well, unscientific. In point of fact, the methods of science have varied between disciplines and across time. Many scientific practices, particularly statistical tests of significance, have been developed with the idea of avoiding wishful thinking and self-deception, but that hardly constitutes "the scientific method." Scientists have bitterly argued about which methods are the best, and, as we all know, bitter arguments rarely get resolved.

In my view, the biggest mistake scientists make is to claim that this is all somehow simple and therefore to imply that anyone who doesn't get it is a dunce. Science is *not* simple, and neither is the natural world; therein lies the challenge of science communication. What we do is both hard and, often, hard to explain. Our efforts to understand and characterize the natural world are just that: efforts. Because we're human, we often fall flat. The good news is that when that happens, we pick ourselves up, brush ourselves off, and get back to work. That's no different from professional skiers who wipe out in major races or inventors whose early aspirations go bust. Understanding the beautiful, complex world we live in, and using that knowledge to do useful things, is its own reward and why taxpayers should be happy to fund research.

Scientific theories are not perfect replicas of reality, but we have good reason to believe that they capture significant elements of it. And experience reminds us that when we ignore reality, it sooner or later comes back to bite us. SA

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Illustration by Jay Bendt

50, 100 & 150 YEARS AGO

INNOVATION AND DISCOVERY AS CHRONICLED IN *SCIENTIFIC AMERICAN*

Compiled by Mark Fischetti

JULY

1971 Virus Control

"To date the only clinically practical way to control virus diseases is to administer a vaccine that stimulates the body to form antibodies against that virus. Another possibility is to rely on what is apparently the cell's own first line of defense: interferon. Our group at the Merck Institute concentrated on the active substance poly I:C. It shows considerable promise for exploiting the interferon mechanism. After some final tests to rule out the danger of autoimmune disorders, poly I:C will be ready for cautious trials in humans for preventing infections, such as the common cold, that are caused by viruses."

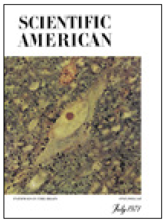
In 2021 researchers have been conducting human trials with interferon as a treatment for COVID-19, but results are unclear.

1921 Immortality for Humans

"A skillful surgeon has kept alive, by artificial means, outside the animal, a bit of tissue from the heart of an embryo chick for more than eight years. The remarkable thing is that there is no doubt that if properly cared for it will live on forever. In connection with other scientists' work its meaning becomes clear: There is no apparent 'aging' of individual cells. While we are theoretically immortals, the reason we are not actually so is because if one part of the body fails, there is failure in other parts dependent on it, and the whole machine collapses. But it would appear that so long as we can prevent a breakdown of any one part, we shall continue to be young and vigorous. Perhaps the day is not far away when most of us may reasonably anticipate a hundred years of life. And if a hundred why not a thousand?"

Marie Curie's Weighty Honor

"Filled with honors, Mme. Curie sailed on June 25th on the *Olympic*, on which was carried her precious gram of radium. The Bureau of Standards provided a beautiful mahogany case lined with lead and steel. Although not large it weighs 130 pounds. In the center are several small compartments, formed of lead and surrounded by steel, each one sized for a small glass tube containing a portion of the radium salts. The lid is inlaid with a gold plate, handsomely marked with the following inscription: 'Presented by the President of the United States on behalf of the women of America to Madame Marie Sklodowska Curie in recognition of her transcendent service to science and humanity in the discovery of radium. The White House, May 20, 1921.'"



1971

1921

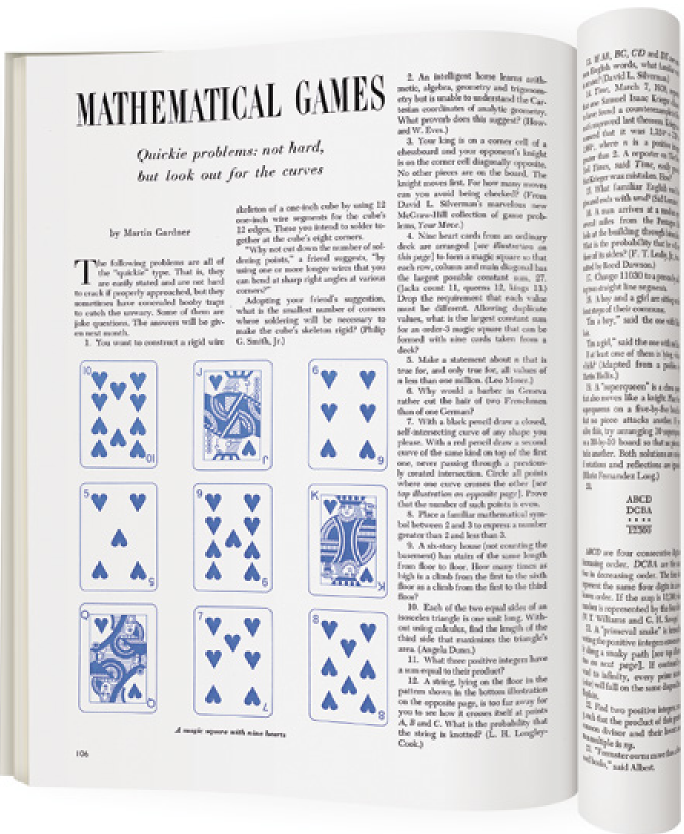

1871

1871 Calculus Is Good for You

"It is admitted by all metaphysicians and educators that the calculus brings into play more faculties of the mind than any other branch of learning. Recognizing this fact, professors should consider their institution a mental gymnasium, which gives the mind exercise that enables it to perform its highest destiny. Herein is the value of solving problems in the calculus, and indeed of all other branches of pure mathematics—that by dealing in abstract ideas, they prepare the mind to apply itself vigorously to profound or complicated subjects connected with the realities of life."

Backyard Gas Well

"In every room in a mansion in Pennsylvania was a gas well apparatus, and fires could at any moment be lighted. In the kitchen was a large and complete range. Nothing is employed in that house for heating and illumination, except this gas. The well is in the backyard, sufficiently removed from the mansion, and is covered by a small house. The bore is five hundred and twenty feet deep, lined with iron pipe, and furnished with a safety valve."



1971: An illustration shows a card problem presented by Martin Gardner in his monthly column Mathematical Games: "Nine heart cards are arranged to form a magic square so that each row, column and main diagonal has the largest possible constant sum, 27. (Jacks count 11, queens 12, kings 13.) Allowing duplicate values, what is the largest constant sum that can be formed with nine cards from a deck?"

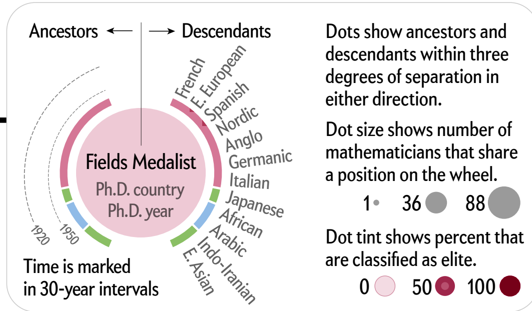
JEROME KUHL; *SCIENTIFIC AMERICAN*, VOL. 225, NO. 1; JULY 1971

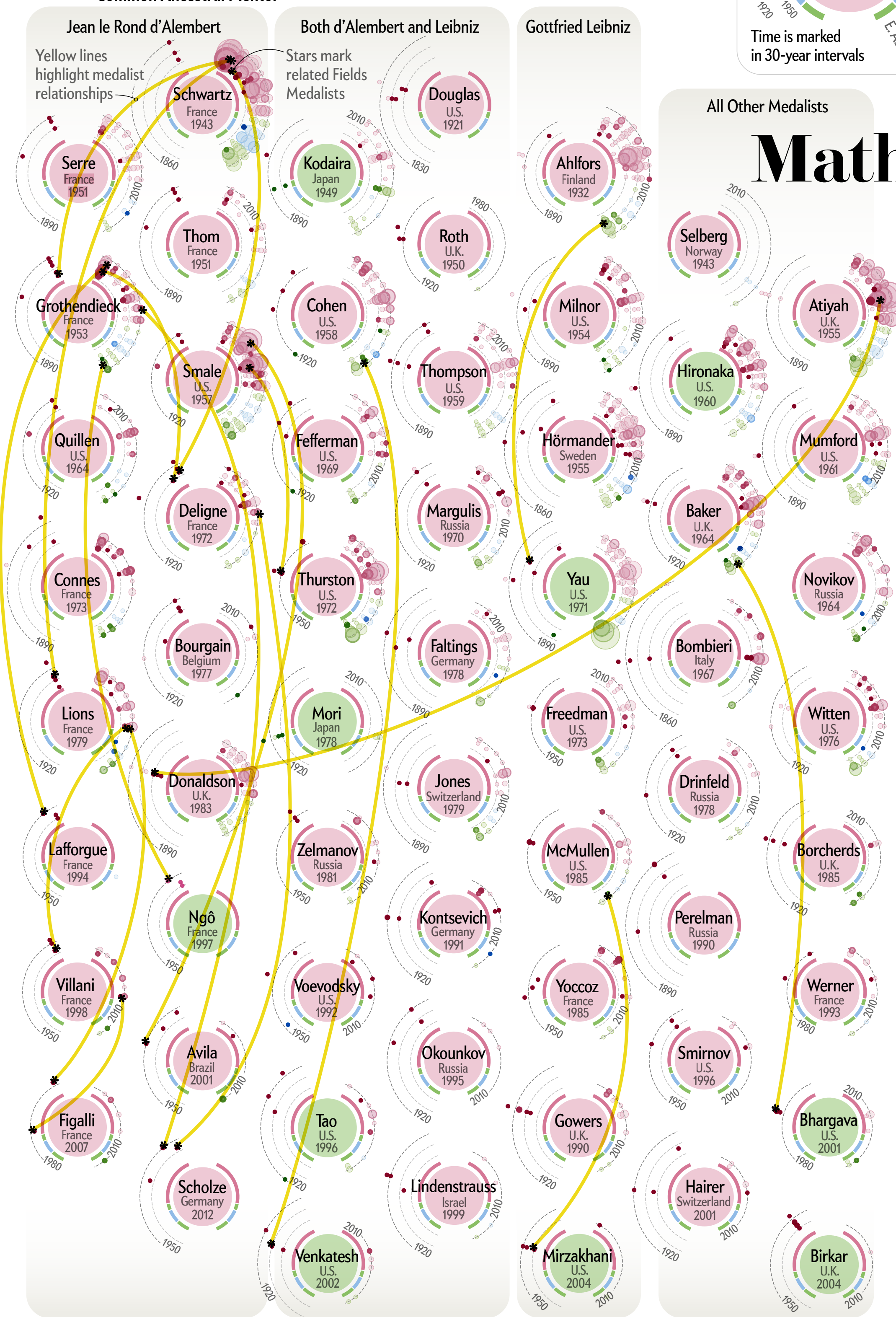
Text by Clara Moskowitz | Graphic by Shirley Wu

Mathematical Privilege

Prestige among mathematicians is often passed down

More than 80 percent of elite mathematicians descend from two early greats—18th-century French mathematician Jean le Rond d'Alembert and 17th-century German mathematician Gottfried Leibniz.





In mathematics, as in many fields, who you know matters. An analysis of mathematicians' "ancestors" (their graduate school advisers) as well as their descendants (the students they advised) shows that elite researchers tend to produce elites. Mathematicians Feng Fu of Dartmouth College and Ho-Chun Herbert Chang of the University of Southern California analyzed connections among 240,000 mathematicians and found that winners of math's highest honor, the Fields Medal, were concentrated among just a few mathematical families. "If you want to win a Fields Medal, you want to study with a Fields Medalist," Fu says.

Fu and Chang also tracked mathematicians' ethnicities* and found that "elite" researchers—defined as Fields Medalists and those closely connected to them—are usually American or European, despite the fact that mathematicians around the globe have made significant discoveries. Moreover, elites tend to have advisers and advisees that are also more American and European than the general population of mathematicians. "This is urging elite institutions to think carefully about how they can help elevate underrepresented mathematicians," Chang says.

*The researchers lacked direct data on the mathematicians' ethnicities, so they used an algorithm to define for each a lingo-ethnic identity based on their name. This technique is imperfect but allows for aggregate estimates.

SOURCE: "ELITISM IN MATHEMATICS AND INEQUALITY," BY HO-CHUN HERBERT CHANG AND FENG FU, IN *HUMANITIES AND SOCIAL SCIENCES COMMUNICATIONS*; JANUARY 2021 (*data*)