SPECIAL ISSUE

THE PERILS OF LONG COVID | A BOOM IN DIAGNOSTICS | SOCIAL MOVEMENTS AND BACKLASH

SCIENTIFIC AMERICAN

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MARCH 2022

HOW COVID CHANGED THE WORLD

Lessons from two years of emergency science, upheaval and loss

INSIDE

- A virus showed the dangers of rugged individualism
- Global health institutions lost trust
- Messenger RNA vaccines opened the door to new therapies
- Conspiracy theories made everything harder
- And more

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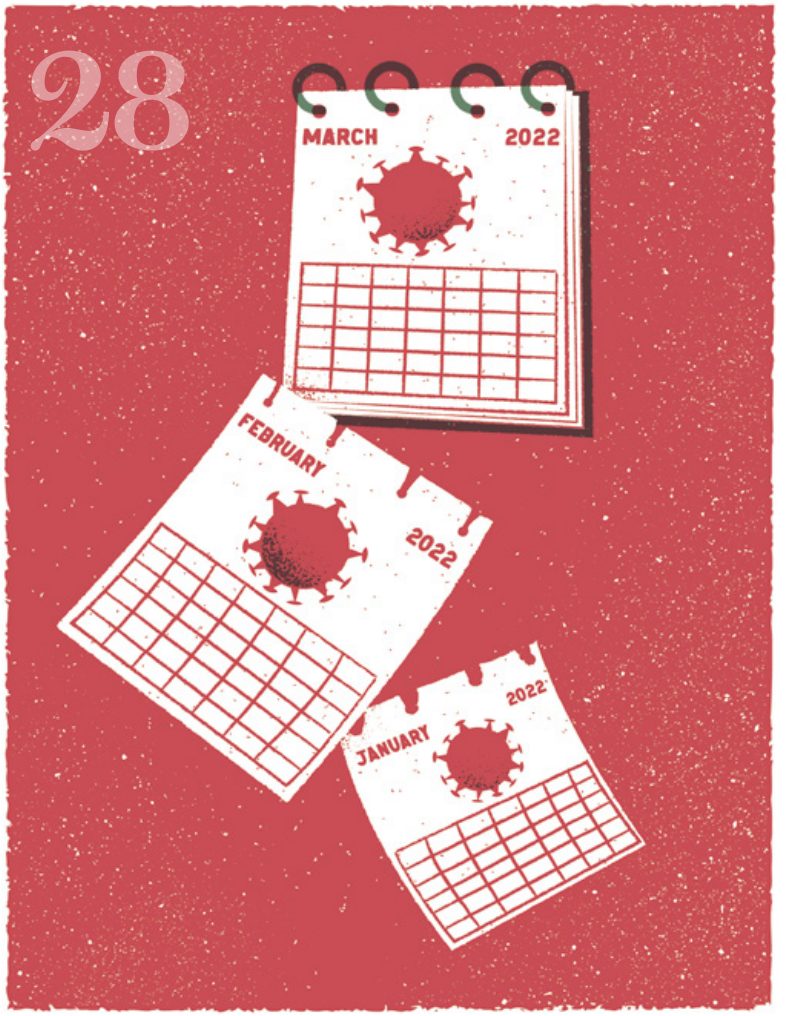

ON THE COVER

Two years into the pandemic, experts reflect on what the virus has done to science and society—what we've learned, what can't be undone and how to move forward. **Illustration by Olena Shmahalo.**

Illustration by James Olstein

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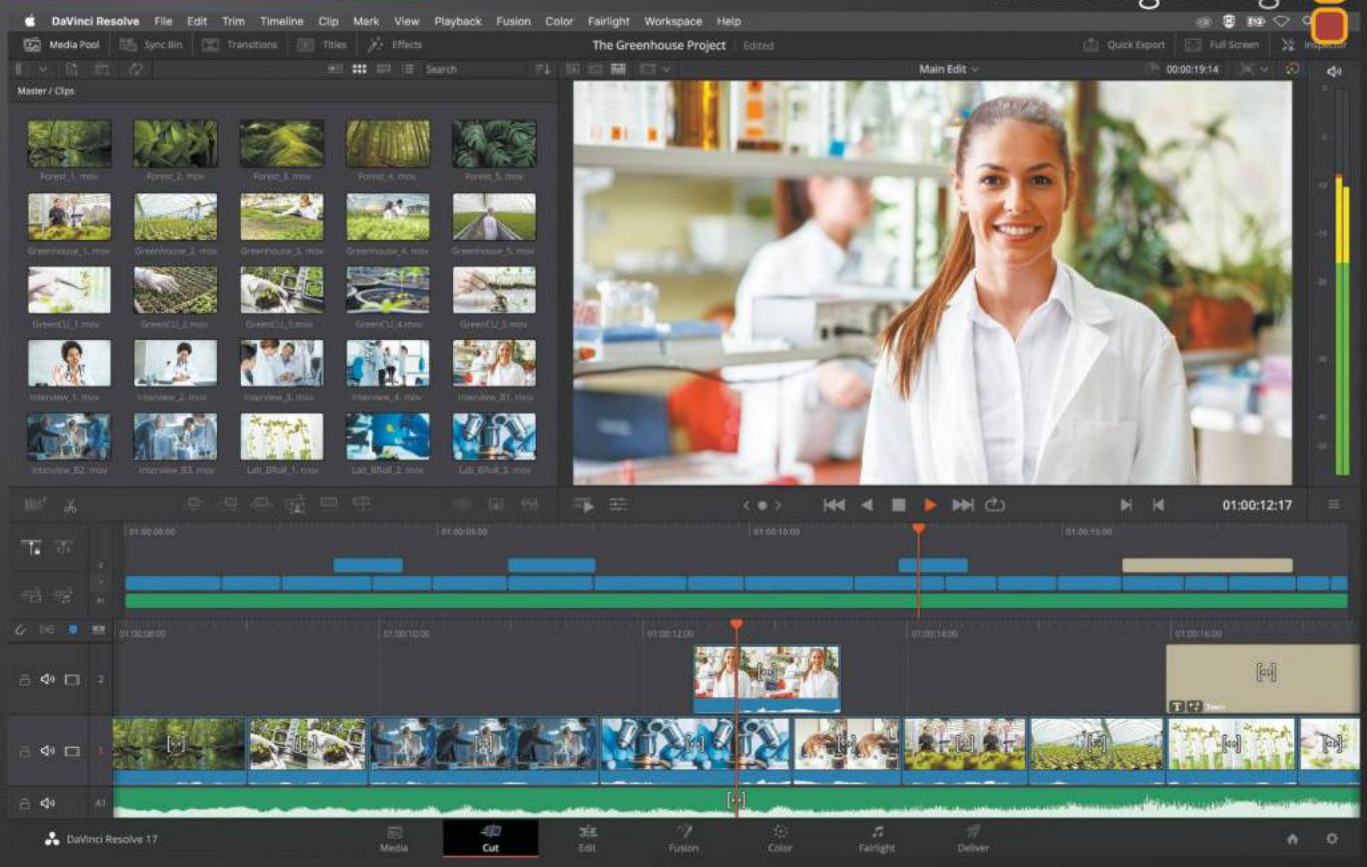

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Laura Helmuth is editor in chief of *Scientific American*.
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How Has COVID Changed Your World?

It's been a tough two years. I hope you and yours are as safe and healthy as possible at this stage of the COVID pandemic. Like everyone, we at *Scientific American* have been thinking about this terrible disease constantly and trying to make sense of it. We've published hundreds of articles about the coronavirus itself, the immune system response, the astonishingly protective vaccines, the psychological toll on society, the trauma of health-care workers, deadly misinformation and the best ways to stop the spread of SARS-CoV-2. We meet weekly to brainstorm about the most important stories we should pursue to inform, engage and protect people, and even two years in we come up with dozens of ideas in every discussion.

In this issue, we look at how COVID has changed the world. We have 24 articles (don't worry, some are quite short) that cover endeavors that have been directly and dramatically transformed, such as disease testing (*page 40*) and vaccine development (*page 75*), as well as some of the more unexpected impacts, such as on climate conferences (*page 70*) and rocket launches (*page 71*).

The main package of articles starts on page 28, with an introduction by senior editor Jen Schwartz, who did brilliant work pulling these pieces together and making sense of the many ways that COVID disrupted society, accelerated research, and amplified the need for science and humanity. Most of the staff contributed to this report, beginning with the early brainstorming sessions (we do a lot of brainstorming), to make sure that we were representing many fields of research and segments of society. Our creative director, Michael Mrak, designed the section with clever illustrations and memorable images, thanks to photo editor Monica Bradley. Words are powerful, but graphics can be even more gripping. If you're reading this issue in print, turn the pages sideways to see a stunning collection of data visualizations, created by graphics editors Amanda Montañez and Jen Christiansen, that show the profound ways COVID has shortened life span, transformed research, and changed education and the economy.

We'd like to hear from you: How has COVID changed your world? Please share your observations about the pandemic's impact on your community, profession, hobbies, schools, or other aspects of life. We'll publish your reports in our Letters to the Editor column, which you can reach at editors@sciam.com.

The COVID pandemic isn't over, of course, and we're anticipating years of important research findings. We'll keep covering new insights on the immune system, long-term effects of viral infections, psychological resilience, children's cognitive development, science-informed policies (we hope), and how to prevent or control the next pandemic. Some of this research will be conducted by people who were inspired by this disaster to pursue careers in science and health.

The 1918 flu pandemic killed an estimated 50 million to 100 million people around the world and raged for years. Afterward, historians have found, the catastrophe slid out of collective memory surprisingly quickly. We hope the dangers and disruption of COVID will ease soon, but we hope the lessons of COVID will last. SA

Illustration by Nick Higgins

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"When state legislatures pass laws that take control of public health and safety measures away from local agencies, the entire population is at risk of COVID."

EMMANUEL PADIN *CLERMONT, FLA.*

STATES OF DISEASE

"States vs. Health," by the Editors [Science Agenda], explains how politicians in several states are trying to prevent the lifesaving work that public health officials are executing to protect the population by requiring masking and physical distancing.

I agree with the presentation of the article and the position that the Editors take on the importance of letting science and good medical practice lead the way to deal with the devastating effects that the COVID pandemic is having in the U.S. and throughout the world. When state legislatures pass laws that take control of public health and safety measures away from local agencies, as the article exposes, the entire population is at risk of contamination and the spread of the virus that causes COVID.

In the piece, Georges Benjamin, executive director of the American Public Health Association, is eloquent in describing how the health strategies being applied by the public health agencies have been proved to be effective for hundreds of years and how what some state legislatures are doing is "equivalent to taking away the ability of doctors to write prescriptions."

I congratulate *Scientific American* for publishing this article and invite the readers to reflect on and support the science and public health strategies that have protected lives from many viruses, including the present one, and to avoid the intrusion of politics in this essential and life-threatening matter.

EMMANUEL PADIN *Clermont, Fla.*

STORM WATCH

"Vapor Storms," by Jennifer A. Francis, describes how increased moisture in a warmer atmosphere is fueling intense hurricanes and flooding rains. Reading the article reminded me of an experience I had camping on the eastern edge of Lake Superior, probably 35 years ago.

That October I was sitting on the shore late in the afternoon. The sky was cloudless several hundred meters offshore, with a breeze blowing in from the lake. The sky above the shore was overcast, tending toward drizzle.

This pattern stayed constant for the hour or so I watched; the clouds were forming over that short distance. Watching weather change over such a small area gave me some appreciation for how difficult climate modeling has to be.

ERICK ERICKSON *South Orange, N.J.*

DIRE WARMING

"IPCC, Your Job Is Partly Done," by Naomi Oreskes [Observatory], argues that the Intergovernmental Panel on Climate Change (IPCC) has fully established the "physical science basis" of climate change and should now focus entirely on analyzing its impacts and potential ways to stop it.

I wonder if Oreskes has heard of the University of Victoria professor Andrew Weaver's recent comment that limiting warming to 1.5 degrees Celsius is now impossible. Weaver, whose Ph.D. is in applied mathematics, has numerous accomplishments, including more than 200 published scientific works and a period as leader of the provincial Green Party here in British Columbia. But most pertinent to his comment is that he was a lead author in several of the IPCC's past assessment reports. I was thus somewhat surprised that he was publicly rebuked by those offended by his assertion.

I happened to hear Weaver interviewed on the CBC, and he clarified that his intention was not to advocate abandonment of the goal of limiting warming as much as possible. Rather it was to recognize that we have passed a point where, if we were to fix levels of greenhouse gases today, we would still see average global temperatures rise by more than 1.5 degrees C.

My observation is that, so far, the public has been somewhat lulled by the nature of scientific statements. That is, science is cautious; science does not practice hyperbole even when it may be necessary from a social perspective. All the projections of climate change I have seen appear to be underestimates of the severity of this accelerating crisis. It may be more in the interest of the greater good to speak plainly.

This dovetails with Oreskes's suggestion that the IPCC's working group on climate change's physical science basis should be wrapped up and that the organization's focus should be directed to its working groups devoted to impacts and mitigation. I would add that the urgency be emphasized by all possible means.

RICHARD "DICK" FAHLMAN
Tla'amin Nation, British Columbia

THE PROBLEM WITH PAINKILLERS

In "Painkiller Risks" [The Science of Health], Claudia Wallis discusses the downsides of high doses of analgesics, including kidney damage from nonsteroidal anti-inflammatory drugs (NSAIDs). I find it lacking, though, that she does not expand on the connection between over-the-counter painkillers and kidney issues other than a brief mention of potential adverse use of NSAIDs during pregnancy.

Long before the current opioid crisis, the scientific community and literature knew of the dangers of NSAIDs and acetaminophen (Tylenol). NSAIDS have been clearly associated with damage to kidneys,

and there is evidence that high doses of acetaminophen can harm them as well. In 1994 the *New England Journal of Medicine* published a study entitled "Risk of Kidney Failure Associated with the Use of Acetaminophen, Aspirin, and Nonsteroidal Antiinflammatory Drugs." This 27-year-old paper estimated that up to approximately 10 percent of the incidence of end-stage renal disease (ESRD), or kidney failure, could be the result of long-term acetaminophen use and that such use of the drug could be responsible for up to $700 million (in 1994 dollars) in annual ESRD-related medical costs.

I applaud Wallis for highlighting the overall risk of acetaminophen toward the end of her article: She quotes pain researcher and professor of medicine Erin Krebs as noting the drug "is very safe up to a certain threshold, and above that line it is very hazardous." Wallis then adds that the same researcher "says it's 'crazy' that the drug is present in more than 600 products," which "makes it all too easy to go overboard."

I believe all products that contain acetaminophen or NSAIDs should require warning labels regarding potential damage to kidneys.

David Rogers *Northport, N.Y.*

CLARIFICATION

"Overcoming Gene Therapy's Long Shadow," by Tanya Lewis [Innovations In: Gene Therapy], did not give Mark Batshaw's current affiliation. He is now a developmental pediatrician at Children's National Hospital in Washington, D.C.

ERRATA

"The Power of Agroecology," by Raj Patel, should have described the small Malawian town of Ekwendeni, not "Ekwendi."

"Painkiller Risks," by Claudia Wallis [The Science of Health], incorrectly describes acetaminophen poisoning as the most common reason people need a liver transplant in the U.S. It is the most common reason for acute liver failure, a condition that leads to about 6 percent of all liver transplants in the country.

"IPCC, Your Job Is Partly Done," by Naomi Oreskes [Observatory], should have given the organization's full name as the Intergovernmental Panel on Climate Change, not the "International Panel on Climate Change."

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Get Ready for the Next One

Contagions worse than COVID will prevail if neglect of global public health continues

By the Editors

After Omicron comes *pi* in the Greek alphabet. And then *rho, sigma, tau*.... Before SARS-CoV-2 finishes its grand tour through the Greek alphabet, the global public health establishment should do what it should have done long before this coronavirus emerged. It must put in place the basic health systems needed to detect new outbreaks and deploy technologies that allow for vaccines and medicines to be manufactured and administered in low- and middle-income countries.

Because they have often refused to treat COVID as a common threat that demands a unified response, policy makers have yet to thwart the predations of a virus that, to channel the Greeks again, affects all (*pan*) people (*demos*). This myopia means that these mistakes could be repeated when a new pandemic arrives.

The next time could be worse. The National Academy of Medicine predicted in November 2021 that a flu epidemic akin to the one in 1918 and 1919 could prove more catastrophic than COVID-19. The preconditions for such a disaster are in place. A warming planet, megacities, mass migration, intercontinental travel and habitat loss are among the reasons that infectious diseases, like intensifying typhoons and hurricanes, have become part of our lives.

Fast-tracked development of diagnostics, vaccines, monoclonal antibodies and antiviral drugs marks an undisputed medical triumph of the COVID era. Also notable, however, is the failure of governments and international organizations to use our current predicament to rectify glaring public health deficiencies.

The Global Health Security Index for 2021 rated the world's 195 countries as "dangerously unprepared" to deal with future epidemic and pandemic threats. The average score for individual countries came in at 38.9 out of 100, about the same as the 2019 rating—before the pandemic began. Many countries failed to grasp that the pandemic presented an unparalleled opportunity to lay the groundwork for coping with not only this public health crisis but also future ones.

Readiness for a COVID-30 or a new pandemic flu strain—or, for that matter, an out-of-control bioweapon—will require new generations of surveillance tools, diagnostics and drugs, as well as, say, a "universal" coronavirus vaccine that can counter any strain. Having sufficient available vaccine formulations with long shelf lives would also help alleviate the inequities that have accompanied distribution of shots. Underscoring the absence of "global" in "global public health," Portugal had fully vaccinated 89 percent of its population by mid-January but Mali only 2.8 percent.

The most pressing priority should be a return to basics, both globally and locally. COVID has served as a painful demonstration that public health is as essential to national security as a standing army. And the cost of health security is minimal. In 2016 the Commission on a Global Health Risk Framework for the Future estimated that for 65 cents a year for every person on the planet, we could upgrade national pandemic preparedness programs worldwide. An investment of $4.5 billion—far less than the price of a single new ballistic missile submarine—might prevent the global loss of millions of lives and an economic hit in the trillions of dollars.

The basics entail not only building new systems to prepare for pandemics but a major strengthening of institutions already in place. Public health legal expert Lawrence O. Gostin notes in this issue (*page 46*) that the World Health Organization has a 2022–2023 budget of $6.12 billion, which is less than those of some major U.S. teaching hospitals. The WHO needs not just money but reforms that give it the authority to better monitor and intervene when new infectious diseases emerge. At the country level, the most basic of basics consist of functioning national systems that furnish medical care for all and financial help, as needed, for child care, food and housing and other measures to waylay the poverty-related chronic diseases capable of sending even a relatively young adult onto a ventilator during a future pandemic.

After repeated outbreaks of horrific diseases such as SARS, Ebola and Zika, perhaps this calamity will prove traumatic enough to allow for a coherent remake of the current system. Deaths from COVID worldwide by mid-January about equaled the population of Norway—and the pandemic is still with us. Only when global public health commands the attention of policy makers in the same way as a new contract for nuclear submarines will Greek letters return to their more familiar role in American life as naming conventions for student groups on college campuses. SA

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Illustration by Martin Gee

A COVID Vaccine for All

This patent-free technology could finally inoculate the world

By Peter J. Hotez and Maria Elena Bottazzi


Peter J. Hotez and **Maria Elena Bottazzi** are professors of pediatrics and molecular virology at the Baylor College of Medicine. They also serve as co-directors of the Texas Children's Hospital Center for Vaccine Development.

As the pandemic entered its third year, the Texas Children's Hospital Center for Vaccine Development and the Baylor College of Medicine gifted the world the first COVID vaccine designed specifically for global health. This patent-free vaccine, called CORBEVAX, is a milestone for global health equity. Based on an older and more widely used technology than the now well-known COVID mRNA vaccines, it could help end vaccine hesitancy in some parts of the world. It also serves as a blueprint for developing a potent vaccine for pandemic use in the absence of substantial public funding.

We are part of the team that developed the vaccine, and our institution licensed the vaccine prototype and transferred its technology in 2021—with no strings attached—to Biological E. Limited, a company based in Hyderabad, India. The Indian government has authorized the vaccine, and Biological E. plans to deliver more than a billion additional doses to other countries. This means that if it is widely authorized, CORBEVAX could soon vaccinate more people than have the vaccine doses donated thus far by the U.S. government or any other G7 country.

This COVID vaccine has several distinct features that make it suitable for use in resource-poor settings: it is safe, effective, inexpensive and easy to store and can be produced locally at high quantities. We expect it will be used in low- and middle-income countries where vaccine availability has basically been abysmal.

CORBEVAX uses the SARS-CoV-2 spike protein to stimulate an immune reaction, but the technology used to develop it resembles that of the recombinant hepatitis B vaccine used in many resource-poor countries. Manufacturing processes for such vaccines are generally well understood and will not require a steep learning curve, like those needed for vaccines based on new technologies such as mRNA (used by Moderna and Pfizer-BioNTech) or adenovirus (AstraZeneca and Sputnik).

Companies in Indonesia and Bangladesh have also licensed the technology, as has California-based ImmunityBio, which is building manufacturing capacity in South Africa and other countries in Africa. Such technology-transfer agreements with suitable partners represent the ideal for how COVID vaccines can and should be produced locally and widely in resource-poor countries.

Our analysis of available data suggests that, like the hepatitis B vaccine, CORBEVAX has an excellent safety profile. In a phase 3 trial conducted in India, CORBEVAX produced no serious adverse events, making it one of the safest COVID vaccines in use. When compared with the AstraZeneca–University of Oxford vaccine manufactured by the Serum Institute of India, CORBEVAX also produced more lasting protection and more neutralizing antibodies against the Delta and Beta variants of SARS-CoV-2. It neutralized variants of concern in laboratory studies and was highly protective in two primate trials in which the animals were infected with SARS-CoV-2 to see how well the vaccine defended them against infection. The human trial results are being submitted to a peer-reviewed journal. Clinical trials in children are underway in India.

Based on the use of the hepatitis B vaccine, we anticipate people will readily accept CORBEVAX and similar recombinant protein COVID vaccines. If there was ever a COVID vaccine that might triumph over vaccine hesitancy and refusal, this could be the one.

Texas Children's Hospital developed this vaccine with no major federal or G7 support, instead relying almost exclusively on private philanthropy based in Texas, New York and elsewhere. Is it possible that had we enjoyed even a small fraction of the support afforded to the biotech or multinational companies producing new-technology vaccines, the world might have been vaccinated by now? Could the emergence of the Delta and Omicron varieties, which likely arose from unvaccinated people, have been prevented? It is not too late. We continue to ask the U.S. and other G7 nations for assistance in co-developing our recombinant protein vaccine with new partners in other low-resource countries and advancing them to the COVAX sharing facility for global distribution.

During 2022, we hope to partner with the World Health Organization and other United Nations agencies to vaccinate the world. We believe that global vaccine equity is finally at hand and that it is the only thing that can bring the COVID pandemic to an end. SA

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Illustration by James Olstein

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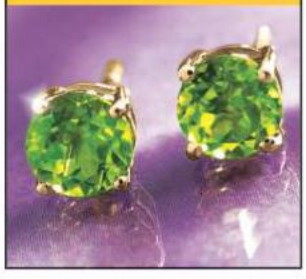

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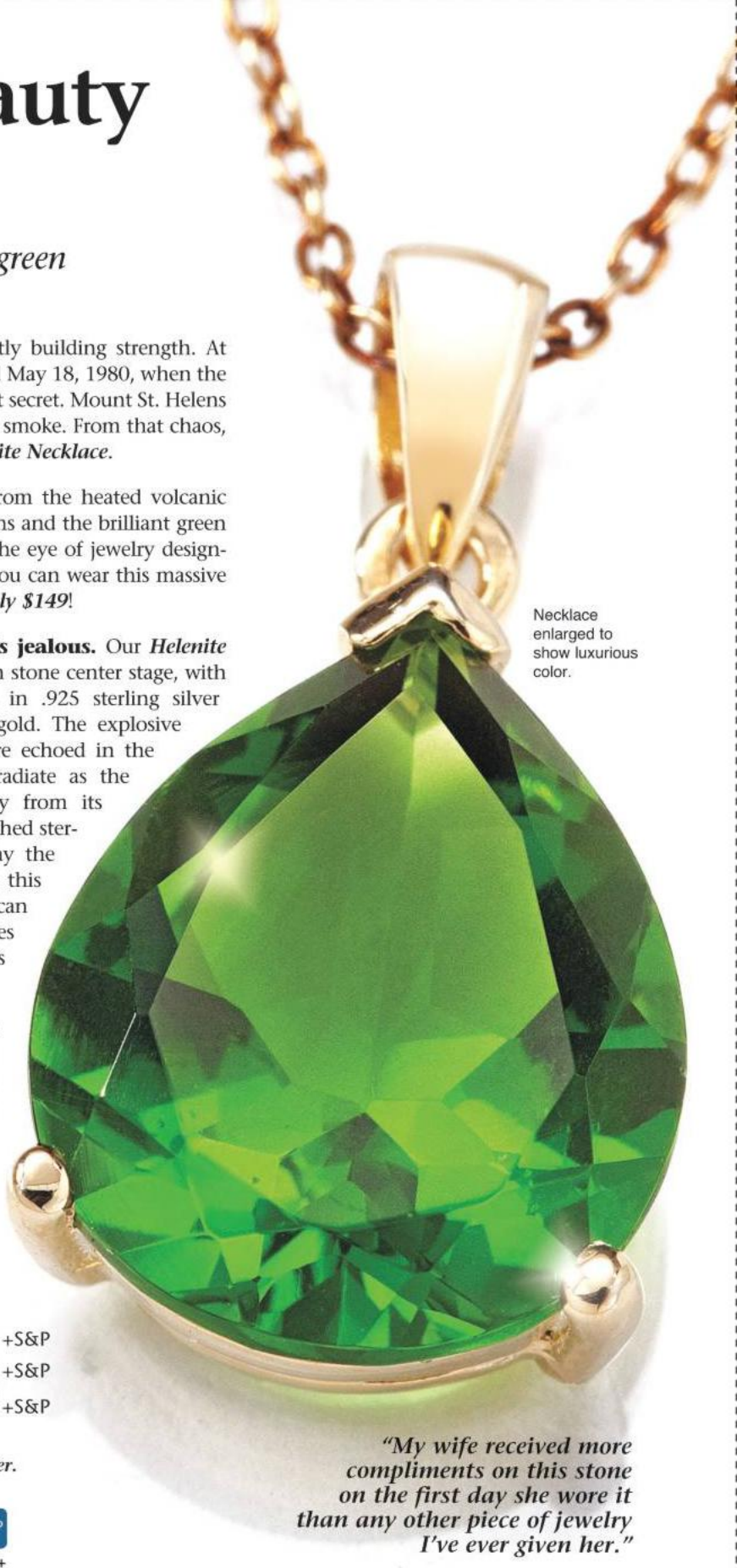

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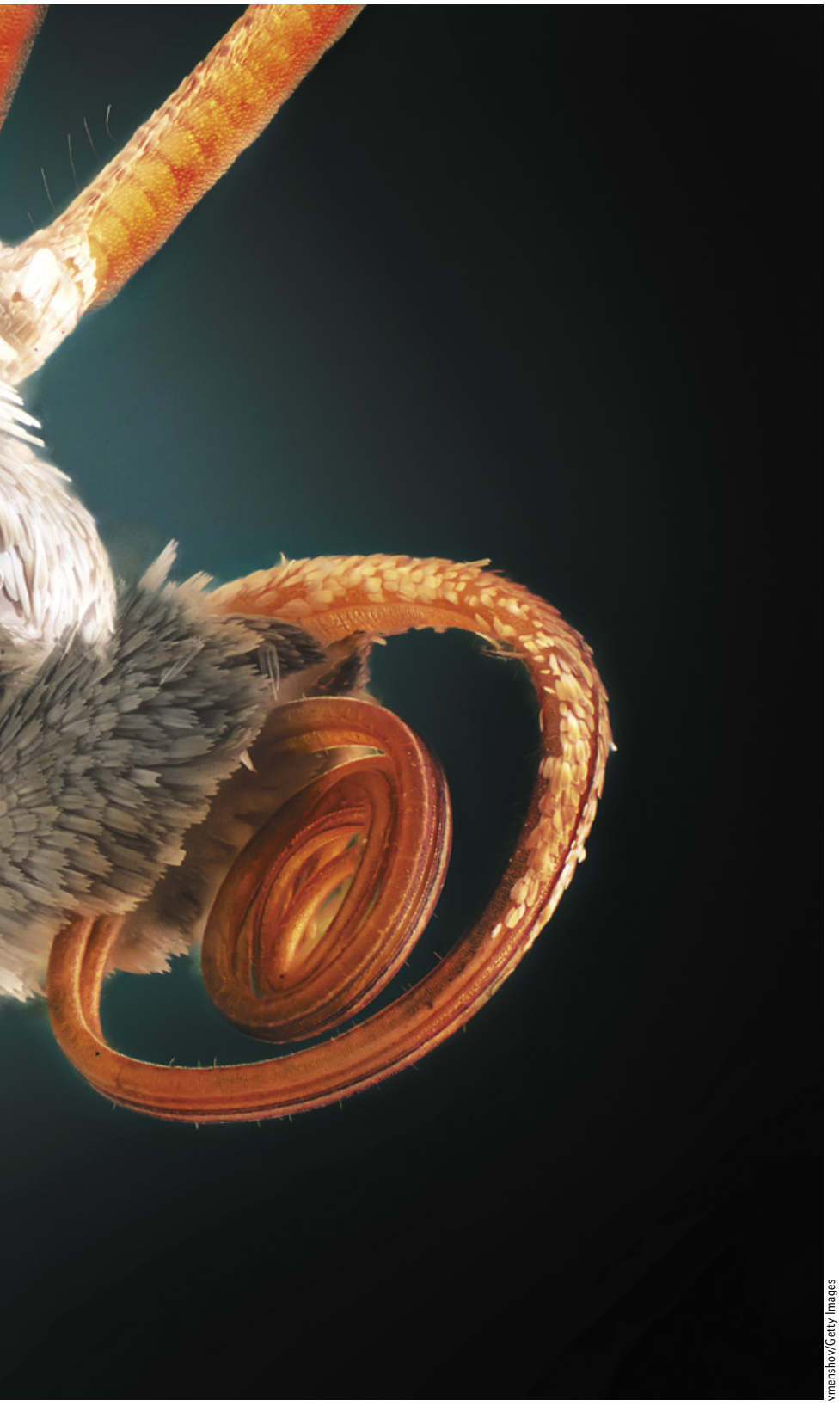
ADVANCES

DNA found in the air may be especially useful to document insects such as moths.



vmenshov/Getty Images

INSIDE

GENETICS

From Thin Air

Airborne genetic material holds clues to Earth's biodiversity

Two decades ago biologists and natural historians around the world launched ambitious projects to create inventories of our planet's biodiversity. After all, they said, you can't work to save what you don't know exists. Even the most optimistic estimates suggest only a quarter of Earth's species are currently known to science, raising concerns about the big picture amid rising extinction rates.

These projects have crept along because of the painstaking work of identifying and describing species—as well as, in many cases, collecting samples of the organisms for DNA sequencing. Now a new approach to cataloguing the world's animals has emerged: vacuuming DNA out of thin air.

The technique is a variation on one previously used in water, soil and elsewhere, in which scientists collect and sequence environmental DNA (eDNA), the genetic material in cells shed by local species. Pulling eDNA from the air could provide an extensive picture of a location's inhabitants. It may also prove particularly useful with organisms such as insects, which are notoriously hard to monitor (and are often killed in traditional DNA-sequencing practices). Analyzing eDNA is faster and less costly than collecting and sequencing individual animals, and it can capture data from many species at once—even in hard-to-reach environments.

Two new papers published in *Current Biology* put airborne eDNA to the test. One group of researchers worked at the Copenhagen Zoo and one in Hamerton Zoo Park in the U.K.—perfect locations to evaluate such sampling because the scientists knew exactly what species were present and how many individuals there were.

The teams used different methods to vacuum or blow air through a filter to extract DNA. Once the DNA was amplified and sequenced, both teams detected many of the species present in the zoo—even those inside buildings or hundreds of meters from the collection sites.

The eDNA sampling also picked up genetic signatures of species outside the zoos' walls. The U.K. group identified Eurasian hedgehogs, which are vulnerable to extinction in the country, and the Denmark group found genetic traces from squirrels and cats.

The researchers say eDNA is a game changer for monitoring biodiversity: other techniques require the animal to be physically present when scientists are looking. "If you have a camera trap, they have to walk in front of your camera—because if they walk behind it, you'll never know," says Elizabeth Clare, a molecular ecologist at York University and a co-author on the U.K. study. "If you're acoustically recording or [conducting] visual surveys, the animal has to be there. But environmental DNA is more like a footprint. It's a really fundamentally different type of data. The animal doesn't physically have to be present, and so you're much more likely to catch rare stuff."

A recent proof-of-concept airborne eDNA project, presented at the conference Ecology Across Borders, took similar techniques into the wild to identify insects based on air samples from three locations in southern Sweden. Conservation scientist Fabian Roger and his colleagues at Lund University found DNA traces and matched them with 85 species, including butterflies, beetles, ants and flies, as well as nine noninsect species such as frogs and birds. When compared with results from a conventional survey, the eDNA process missed some species but found others the survey had overlooked.

Roger, now at ETH in Zurich, says he was inspired to try sampling airborne eDNA after monitoring aquatic ecosystems for new species. "It hit me how difficult it was to get good data on populations," he says. "And with recent research showing a 70 percent reduction in insect biomass, we have a crucial lack of data."

Researchers estimate that scientists have described only one million of the world's 5.5 million insect species, so looking to the air to monitor biodiversity is an exciting development that might speed up conservation efforts. "The time is ready for environmental DNA to take on this new substrate," says Kristine Bohmann, an ecologist at the University of Copenhagen, who co-authored the Denmark study. She adds that she has worked on eDNA from fecal samples, and others have looked at soil and water—and even flowers to discover which pollinating species have landed on them.

There are still questions about airborne eDNA: for one, it is unclear how long genetic material persists in the air. Are researchers detecting a recent presence or one from months earlier? Studies have found intact DNA in permafrost up to 10,000 years after its source organisms perished. But in other conditions, such as exposure to ultraviolet radiation from the sun, DNA may degrade quickly.

Another big question involves abundance. Does a larger signal of a species' DNA indicate the presence of many individuals or just one that happens to be closer to the sampling station? This is one of the hottest topics in eDNA research circles, Clare says. "The simple answer is no," she adds. "You can't know the abundance unless you have extremely controlled conditions."

Still, the implications of using eDNA from the air to remotely monitor biodiversity are enormous. A global network of air-collecting stations could let farmers know about invasive creatures entering their areas or inform conservation scientists if an endangered bird still lives in a specific area, the researchers say. It would also provide a snapshot of what is out there, faster and cheaper, without people having to do laborious sample collection in hard-to-reach locations. Bohmann once trudged through Madagascar to deliberately attract leeches—and later analyzed the DNA inside the bloodsuckers' stomachs to learn about the forest's inhabitants. "If I could avoid being human bait and get the results beamed to me at my computer," she says, "that would be amazing."

—Katharine Gammon

Todor Dinchev/Alamy Stock Photo

ANIMAL COGNITION

Bird Memory

Pigeons remember specific routes home after years away

Homing pigeons combine precise internal compasses and memorized landmarks to retrace a path back to their lofts—even four years after the previous time they made the trip, a new study shows.

Testing nonhuman memory retention is challenging; in research studies, "it's rare that there is a gap of several years between when an animal stores the information and when it is next required to retrieve it," says University of Oxford zoologist Dora Biro. For a recent study in the *Proceedings of the Royal Society B*, Biro and her colleagues compared domestic homing pigeons' paths three or four years after the birds established routes back to their loft from a farm 8.6 kilometers away. The study built on data from a 2016 experiment in which pigeons learned routes in different social contexts during several flights—on their own or with peers that did or did not know the way.

Using data from GPS devices temporarily attached to the birds' backs, the researchers compared the flight paths a cohort of pigeons took in 2016 with many of the same birds' routes in 2019 or 2020, without the birds visiting the release site in between. Some birds missed a handful of landmarks along the way, but many others took "strikingly similar" routes to those they used in 2016, says Oxford zoologist and study co-author Julien Collet: "It was … as if the last time they flew there was just the day before, not four years ago."

The team found that the pigeons remembered a route just as well if they first flew it alone or with others and fared much better than those that had not made the journey in 2016.

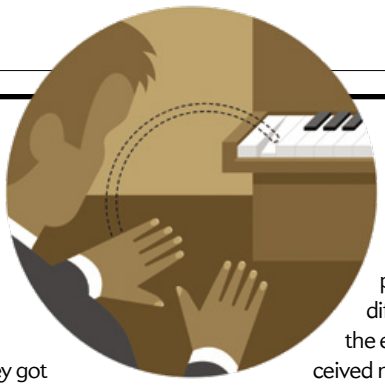
The result is not surprising, says Verner Bingman, who studies animal navigation at Bowling Green State University and was not involved with the study. But it provides new confirmation of homing pigeons' remarkable memory, he says: "It closes the distance a little bit between our egocentric sense of human cognitive abilities and what animals can do."

—Robin Donovan

NEUROSCIENCE

Phantom Finger

An unusual illusion points to philosophy and robotics



Brains contain maps of the bodies they inhabit, with neurons dedicated to the perception or control of particular parts—and research suggests there may be quite a bit of wiggle room in that representation. In 2016 scientists set up an experiment that made subjects fleetingly feel like they had a sixth finger on one hand (one subject yelled, "Witchcraft!"), and in 2020 another research group extended that sensation indefinitely. The second group went further in its latest work, published in *Cognition*, to make participants feel as if they had a sixth finger—and to control the invisible digit's perceived length.

To experience the mental illusion, the participants placed their hands on a table with a vertical mirror between them, positioned to show the reflection of the right hand where the left hand should be. Starting with the thumb, experimenters stroked the top of each finger up and down twice, stroking the right and left hand simultaneously. When they got to the pinky, the experimenters stroked the top of the right pinky and the inner side of the left pinky. Finally, they made 20 double strokes on the table next to the right pinky while stroking the outer side of the left pinky, creating a self-reported feeling of an invisible sixth finger on the left hand.

"It's quite honestly scary," says Denise Cadete, a neuroscience graduate student at Birkbeck, University of London, and lead author on the new paper. "Even if we understand all that's happening, the illusion doesn't go away—it's a very striking feeling."

In her group's latest study, the strokes on the table were sometimes half or double the length of a typical pinkie. Twenty right-handed participants then used a mechanical slider to indicate how long the new finger felt—reporting it felt on average about 1.5 centimeters shorter or about three centimeters longer than their real-life pinky, respectively. These differences suggest that the extra finger was perceived not merely as a duplicate pinky but as its own entity.

Cadete says that beyond its intriguing philosophical implications about humans' sense of self, this research could also be useful for people with robotic limbs. She says a mechanical appendage might transfer sensation to a nearby body part via these brain illusions, even for limbs with complex, "Swiss Army–like" features.

The experiment is well done, says Etienne Burdet, a roboticist at Imperial College London who has studied the one-handed capabilities of people born with six fingers and was not involved in the research. Future studies could explore whether the phenomenon applies beyond an extra pinky; if he wanted to start a company to make robotic body parts, Burdet says, "I would start with an arm."

—Matthew Hutson

BIODIVERSITY

Weight of Life

Humans may have altered the mass distribution of sea life

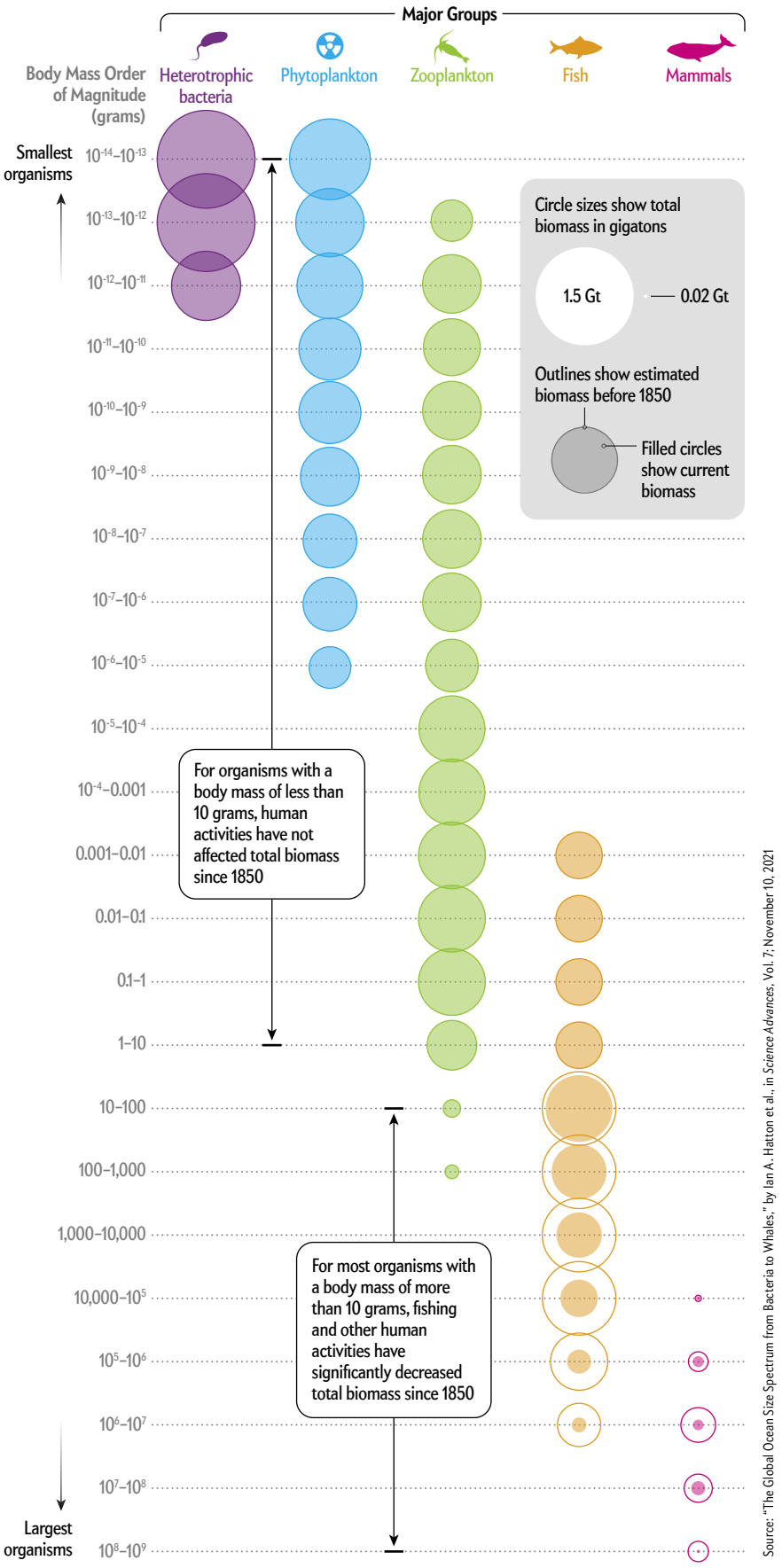
Weigh all the creatures that roam the sea, and a striking balance emerges. Researchers have found that the total mass of this life, when grouped in size classes, roughly follows a regular mathematical distribution—although humans may have disrupted part of the pattern.

For a study in *Science Advances*, researchers combined satellite images, water samples, commercial fishing catch data and computer simulations to estimate the combined weight of all the organisms that move through the open ocean. Next they visualized biomass distribution by placing species on a size spectrum segmented into 23 weight classes. To accommodate the vast size differences, the researchers divided classes using a mathematical function called a logarithm: the average weight of organisms in one class differed by a factor of 10 from adjacent classes. One class contained organisms weighing between 0.01 and 0.1 gram, another between 0.1 gram and 1 gram, and so on.

The scientists found that most of the weight classes contain roughly one gigaton of life each. "This could be one of the largest-scale regularities among life on Earth," says the study's lead author Ian Hatton, a biologist at the Max Planck Institute for Mathematics in the Sciences in Leipzig, Germany.

Exceptions included a few classes containing bacteria, which were overweight because of microbes' domination of deep waters, and classes containing animals bigger than 10 grams, which had disproportionately little mass. Wondering if humans had contributed to this divergence, Hatton's team used previously published computer simulations and animal population estimates to reconstruct the ocean size spectrum of the 1850s, before modern industrial fishing. The researchers found that the combined weight of organisms above 10 grams, including whales and many fishes, has decreased by 60 percent since then.

Overfishing is a well-known problem, but this work helps illuminate its extent, says Andrea Bryndum-Buchholz, a marine ecologist at Memorial University in Newfoundland, who was not involved in the study. "It visualizes how we've actually changed the ocean fundamentally," she says. —*Nikk Ogasa*



Graphic by Amanda Montañez

A 2019 "running of the bulls" in Pamplona, Spain

Reuters/Alamy Stock Photo

CROWD DYNAMICS

The Speed Also Rises

Bull runners show how panicked crowds move

One of the last things a pedestrian wants to see is a charging bull. Yet every July thousands of people voluntarily jam the narrow streets of Pamplona, Spain, to run alongside six agitated fighting bulls. Although the entire course is just half a mile, most runners do not complete it because of the dense crowd and the animals' break-neck speed. These blistering bovines cover nearly 20 feet per second on average.

This tradition has been criticized as reckless and cruel, and it is increasingly controversial. But for some researchers it presents a fascinating case study of how crowds respond to danger—a difficult scenario to replicate in scientific study. "You cannot make experiments putting people in real danger to see what happens," notes Daniel Parisi, who studies pedestrian dynamics at the Buenos Aires Institute of Technology. But in Pamplona, he says, people eagerly put themselves in harm's way.

To gauge runners' collective response to rampaging bulls, Parisi and his colleagues monitored two 2019 bull runs. They perched cameras along the famed Estafeta Street, where the course narrows like a funnel, and tracked runners' and bulls' movements through each recorded frame.

Their findings, published in the *Proceedings of the National Academy of Sciences USA*, challenge a core tenet of pedestrian dynamics: people slow down when crowd density increases. Like cars crawling through traffic, pedestrians typically reduce speed to avoid bumping into others. A charging 1,300-pound bull, however, flips that relationship on its head. Pamplona runners sped up as they jostled to keep pace with the animals—and avoid their horns. Even with other runners close by, Parisi says, "when a bull is near, they want to run at maximum speed no matter what."

But these runners can move only so fast. The researchers found that as the bulls caused speed and density to simultaneously increase, faster runners were more likely to become tangled with others and fall. In the past, multiple falls have triggered major pileups that cause injuries and occasionally turn deadly.

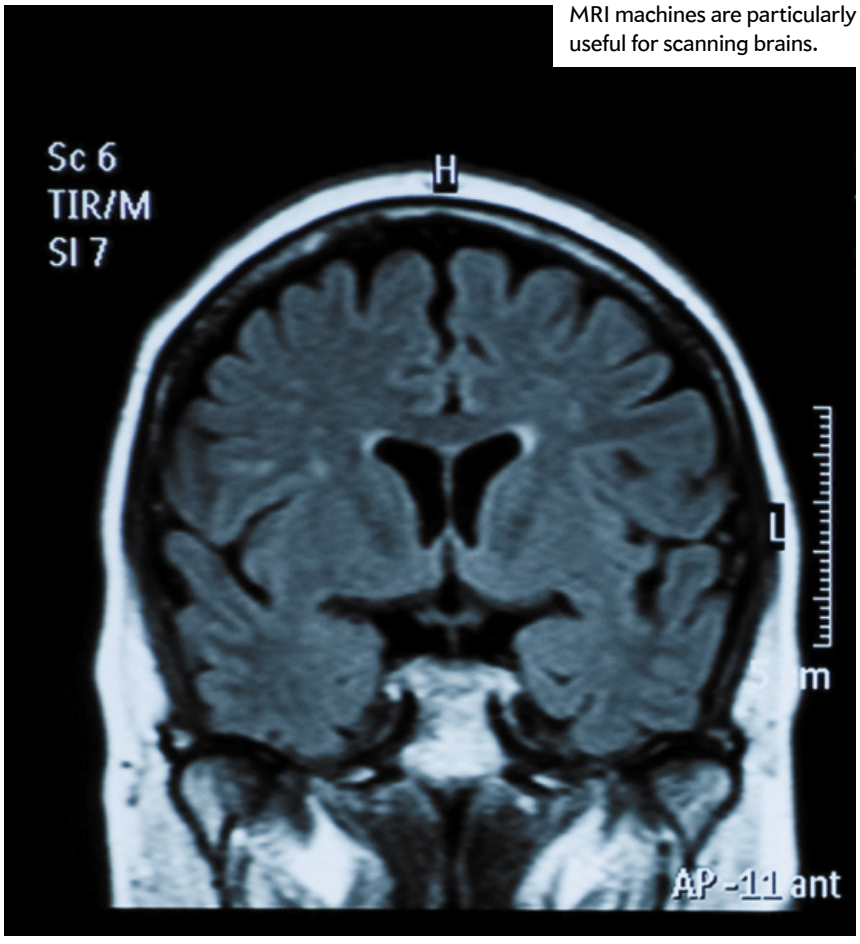
Bulls rarely stampede through congested business districts, but Parisi hopes lessons learned from this study will provide insights into how crowds respond to other kinds of dangerous situations. Alethea Barbaro, a researcher at the Delft University of Technology in the Netherlands who was not involved in the study, agrees the findings have real-world implications. Barbaro, who has modeled phenomena ranging from fish migrations to gang territorial disputes, says the Pamplona data could help calibrate models for stressed crowds to aid architectural design and evacuation planning. Plus, she says, "such models would allow emergency response personnel to have insights into potentially averting the crowd-based tragedies that we regularly see in the news."

—*Jack Tamisiea*

MEDICINE

Portable View

Compact MRIs could bring down the cost of powerful medical scanning



MRI machines are particularly useful for scanning brains.

Magnetic resonance imaging (MRI) scanners are crucial tools in modern medicine. But these behemoths typically cost $1 million to $3 million; they require purpose-built rooms to contain their powerful magnetic fields and block outside signals, plus elaborate liquid-helium cooling systems. About two thirds of the world's people lack access to such devices, 90 percent of which are located in high-income countries.

Now, however, lower-cost alternatives are coming closer. In *Nature Communications*, researchers at the University of Hong Kong, led by biomedical engineer Ed Wu, describe an MRI scanner that is compact enough to move on wheels, needs no shielding and draws power from a standard wall socket. This approach—a new entry in a category known as ultralow-field (ULF) MRI—lacks the resolution needed for some precision diagnostics, but its material costs are estimated at under $20,000. And its design and algorithms are open source, inviting researchers everywhere to help develop the technology.

MRI exploits the fact that we are mostly made of water. The protons in water's hydrogen atoms have magnetically charged "spins," which can be temporarily aligned by a scanner's magnetic field and then probed by radio-frequency pulses. Different tissues have distinct water concentrations and magnetic properties, which generate light and dark contrasts in reconstructed images.

Instead of the standard superconducting electromagnets, this ULF design uses permanent magnets that do not require cooling. It also generates far less magnetism than a standard MRI scanner, eliminating the need for shields. The main trade-off is that the signals are weaker, resulting in lower image resolution.

To enable portability, the new design eschews physical shielding against external radio-frequency noise. Instead a "deep-learning" algorithm recognizes and predicts interference signals, then subtracts them from the measured signals. "That's one very useful innovation here," says biomedical engineer Sairam Geethanath of Columbia University, who was not involved in the new research. "It's similar to noise-cancellation headphones, where you're trying to learn the noise pattern in real time and suppress it."

The team demonstrated the device by scanning 25 patients and comparing the images with those from a standard high-powered MRI machine. The researchers could identify most of the same pathologies, including tumors and stroke. "The images appear to be of sufficient quality to be clinically useful in a number of scenarios," says neuroscientist Tom Johnstone of Swinburne University of Technology in Melbourne, Australia, who was also not involved in the study. "Rapid assessment of stroke, which has a large impact on success of interventions, could be facilitated by ULF MRI being located in more towns or even mobile units."

The new design joins a growing list of ULF MRI scanners being developed. A U.S. company called Hyperfine received FDA approval last year for a portable scanner, but details of the design are proprietary; Wu and his colleagues have made their data, designs and code available online, which could speed improvements to ULF.

Ultimately ULF devices are not intended to completely replace high-field scanners. Instead they hold promise in triage settings, where patients cannot be moved or time is critical, Geethanath says.

Wu says he believes the range of applications will likely grow as performance improves. "Right now MRI systems are built as if we don't know anything about what we're scanning," he says, "but often the information we need is very subtle"—namely, to identify what is different from the expected. "That's going to be a huge revolution, driven by cheap computing."

—*Simon Makin*

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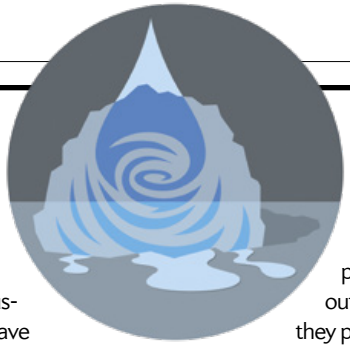
FLUID DYNAMICS

Unusual Flow

A strange fluid effect revealed



For most fluids, an increase in pressure should lead to a burst of speed, like squeezing ketchup from a tube. But when flowing through porous materials such as soil or sedimentary rock, certain liquids slow down under pressure. Pinpointing the cause of this slowing would benefit industries such as environmental clean-up and oil extraction, where pumping one liquid into the ground forces another out; however, such movement is challenging to observe directly.

Princeton University chemical engineer Christopher Browne and physicist Sujit Datta offer a solution to this puzzle. By tweaking a special liquid to be transparent and pumping it through the pores of an equally transparent artificial rock, they documented how the liquid's movement becomes chaotic, causing swirling eddies that gum up the pores and slow the flow.

The fluids of interest, called polymer solutions, are dissolved versions of large stretchy molecule chains common in biology as well as the cosmetics and energy industries. Theoretical studies have suggested that when the chains stretch through a nearly flat channel and then recoil, they generate forces that stir up eddies. But whether that turbulence "arises in realistic 3-D soils, sediments and porous rocks has been hotly debated," Datta says.

To resolve the controversy, the researchers pumped a synthetic polymer solution into a simulated "sedimentary rock" built from a box filled with tiny glass beads. They tweaked the polymer solution's precise chemistry by diluting it slightly to change how light refracts, rendering the "rock" fully transparent even when saturated.

The scientists laced the polymer with fluorescent chips and tracked its movement through the pores under a microscope, recording patchy regions of eddies and measuring how the solution flowed under differing pressure. This confirmed that the macroscale slowing had its microscopic origins where researchers had suspected: polymer chains stretching out and then coiling back as they passed through pores. The findings appeared in *Science Advances*.

"Visualizing flow inside a 3-D porous media literally gives a window into something that was impossible to see," says University of Pennsylvania biochemical engineer Paulo Arratia, who was not involved in the study. As a next step, "if you could actually see the molecules stretching and recoiling, that would be wonderful [to] connect the molecular point of view to the microscopic."

Industrial applications require knowing which specific pressures are needed to push a polymer solution through a porous material at a given flow rate. The study provides a physical model describing that relation and could predict, for example, how much contaminant can be retrieved from a chemical site by injecting a solution. "Without predictability," Datta says, "injection operations are trial and error."

—*Rachel Berkowitz*

BIOMECHANICS

Science in Images

By Gary Hartley

To wrangle a ride on their honeybee hosts, wingless parasitic flies need a truly phenomenal grasp. Now a new study reveals how *Braula coeca* manages to walk around on a flying bee while exhibiting what researchers say is the highest attachment force per body weight of any land-based insect ever measured.

This force relies on the parasite's highly adapted feet, called tarsi, which are equipped with toothed claws. Each foot has a total of 28 teeth, or claw tips, which let the parasite lock onto sparse honeybee hairs during flight.

"The claws are unique, from what we know so far. Usually insects have claws with one tip only. A few species have two to three tips. But this species possesses comblike claws with several tips and deep interstices [gaps]," says Thies Büscher, a zoologist at Germany's Kiel University and co-lead author of a recent study in *Physiological Entomology*.

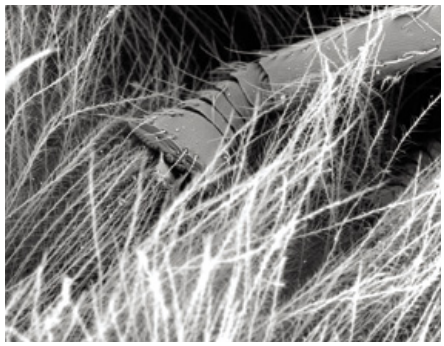
The claws are complemented by soft lateral ridges and "stoppers" along the foot, letting the fly swiftly break its rigid grip with a simple twisting motion and detach from the hairs as it moves—a trait likely to be intriguing to researchers working in biology-influenced design, or biomimetics. The parasite's feet also feature pads that firmly cling to smooth surfaces, such as the wax in beehives.

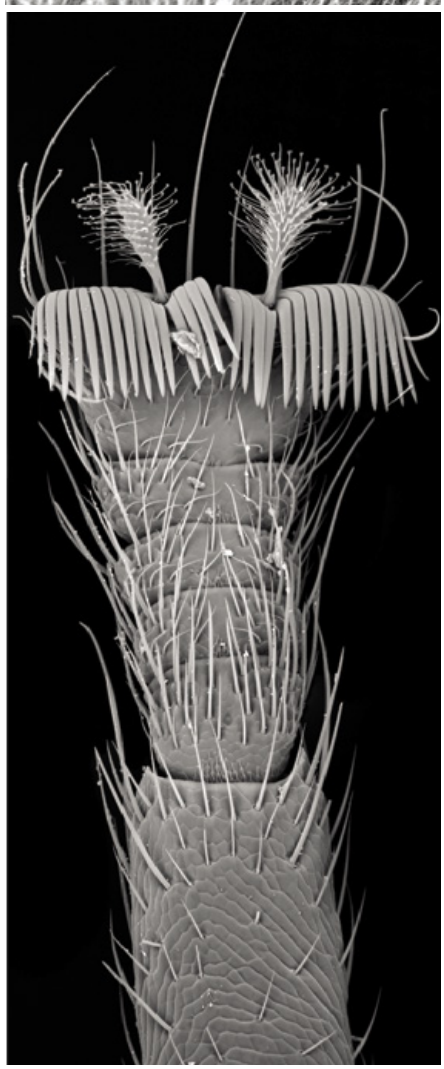
"Other strongly attaching animals either secrete strong glues or anchor with structures that damage the surface," Büscher says. "Both solutions are more or less permanent and do not allow for fast detachment and locomotion." But because *B. coeca*'s grasping mechanisms are purely mechanical, they could prove useful for both terrestrial and underwater robots.

"Attachment technology is a prominent domain within biomimetic research," says Shoshanah Jacobs, an integrative biologist at the University of Guelph in Ontario, who was not involved in the research. Jacobs agrees with Büscher on the finding's potential value but notes that designers working on attachment problems might not readily become aware of such discoveries in insect physiology.

"Biomimetic researchers grapple with the challenges of knowledge mobilization across disciplinary silos," Jacobs says. "When we've figured out how to do this better, we may very well be opening a floodgate of innovation."

To see more, visit ScientificAmerican.com/science-in-images





Source: "The Exceptional Attachment Ability of the Ectoparasitic Bee Louse *Braula coeca* (Diptera, Braulidae) on the Honeybee," by Thies H. Büscher et al., in *Physiological Entomology: How Insects Work—Linking Genotype to Phenotype*; November 29, 2021 (https://doi.org/10.1111/phen.12378)

Rafflesia blooming in Sumatra

BIOLOGY

Parasite Challenge

A giant, meaty flower has a fraught relationship with its host plant

Little is known about how the parasitic *Rafflesia*—a genus that produces the world's largest and stinkiest flower—infects its host plants. *Rafflesia* spends most of its life span as a tangle of strandlike cells lurking inconspicuously underneath the bark of a woody vine called *Tetrastigma,* before emerging as drab, golf ball–sized buds. These eventually burst into fleshy blooms that smell like rotting meat and can reach 20 pounds and three feet across. Since 2017, Long Island University plant biologist Jeanmaire Molina has been trying to infect *Tetrastigma* seedlings with *Rafflesia* seeds in the laboratory, so far without success; her latest work delves further into how some potential hosts manage to thwart this spectacular parasite.

For a new study in *Planta,* Molina and her colleagues extracted and screened over 10,000 chemicals produced by infected and noninfected *Tetrastigma* cuttings from rain forests in the Philippines. The researchers found that noninfected cuttings contained elevated levels of benzylisoquinoline alkaloids, a group of compounds that includes morphine and codeine.

Such substances have never been reported before in *Tetrastigma* or other creepers in the same family (which includes the common grape). Molina says she is intrigued that *Tetrastigma* can produce such biologically potent substances, and the precise reasons it does so are not yet known. She suspects *Tetrastigma* may brandish these alkaloids preemptively to stave off infection. Perhaps, she adds, *Rafflesia*'s opening gambit is to suppress this secretion and besiege its host.

In any case, the finding is "pretty surprising," says Harvard University evolutionary biologist Charles Davis, who was not involved in the study. "Plants are incredible chemists." He adds that the work is an important step toward demystifying interactions between parasite and host.

Next, Molina hopes to learn how to tip the balance toward *Rafflesia.* Her long-term goal is to bring some of these endangered flowers out of their Southeast Asian habitats and make them more accessible to the outside world. Learning how *Tetrastigma*'s defenses work—and how to subvert them—is a place to start.

Molina keeps a potted *Tetrastigma* in her university office, regularly sprinkling the plant with *Rafflesia* seeds in the hope they will miraculously catch. So far, nothing. But she still maintains the routine. "I think there is a way. We just don't know it yet," she says. "We'll get there somehow." —*Shi En Kim*

EVOLUTION

Slow and Steady

Snakes and lizards played it safe in early evolution—outcompeting ancient cousins

Earth is crawling with lizards and snakes. More than 10,000 species of these reptiles, called squamates, have adapted to thrive across almost every continent. But this vast assortment took a surprisingly long time to develop, according to University of Bristol paleontologist Jorge Herrera-Flores and his colleagues. Instead of trying new adaptations as quickly as possible, squamates succeeded by evolving with a relatively slow and steady pace, the researchers say—an idea counter to many biologists' assumptions about how and why life generates diversity.

The researchers charted squamates' evolution in a new study published in *Palaeontology,* contrasting them with elusive reptilian relatives called rhynchocephalians. Today the latter are represented by just one living species—New Zealand's tuatara—but there were far more in the deep past. "For many decades," Herrera-Flores says, "it has been questioned what was the real cause of the decline of the rhynchocephalians."

The researchers observed a strange pattern: the two groups' evolutionary trajectories were flipped. Squamates evolved differences in body size slowly during the first two thirds of the group's existence, from about 240 million to 80 million years ago. At the same time, rhynchocephalians were rapidly splitting into a profusion of different sizes—until their diversity collapsed.

Until now, it had seemed that quick bursts of evolutionary experimentation built long-term staying power. Previous studies of two other reptile groups, dinosaurs and crocodiles, proposed that fast early evolution helped these animals shoulder out competitors and quickly dominate the landscape. By that logic, rhynchocephalians' speedy variations should have presaged greater success. Instead, Herrera-Flores and his colleagues suggest, fast evolution might create a kind of volatility that leads more readily to extinction. Squamates' slower pace resulted in a more stable history, followed by a later burst of diversity when tuatara relatives were already on their downturn.

Reptiles are not alone in this apparent "slow and steady" strategy. Even though modern bony fishes are much more diverse today, a previous study found that in the past they were not as numerous or varied as holosteans—the prehistoric relatives of today's gar and paddlefish. Such studies suggest that quickly diversifying to fill more niches is not always a route to long-term success.

And unlike its cousins, the specific rhynchocephalian lineage that led to today's tuatara had "exceptionally low rates of evolution," notes Harvard University herpetologist Tiago Simões, who was not involved in the new study. This is what makes the tuatara stand out as a "living fossil," an echo of an ancient evolutionary boom that eventually went bust. —*Riley Black*

mazzzur/Getty Images

IN THE NEWS

Quick Hits

By Nikk Ogasa

CANADA

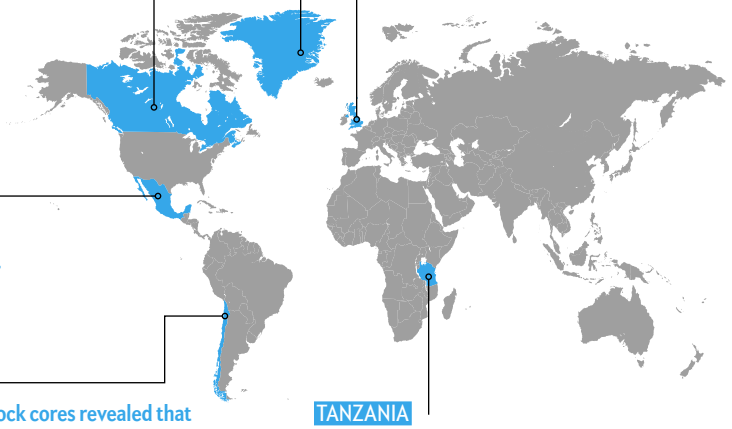
Scientists found evidence of bacteria "mining" silver in ancient underwater worm poo. A microscopic analysis of fossilized feces revealed specks of the metal, which likely accumulated about 500 million years ago as dung-dwelling bacteria extracted it from the surrounding water.

GREENLAND

Computer simulations suggest climate change was among the reasons Vikings abandoned Greenland in the 15th century. An expanding ice sheet would have depressed the land and pulled seawater onshore, flooding coastal settlements with up to five meters of water.

MEXICO

Small freshwater fish called sulfur mollies synchronously splash their tails to create waves, and scientists have now demonstrated that this strategy can deter hungry birds. Researchers triggered the wave-making process using slingshots and found that birds waited twice as long between attacks.



U.K.

Researchers in northeastern England unearthed an exoskeleton fragment from the largest arthropod ever discovered, in a genus called *Arthropleura*. By referencing related fossils' body proportions, the team estimates this millipede would have weighed 50 kilograms and measured 2.6 meters long.

CHILE

An investigation of sedimentary rock cores revealed that a large, previously undocumented tsunami slammed into Chile's coast in 1737. The finding suggests that tsunamis hit the country's coastline more often than previously thought and that hazard assessments should consider both geologic and historical records.

TANZANIA

New work suggests 3.66-million-year-old footprints might come from a hominin that walked with a strange gait, strutting by crossing one foot in front of another. The tracks are distinct from *Australopithecus afarensis*—the area's known hominid species—suggesting early humans with very different strides may have coexisted.

For more details, visit www.ScientificAmerican.com/mar2022/advances

OTHER WORLDS IN FEW WORDS

The following haiku, written in the traditional three-line, 17-syllable format by teams of planetary scientists, summarize research results reported at the 52nd Lunar and Planetary Science Conference, which was held virtually March 15–19, 2021.

"Detailed Chloride Mapping in Terra Sirenum, Mars"

Oceans long since past
Dry, cracked ground, no trace remains
But the taste of salt.

—E. M. Harrington, B. B. Bultel, A. M. Krzesińska and S. Werner

"Identifying Landing and Sample Tube Depot Sites and Characterizing Traverse Terrains for Mars Sample Return"

Three summer interns
Helping a little rover
Return rocks from Mars.

—M. C. Deahn, M. M. Morris, C. L. Brooks, N. R. Williams, M. P. Golombek, F. J. Calef III, S. Do and A. K. Nicholas

"Are Maryland and Other Craters on CCKBO Arrokoth Compaction Craters, and Does it Matter?"

Compaction craters
Explains Arrokoth's surface
Saves its neck from harm.

—W. B. McKinnon, X. Mao, K. N. Singer, J. T. Keane, P. M. Schenk, O. L. White, R. A. Beyer, S. B. Porter, D. T. Britt, J. R. Spencer, W. M. Grundy, J. M. Moore, S. A. Stern, H. A. Weaver, C. B. Olkin and New Horizons Science Team

"Investigating Icequakes on Enceladus Using an Antarctic Analog: Application of Seismic and Machine-Learning Techniques to Characterize Tidally Induced Seismicity along Icy Rifts"

Antarctic ice quakes
Can this then tell us how does
Enceladus shake?

—K. G. Olsen, N. C. Schmerr, M.-H. Huang, T. A. Hurford and K. M. Brunt

PANORAMA: This view of Mars's Teal Ridge was captured by NASA's Curiosity rover in 2019.

NASA/JPL-Caltech/MSSS

"Seasonal Variability of Titan's Global Wind Field"

The gales of Titan
Oh, how they blow! What fury!
And how they do change!

—S. L. Light, M. A. Gurwell, C. A. Nixon and A. E. Thelen

"Habitability of Cloudy Worlds: Intersecting Constraints and Unknowns"

Why clouds are not green:
Where there's water, there is life*
*Exceptions apply.

—D. M. Gentry, L. Iraci, E. Barth, K. McGouldrick and K.-L. Jessup

Abortion Pill Barriers

Politics, not science, restrict access to a safe, effective drug

By Claudia Wallis

Ever since it was approved in 2000 as an abortion pill, mifepristone has been regulated as if it were a dangerous substance. The U.S. Food and Drug Administration required doctors to be specially certified to prescribe it. Patients had to sign an agreement confirming that they had been counseled on its risks. Most onerously, the pill had to be given in person in an approved clinical setting—even though a second drug used to complete the abortion, misoprostol, could be taken at home. In addition, 17 U.S. states have passed laws requiring an ultrasound scan before mifepristone can be prescribed. Yet decades of study have shown that the medication is safe and that those restrictions are needless, according to the American College of Obstetricians and Gynecologists and other medical groups. The rules have more to do with politics and ideology than with science.

It took the COVID pandemic to strip away the fig leaf of scientific justification from one regulation. The U.S. and several other countries that restrict mifepristone suspended the requirement of in-person distribution. Patients could access care via telemedicine and get the pills by mail rather than risk catching COVID at a clinic. A natural experiment unfolded that highlighted the safety of this approach. Last December the FDA acknowledged as much by permanently scrapping the in-person rule.

The agency did not, however, remove the other regulations. And although patients will be able to get their prescription at a drugstore or by mail, the FDA is requiring a new certification for pharmacies that dispense the drug. Such measures "continue to be necessary to ensure the benefits of mifepristone outweigh the risks," according to the FDA. Researchers who study medical abortion see this split decision as both a step forward and a missed opportunity at a time when abortion rights are in peril.

Mifepristone works by blocking progesterone, a hormone that maintains pregnancy. In a standard protocol, the drug is followed by a dose of misoprostol, which triggers contractions and expulsion of the embryo. "It is identical to how we often treat early miscarriage," notes Lesley Regan, who chairs the abortion task force of England's Royal College of Obstetricians and Gynecologists. In the U.S., the pills may be used during the first 10 weeks of gestation, although the World Health Organization considers them safe up to 12 weeks. Research confirms that medication abortion is about 95 percent effective in ending pregnancy. The risk of complications that require further medical attention—such as hemorrhage or infection—is less than 1 percent.

During the COVID era, at least three studies showed that the efficacy and safety hold up without in-person clinical visits. In fact, a large study done in the U.K.—where the government also provisionally allowed telehealth care—identified distinct advantages. It compared outcomes in more than 52,000 medication abortions during the two months before and after the government decision. Researchers found no increase in complications.

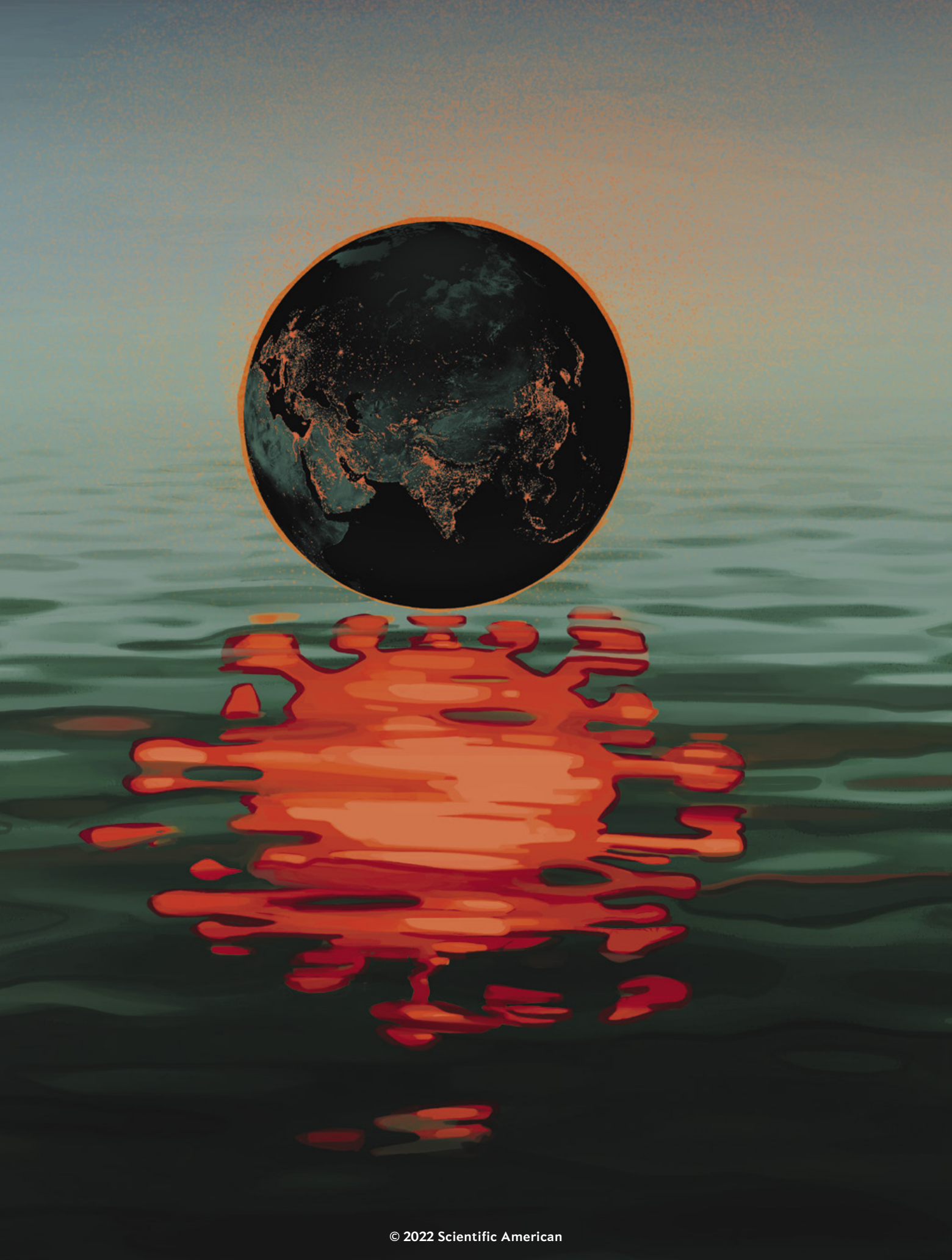
Moreover, the average wait time for treatment dropped from 10.7 days to 6.5 days, and 40 percent of abortions were completed at six weeks or earlier; only 25 percent met that mark with in-person drug treatment. Patient satisfaction was also higher with telemedicine, says the study's lead author, Abigail Aiken, an expert in reproductive health policy at the University of Texas at Austin. One reason is that people can be treated sooner: "When someone is facing a pregnancy that they didn't want, the mental stress and anxiety take a toll." Telemedicine is also more convenient and less expensive. Regan notes that it takes fewer health-care resources and better serves people who live far from an abortion clinic.

The U.K. study, along with two done in the U.S., also showed that an ultrasound scan is unnecessary except when patients report issues that warrant it, such as symptoms of an ectopic pregnancy (one outside the uterus), or if they cannot recall the date of their last menstrual period. Research shows that the date suffices to determine gestational age before abortion.

Ironically the FDA's sensible move on telemedicine is likely to widen state-by-state inequities in access to abortion. In most states access will improve. But 19 have laws mandating in-person abortion care, and "six specifically ban mailing the pills," notes Elizabeth Nash of the Guttmacher Institute. Further restrictions are probable in abortion-hostile states if the U.S. Supreme Court fails to protect abortion rights later this year, as is widely expected. Aiken predicts that "we're going to see this picture of uneven access—this zip code lottery—diverge even further." SA

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*.

Illustration by Fatinha Ramos



HOW COVID CHANGED THE WORLD

Illustration by Olena Shmahalo

In the spring of 2020 a cartoon was making the rounds on social media. It showed a city perched on a tiny island, surrounded by ocean. A speech bubble emerged from the skyline: "Be sure to wash your hands and all will be well." Not far out at sea, a giant wave labeled "COVID-19" was about to crash over the city. Behind it was an even bigger wave marked "recession." And beyond that one was a tower of water that threatened to swallow it all: "climate change."

I've often thought of that statement, by Canadian cartoonist Graeme MacKay, in moments that seem to define our pandemic disorientation: the botched messaging, willful unpreparedness and exhausted confusion. In America, though, the cartoon didn't play out exactly as drawn. The economy actually *grew* in 2021. Does that mean the damage wasn't as bad as many predicted? That question can only be answered in the context of another superlative: the U.S. claims the highest reported number of COVID cases—as well as COVID deaths—in the world.

The past two years have been full of incongruities, paradoxes and absurdities. Consider the mRNA vaccines (*page 54*). Scientists formed a global hive mind (*page 34*) and delivered a supereffective vaccine faster than anyone thought possible. But more than a year after the shots became available, the U.S. has one of the lowest vaccination rates among wealthy countries. Some Americans think the vaccine represents a weapon of oppression, if not a literal weapon.

The politicization of our best tool for ending the pandemic surprised everyone. Except for the behavioral scientists, misinformation researchers, sociologists, historians and speculative fiction writers who spent 2020 waving their arms (sometimes in the pages of this magazine), calling attention to cognitive bias, influence operations, accessibility issues (*page 70*) and barriers to trust. COVID was never going to be the "common enemy" that finally united Americans. As Alondra Nelson, who is now deputy director for science and society at the White House Office of Science and Technology Policy, explained it to me in December 2020: "This idyllic idea of solidarity, especially in a wartime modality, is created by making an enemy of someone else." Indeed, former president Donald Trump tried to make an enemy by blaming the virus on China. His xenophobic rhetoric has spread, feeding dangerous conspiracy theories (*page 72*), threatening scientific research and leading to a rise in hate crimes.

The virus provoked other reckonings and pivots—not all of them bad. Many of us who could do our jobs remotely discovered the power of owning our time (*page 64*). COVID concerns made it easier for European cities to install miles and miles of bike lanes, giving us a glimpse of a car-free urban future (*page 51*). The pandemic revealed strange hidden interdependencies; hospital demand for liquid oxygen, for example, delayed rocket launches (*page 71*). It also worsened inequality (*page 66*), increased the prevalence of depressive disorders, added "moral injury" to the common lexicon and set back students' learning trajectories for years to come.

Amid the noise of an ongoing emergency, it can be hard to notice troubling new trends (*page 58*). We should be far more concerned about the shadow of long COVID. If millions of people end up developing persistent health issues after the acute disease stage, they will likely encounter a medical system unable to do much more than shrug. As with the climate crisis (*page 50*), many of us avert our eyes from the specter of long COVID because its effects tend to be more insidious than dramatic, and the fixes aren't quick or easy. Dealing with the problem requires acknowledging what was already broken. Yet for every bleak future there's a hopeful one. Propelled by the force of patient advocates, research into long COVID could lead to new understanding of other postinfection illnesses and autoimmune disorders (*page 56*).

When we planned this issue, Omicron had not yet emerged. I wondered if people would be interested in stories about a pandemic that wasn't over, even if they were over the pandemic. Would we be fearmongering to suggest that the pandemic hasn't ended (*page 78*) because we haven't vaccinated the world, leaving us susceptible to variants that are more transmissible?

We're *all* over COVID. But we can't give up and leave our collective fate to the machinations of a virus, sighing in relief when one peak crests (for those of us still unharmed) and leaning on wishful thinking that only the best-case scenarios will come to pass. Avoiding adaptation isn't the key to reaching the endemic stage, nor will it help us prepare for the even bigger waves of climate crises. We assembled this collection of stories to reflect on how COVID has already changed our world, as well as how our world has been resistant to change—even when a virus disrupts everything, even when it shows us what we need to change the most.

Jen Schwartz is a senior editor of features at *Scientific American* who covers how people are adapting, or not, to a rapidly changing world.

Illustration by Hanna Barczyk

A Microbe Proved That Individualism Is a Myth

Humans evolved to be interdependent, not self-sufficient

By Robin G. Nelson

For countless Americans, there was a dull but persistent pain to prepandemic life: high-priced housing, nearly inaccessible health care, underresourced schools, wage stagnation and systemic inequality. It was a familiar ache, a kind of chronic hurt that people learned to live with simply because they had no other choice. Faced with threadbare safety nets and a cultural ethos championing nationalist myths of self-sufficiency, many people did what humans have always done in times of need: they sought emotional comfort and material aid from their family and friends. But when COVID-19 hit, relying on our immediate networks was not sufficient. Americans are gaslit into thinking that they are immeasurably strong, impervious to the challenges people in other countries face. In reality, our social and economic support systems are weak, and many people are made vulnerable by nearly any change in their capacity to earn a living. The fallout from the pandemic is an urgent call to strengthen our aid systems.

Anthropologists have long recognized that exceptionally high degrees of sociality, cooperation and communal care are hallmarks of humankind, traits that separate us from our closest living relatives, the chimpanzees and bonobos. This interdependence has been key to our success as a species. Viewed this way, we humans have an evolutionary mandate to be generous and take care of one another. But unlike early humans, who lived in comparatively small groups, we cannot just rely on our immediate family and friends for support. We must invest in national policies of communal care—policies that facilitate access to resources for people who need help—to a degree that is commensurate with the size and complexity of today's globalized societies.

In a sense, the entanglement of our everyday lives made us all the more vulnerable to an airborne virus that demanded social isolation, blowing up the facade of normalcy in the spring of 2020. The new COVID normal, with its mask wearing, social distancing, lockdowns and closed schools, compelled us to abandon our most basic instincts and turn away from our closest friends and family. It rent the social fabric on which we all rely.

Infectious diseases present an unusual challenge: to combat them effectively, we must render aid appropriately and consistently at scale. This pandemic exposed the fragility and faults in each layer of our lives—from our innermost circle of family and friends to the nation state at the periphery—and the differential risk experienced by any individual's core community. Communities that were already heavily invested in social safety nets with measures such as paid sick leave were able to lower COVID rates. Those invested in the ideology of self-sufficiency and individualism prolonged suffering and loss of life.

New Zealand (Aotearoa in Māori), a country with a long history of reckoning with its colonial past and building community, has been a standout success story in the pandemic. The government there countered COVID with nationwide stay-at-home orders, border controls, hygiene campaigns, accessible testing and contact tracing. The results were dramatic: 18 months into the pandemic, the country had seen only 27 COVID deaths. By late 2021, 90 percent of eligible citizens were fully vaccinated. Although new variants have been challenging these successes, the government remains deeply committed to care.

Similarly, Taiwan defied predictions that it would struggle with COVID infections like its neighbors in China by instituting a 14-day isolation policy for travelers entering the country, stepping up mask production, increasing border controls and deputizing quarantine officers who could help isolated citizens. By March 2021 there had been only 10 COVID deaths in a country of nearly 24 million people. Taiwan has fought each new wave of the pandemic with these tactics. Although we may call on our inner circle most frequently during our times of need, ultimately we must rely on local and national officials on the periphery of our lives to be exquisitely human—as the leaders of New Zealand and Taiwan have been—when they develop and enact health policies.

In the U.S., government support was

Illustration by Ellen Weinstein

inconsistent, and citizens struggled to work together to keep the virus at bay. The roots of these problems run deep. Since this country's inception, the dominant ideologies here have encouraged not only individualism but also the dehumanization of certain groups, as evidenced by the enslavement of Black people and the displacement of Indigenous communities from their ancestral lands. This dehumanization continues today in the form of the bootstrap narrative—the myth that anyone can prosper if only they work hard enough—and in efforts to weaken relief programs for people who need help. As a result, even though we now know how the virus spreads and causes disease and we have effective vaccines against it, the death toll from COVID is higher in the U.S. than anywhere else.

There have been some success stories in the U.S.—they can be found in groups that have a fundamentally different ideological relationship to community interdependence. The Navajo Nation, which early on saw some of the highest rates of COVID-related illness and death, ran its own vaccine education campaigns and implemented in-house vaccine-distribution policies. It achieved far higher vaccination rates on its reservations than surrounding areas did. Tribal values that prioritize the group over the individual helped motivate members to get their shots. Unfortunately, in late 2021 the virus surged among the Navajo again, perhaps because of low vaccination rates in neighboring areas.

A microbe revealed the lie of rugged individualism. We are not self-sufficient and independent; we never have been. Our fates are bound together. Taking care of others is taking care of ourselves. With the arrival of the highly infectious Omicron variant, we are paying the price for not having developed strong policies early on and stuck to them. But that does not mean we should just give up the fight. Instead we need to redouble our efforts to provide care and resources to vulnerable community members. The emergence of each new COVID variant is an opportunity to reflect on what worked and what did not with the last one, whether locally or on the other side of the world. Committing ourselves to upholding our evolutionary mandate to help one another—not just the people we see every day but everyone, everywhere—is the only thing that will save us.

Robin G. Nelson is a biological anthropologist at Arizona State University. She studies human sociality and health outcomes through the lens of evolutionary theory.

A High-Speed Scientific Hive Mind Emerged

Researchers found new forms of rapid communication and collaboration

By Joseph Bak-Coleman and Carl T. Bergstrom

Most of the time science is a slow and tedious business. Researchers toil away for decades at obscure limits of human knowledge, collecting and analyzing data, refining theories, writing, debating, and advancing our understanding of the world in tiny increments. Working in small teams on highly specialized projects far from the public eye—that is what most of us are accustomed to doing.

But a calamity upends everything. In early 2020 COVID spread around the globe. Millions of lives were at stake. Yet we knew next to nothing about the nature of the threat. Just a few months earlier no one had ever seen the SARS-CoV-2 virus.

For researchers, the emergence of the disease was an all-hands-on-deck moment. Biologists such as the two of us, along with virologists and immunologists, all pivoted to focus on the new pathogen. And other researchers from across the scientific ecosystem—economists, physicists, engineers, statisticians, psychologists, sociologists, and more—dropped everything to learn about COVID and figure out how they could contribute. Public interest exploded. Scientists with scant experience in public communication learned to work closely with journalists, informing a worried public about what was happening, what to expect next and what people could do to keep themselves safe. The scale of cooperation and collaboration is staggering. Large-scale surveys of scientists done in 2020 and 2021 show that roughly a third of researchers in the U.S. and Europe contributed to the effort.

This vast collaboration moved quickly and effectively in several areas. On December 30, 2019, an epidemiological surveillance network published the first English-language note about a cluster of pneumonia cases of unknown cause in Wuhan, China. Eight days later Chinese scientists identified the pathogen as a novel coronavirus. The full genome sequence was published just two days after that. Then on January 13, 2020, the World Health Organization published instructions for a PCR-based diagnostic test based on that genome.

The genome sequence also opened the door for vaccine development. Scientists used it to determine the 3-D structure of the SARS-CoV-2 spike protein, and by the end of January they had figured out how to stabilize the protein to make it an effective vaccine component, leading to mRNA-based and other vaccines, which were developed, tested and distributed in less than a year.

The urgency of COVID drove scientists to adapt. Discussions that previously took place at conferences, on the telephone or in revision notes on manuscripts moved to social media platforms such as Twitter, review sites such as PubPeer and all-hours Zoom rooms. Researchers and clinicians spontaneously organized into focused teams and working groups. By rapidly sharing information on their patients, physicians figured out that people with severe COVID were at high risk for dangerous blood clots in their lungs, so anticoagulants became a standard of care and saved lives.

In general, traditional modes of publication were far too slow. We embraced a rapid alternative model: preprint archives, where papers are posted prior to peer review or consideration at a scientific journal. The number of papers submitted to medRxiv, a key repository of biomedical preprints, increased 10-fold in the first few months of the pandemic.

These changes also shifted early-stage science from a private activity to part of the public discourse. Instead of presenting the world with polished scientific articles, investigators worked in open view, thinking aloud, offering preliminary speculations, arguing, making wrong turns, following dead ends and pursuing some hypotheses that would ultimately be refuted.

This approach to communication does have a downside. Previously private communications were now open to exploitation and distortion by politicians and pundits. For instance, flawed blood-sample research reported in an April 2020 medRxiv paper purported to show that COVID was a mild disease with a very low fatality rate. Although the scientific community quickly pointed out a host of problems with the work, people seeking to avoid business restrictions, school closures and mask mandates ignored the criticism and used the paper to undermine public health interventions.

Rapid and unorthodox channels of communication also could not solve all the problems scientists encountered. We took too long to recognize the importance of airborne transmission of the virus. We spent early 2020 washing our groceries but not wearing masks. Most critically, we have been largely unsuccessful at anticipating and managing the human element of the pandemic. By not accounting for ways that behavior would change in response to information—and misinformation—we have struggled to predict the size and timing of successive disease waves and virus variants. A collective failure to stop misinformation from spreading on social and traditional media platforms has left large segments of the population unvaccinated, vulnerable and un-

willing to embrace measures such as masks and social distancing.

By some measures COVID has also hampered scientific productivity overall, researchers suggested in a paper in *Nature Communications* late last year. Some of the 2020 survey data revealed that scientists were spending an average of seven fewer hours per week working on research. The group, led by Dashun Wang of Northwestern University, wrote that the decrease in productivity will likely have lasting effects, with scientists reporting fewer publications, collaborations, submitted papers and new projects started during the pandemic. Lockdowns, school closures and other changes took a disproportionate toll on women scientists juggling work and child care—a major problem that requires urgent redress.

But a publication dip is precisely what we would expect when scientists shift from day-to-day research to an emergency response. Placing papers in journals becomes secondary to fixing problems. Dealing with urgent issues is one of the most important roles of the publicly funded scientific ecosystem, which has millions of researchers effectively on retainer. When global crises arise, they organize, learn and coordinate. And that, ultimately, leads to solutions.

Joseph Bak-Coleman is a postdoctoral fellow at the University of Washington Center for an Informed Public. He studies how communications technology affects collective decision-making.

Carl T. Bergstrom is a professor of biology at the University of Washington. He studies how evolution encodes information within genomes and how institutions and behavioral norms influence scientific communication.

Illustration by James Yang

Luca Locatelli/INSTITUTE

SCALING UP VACCINES: The Pfizer-BioNTech mRNA vaccine became a major protective shield against COVID. This time-lapse image shows technicians at BioNTech's facility in Marburg, Germany, filtering batches of the vaccine, in one of the final stages before shipping it out.

Science Journalism Shifted with New Realities

It is no longer possible to separate science and politics

By Tanya Lewis

When I first heard the reports of a "mysterious pneumonia" spreading in Wuhan, China, in January 2020, I thought I would write a story or two about it and move on to the next big medical news development. As a health journalist, disease outbreaks are not a rare occurrence on my beat, and most do not rise to the level of an international emergency. But the story of COVID-19 would turn out to be unlike anything I had covered before or am likely—I hope—to ever cover again.

Reporting on the pandemic was like building a plane while flying it—at warp speed in a hurricane. The underlying science was evolving daily, so there was no expert consensus or body of established research to draw on. And there were plenty of people willing to exploit this information vacuum, creating a secondary epidemic of misinformation.

Early on Chinese authorities suppressed information about the virus, and the Trump administration downplayed its threat to the U.S. Testing blunders and shortages prevented this country from recognizing the number of COVID cases circulating within its borders in the critical early phase when we could have slowed its spread. And for months health authorities said SARS-CoV-2 was spread primarily by symptomatic people through large respiratory droplets from a cough or a sneeze or by contaminated surfaces (remember the now ridiculous-seeming grocery-disinfecting ritual?). That guidance was based on how some other respiratory diseases circulate, but of course we now know this novel coronavirus commonly spreads through aerosols that linger in the air, often exhaled by a person showing no symptoms at all.

At the heart of science journalism is a focus on evidence. But one of the hardest lessons many other journalists and I learned while reporting on COVID is that absence of evidence is not evidence of absence—and that even advice from renowned public health authorities should sometimes be questioned. Take face masks, for example: in the pandemic's first crucial weeks, the Centers for Disease Control and Prevention and the World Health Organization said the public did not need to wear masks (despite the fact that medical workers and many people in Asia use them routinely to protect against respiratory diseases). At the same time, CDC and WHO officials specifically told people not to buy high-quality respirator masks because health-care workers needed them—breeding confusion and mistrust.

At the time, I debated with my editor over whether to recommend that people wear masks, against the guidance of these esteemed health agencies. I resisted doing so, in part out of deference to these authorities and in part because of a lack of published studies that masks—especially nonmedical ones—were protective for the wearer. In retrospect, I should have followed the precautionary principle; in the absence of direct evidence, masks were a reasonable precaution to protect against a respiratory virus. That episode highlighted for me just how challenging it can be when the evidence is shifting in real time and even the experts can't keep up. It wasn't until two years into the pandemic that the CDC and others finally started to emphasize the importance of high-filtration masks, which had been abundantly available in the U.S. for many months.

It didn't take long for bad actors to weaponize the confusion to spread misinformation. Patient zero in this "infodemic" was Donald Trump. The former president routinely downplayed the virus's severity, calling it "no worse than the flu." He blamed China, stoking xenophobia rather than urging people to protect themselves and others. He mocked people who wore masks, politicizing a basic public health measure, while promoting baseless COVID treatments. It wasn't just Trump—Fox News personalities and celebrities such as Joe Rogan and Aaron Rodgers have used their platforms to spread falsehoods about the virus and the vaccines. As a health journalist, my job was no longer purely about explaining the science—I now had to contend with politics and human behavior. Actions as seemingly innocuous as wearing a mask or getting a vaccine to avoid getting a disease had become political statements.

There has perhaps been no more consequential or bitter battleground in the U.S. epidemic than vaccines. The anti-vax movement—a small faction but already a potent force before COVID—took advantage of people's hesitancy about the speed with which the new vaccines were developed to spread lies and misinformation about their effects. COVID anti-vaxxers promoted their dangerous claims under the guise of "freedom," never acknowledging that it comes at the cost of people's lives and the freedom to live without threat of a deadly virus.

As science journalists, it was not enough just to report the facts and debunk misinformation—we had to engage with the reasons people believe such falsehoods. We learned to use the latest research on how misinformation spreads to try to expose lies without amplifying them and replace conspiracy theories with truth.

All of this has played out against the backdrop of vast inequities in access to vaccines and health care, both nationwide and globally. One of the biggest lessons of the pandemic for many of us has been that racism, not race, explains why COVID has been even more devastating for people of color.

The arrival of new viral variants further complicated messaging. The mRNA vaccines achieved an effectiveness beyond any expert's wildest dreams. But their protection waned over time, and they have been less effective against the highly contagious Delta and Omicron variants, prompting a return to mask wearing and a hastily implemented booster shot campaign. As I write this, Omicron is spreading rapidly and overwhelming hospitals because it is so transmissible. As journalists, all we can do is try to make sense of the evidence as it develops, hope in hindsight we made the right call, and remind readers it's normal, not bad, to update our knowledge as the virus—and our understanding of it—evolves.

Reporting on COVID has fundamentally changed the way I approach science journalism. I have gained a deeper appreciation for scientific knowledge as a process, not merely an end result. I have seen that it is not enough to simply follow the science—that skepticism of authority is warranted even when that authority comes from respected public health experts. And I have learned that science is *always* political—despite what many scientists like to think. These lessons have been won at a terrible expense. But failing to heed them could doom us to repeat this tragedy when the next pandemic comes.

Tanya Lewis is a senior health and medicine editor at *Scientific American.* She co-hosts a biweekly podcast, COVID Quickly, with fellow senior medicine editor Josh Fischman.

Illustration by Thomas Fuchs

WILLY SSENGOOBA, shown here in Kampala, Uganda, in January 2022, set up COVID testing at Uganda's borders.

COVID Set Off a Boom in Diagnostics

The pandemic accelerated the development of cutting-edge PCR tests—and made the need for them urgent *By Roxanne Khamsi*

A DECADE AGO WILLY SSENGOOBA BEGAN CRISSCROSSING UGANDA, TRAINING HEALTH-CARE workers on how to use a new machine to detect tuberculosis. The deadly lung disease infects around 90,000 people in the East African nation annually, but it can sometimes take months to diagnose using traditional methods such as culturing samples of coughed-up sputum. These new machines used rapid molecular testing to yield results within a couple of hours, meaning patients who tested positive could immediately be referred for lifesaving treatment. Ssengooba, who is scientific director of the mycobacteriology research unit at the Makerere University College of Health Sciences in Kampala, helped to set up 265 of the devices in clinics around the country. By increasing the number of early diagnoses—especially among vulnerable groups such as children and people living with HIV—deaths associated with tuberculosis dropped, too. Ssengooba saw this as a major success and wanted to deploy more machines. But it was hard to make politicians aware of the technology's power.

Then COVID arrived. Not long after the first case was reported in Uganda on March 21, 2020, Ssengooba received a message from a commissioner under the Ministry of Health. It had quickly become apparent that most of the new cases were coming through the border crossings, so screening people there would be a priority. Could Ssengooba make it possible to test everyone who wanted to enter Uganda? His entire country was counting on him.

Ssengooba and his team began facilitating the collection of nasal swabs taken from truckers at popular entry points, where imported goods are brought into the landlocked country. Those samples—sometimes more than 1,000 a day—then needed to be shuttled 150 miles to Kampala. The capital city was the nearest place with laboratory technology set up to run a process known as polymerase chain reaction—or PCR. Using fluorescent probes that latch onto portions of the coronavirus genetic sequence, these massive machines could determine whether a sample was positive for the genetic material of SARS-CoV-2.

Ssengooba's team had to shuttle the samples themselves. A crew of about 50 workers collected the samples in pickup trucks and delivered them to the lab, then turned around to go back for the

Photographs by Esther Ruth Mbabazi

next batch, spending long, exhausting nights on the road. As the pandemic intensified, they couldn't keep up. Truckers awaiting their test results were stalled at the border for days, in part because the sample analysis in Kampala would sometimes take up to 72 hours to return a result. A queue of trucks formed, stretching for kilometers, holding up the import of everything from home appliances to construction materials to replacement parts for cars. Making matters worse, authorities had closed the airport.

The government was desperate to alleviate the backlog. Ssengooba considered the 265 machines he had set up throughout Uganda over the years to test for tuberculosis. He realized he could repurpose some of those small PCR machines to test for the coronavirus by using a different sample-processing cartridge. He relocated that equipment directly to the border entry points and engineered some basic infrastructure (electrical power; benchtop safety spaces) to support their use. Unlike the lab setup in Kampala, which requires multiple machines spread across different rooms and experienced technicians to prepare and process the samples, these so-called GeneXpert modules were automated and about the size of a printer. They still used PCR technology but could return results on the spot in around half an hour.

By May the first COVID testing systems were working at the crossing point in the Kenya-Uganda border town of Malaba, reducing the waiting time for truck drivers from days to around half an hour. Within a week the equipment was set up at two other major border points. Many countries, even wealthy ones, struggled to get COVID screenings off the ground in the early months of the pandemic. But Ssengooba understood how to balance the needs of public health and the economy. By cobbling together testing infrastructure where it was most needed, he was preventing disease while keeping critical goods flowing into the country.

Ssengooba's creative repurposing of Uganda's limited testing resources was "tremendous," says Wilber Sabiiti, an expert at the University of St. Andrews in Scotland in the development of diagnostics tests. After Ssengooba had worked tirelessly for years to try to make PCR testing more accessible for tuberculosis, his efforts finally seemed to be getting validated. The pandemic, he says, has clarified the urgency of deploying PCR technology more widely for all kinds of infectious diseases, especially to politicians, who are now allocating more money to the technology. "The SARS-CoV-2 outbreak has been like a blessing in disguise for the scale-up of molecular assays," he says.

Ssengooba is hardly alone in his thinking. Alex Greninger, assistant director of the clinical virology labs at the University of Washington Medical Center, says that in the past, the facility where he works typically ran 50,000 PCR tests a year for diseases such as influenza and HIV. Between early 2020 and the end of 2021, it had done four million PCR tests, mainly for COVID. Unlike in the past, however, the results have been vital to informing immediate behaviors: those who test positive self-isolate or are kept in a special ward of a hospital. This has created a massive new reliance on testing to guide such decisions. "We [did] 81 years' worth of molecular testing in the virology lab in the first 22 months" of the pandemic, Greninger says. He expects the demand for PCR testing to stick around even after COVID ebbs. The general public is much more aware of virology now, he says, and as rapid antigen tests become a more routine part of living amid COVID and its potential future surges, people will seek out PCR tests to confirm positive results.

COVID has not just increased the scale of disease testing and created demand from pretty much everyone; it has also spurred the adoption of more advanced versions of the tests themselves. Hospital systems have begun purchasing PCR machines that are small enough to install at a doctor's office so that samples do not have to be sent offsite to a huge, centralized lab. That means patients can get a diagnosis on the spot and isolate immediately, if needed—and take whatever antiviral or antibiotic is most appropriate. Companies and university researchers around the globe who are working on PCR technologies say there is escalating interest in their innovations, such as handheld versions that would make testing anywhere—from supermarket parking lots to remote villages—more feasible.

All of this may benefit more than just individual patients. As the emergence of the quick-spreading Omicron variant demonstrated in late 2021, ramping up testing at the population level is crucial to keep tabs on how COVID might morph and push hospital systems (among other sectors of society) to a breaking point. The sweeping uptake of PCR for COVID could also pave the way for stronger public health surveillance systems that can spot future pandemics by scanning for dozens of pathogens at once. According to Jeffrey Townsend, a biostatistician at the Yale School of Public Health, PCR is a powerful tool to use for disease surveillance, and "there's a lot of people who say we need to be doing it even more."

A STRANGE TRIP

IN 1983 KARY MULLIS WAS DRIVING up to his cabin on the northern coast of California with his girlfriend, a chemist at the biotechnology company where they had been hired to synthesize genetic fragments. Mullis had spent earlier years completing a Ph.D. at the University of California, Berkeley, where he would trip on LSD while making new chemicals. His girlfriend had fallen asleep, and as he drove he had a vision of molecules dancing on the mountain road. It was then that the idea for polymerase chain reaction came to him. He pulled over the car and scribbled down his thoughts. It won him a Nobel Prize a decade later.

At its heart, PCR is a method of making copies of genetic sequences. There are now many dozens of different kinds of PCR, but the most basic form that Mullis devised started with a tiny bit of DNA and then used various cycles of heating and cooling to replicate it. First, the process would heat the DNA to break its double helix structure into two strands. Next, it would cycle to a cooler temperature that would allow specially tailored primers to bind to specific target sequences within the strands. The samples would be warmed up again, and enzymes would get to work building off those primers to finish replicating the complementary DNA sequences. The cycle would then repeat. Ultimately it yielded a lot of copies of the target strands. Special fluorescent tags were later added to the process to flag the presence of those amplified short sequences of interest.

It became possible to use this method to detect the presence or absence of pathogens: if a virus was present in a person's blood sample, for example, the PCR machine would make a lot of copies of its sequence, and the fluorescent tags would shine brightly. If there was no virus, there would be only darkness.

The incorporation of fluorescent tags meant that the PCR machines could also indicate how *much* virus was in a person's system. If the fluorescent light shined more strongly and sooner in the replication cycling, it meant more virus was present. A PCR could not only detect DNA, it could also detect genetic material

known as RNA. This opened up a whole new world of diagnostics because many viruses, such as HIV, are RNA-based organisms. As the AIDS pandemic tore through the globe, doctors wanted to know *how much* HIV was circulating in their patients' bodies and whether the antiviral drugs they prescribed were working to keep the levels low. PCR could finally give them an answer.

The machines that did the analyses, though, required lab technicians with highly specialized expertise to prep samples and took half a day or more to return results. That changed after the U.S. Postal Service launched a competition for technology that could quickly screen mail for deadly anthrax spores, which a bioterrorist sent in letters to the offices of U.S. senators and journalists after 9/11. The winner, announced in 2002, was a GeneXpert prototype from Cepheid, a Silicon Valley diagnostics company founded in the late 1990s. The system automated many of the previously laborious sample preparation steps by using cartridges and valves that pull liquids through tiny channels and mix them together. And it returned results in minutes rather than hours. In the decades since, the GeneXpert platform has received approval to test for pathogens such as norovirus, chlamydia, tuberculosis and SARS-CoV-2.

Cepheid says there are now more than 40,000 GeneXpert machines around the world, up from 23,000 in 2020. (The diagnostics branch of the major biomedical company Roche also has a PCR machine for clinics that is about the size of a coffee machine.) Increasingly, they are found at doctors' offices and at locations such as the border crossings in Uganda—rather than just at centralized labs. In September 2020 Cepheid received FDA authorization for a GeneXpert test that looks simultaneously for influenza A and B, SARS-CoV-2 and a pathogen that is particularly dangerous in young kids called respiratory syncytial virus. The test results, which can come back in about half an hour, help clinicians know what specific antiviral to give if a patient is sick—Tamiflu for influenza, for example, and Paxlovid for COVID. That is all the more crucial during a pandemic when your infection determines your isolation behavior.

REAL-TIME WARNING SYSTEMS

IT WAS NOT UNTIL the past decade or so that scientists established global surveillance systems that rapidly tracked outbreaks of viruses. Testing for pathogens fell to individual labs, and molecular diagnostics approaches such as PCR were expensive or unavailable. Furthermore, to do PCR testing for viruses of interest, scientists needed specific probes that would recognize a genetic sequence in the pathogens. But they lacked easy tools to create these probes. The barriers to conducting PCR and the dearth of repositories to upload such data made tracking the ebb and flow of viruses in populations spotty.

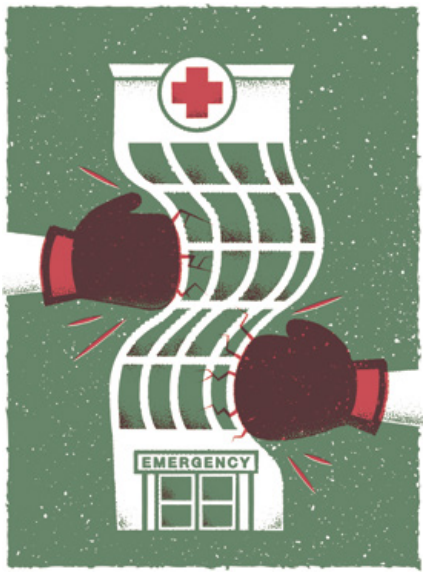
In 2012 the California Department of Public Health received several reports of a mysterious poliolike disease striking children. It manifested as a sudden onset of muscle weakness in the limbs, sometimes also leading to slurred speech and difficulty moving the eyes. The sick

Illustration by James Olstein

American Public Health Revealed Its Fragility

EPIDEMICS EXPOSE a society's vulnerabilities. And we were already an unhealthy population before COVID emerged. Compared with some other developed countries, the U.S. has extraordinary rates of chronic obstructive pulmonary disease, diabetes and other afflictions that leave people more susceptible to severe COVID. These vulnerabilities were influenced strongly by social factors—not purely genetics.

How did we get here? Partially it was because our public health system had been depleted and eroded. Public health has long been the second-class cousin of the individual health-care system, even though they are closely related. In recent history, we spent lots of money on individual treatment and invested far less in *population* health. Public health systems lacked adequate personnel, data systems for analysis, the latest technology and government support.



Adding to an already perilous situation, the pandemic exposed and accelerated preexisting trends in our society, such as growing distrust of institutions, including of science. In the past 20 years or more American conservatism transformed to anti-science populism. Even in the legal sphere, there has been a dramatic change in the past year in how many courts, including the U.S. Supreme Court, look at public health—a shift from perhaps being excessively deferential to public health policies to becoming hostile to public health, embracing an antiregulatory approach that spans various doctrinal categories.

With such a great push toward individualism, populism and a judicial review that is skeptical of public health, how do we keep the gains we've made against childhood diseases such as polio and measles, chronic illnesses such as those caused by smoking, and motor vehicle accidents? Life expectancy climbed in the 20th century not only because of tremendous scientific advancements and increasing wealth but also because public health campaigns and public health laws accomplished a lot. In the backlash against COVID restrictions and policy, we risk undoing all that.

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children did not have poliovirus, and health authorities ruled out other possible culprits, including West Nile virus, stroke and botulism. What the children *did* have was an obscure virus called enterovirus D68, or EV-D68, which had first been identified decades ago. It had recently been linked with acute flaccid myelitis. Although some children make a full recovery from this condition, it can cause permanent paralysis and even death.

Around the same time that acute flaccid myelitis became associated with EV-D68, BioFire Diagnostics, a Utah-based molecular biology company that is now a subsidiary of the global diagnostics giant bioMérieux, began offering a comprehensive PCR-based respiratory test. It looked for 17 viruses and three bacteria in a single deep nasal swab taken from a patient.

Although the respiratory panel does not test specifically for EV-D68, it tests for the presence of the general family of viruses to which it belongs. BioFire wanted to find a way to catch EV-D68 outbreaks so that doctors and public health officials could know to keep patients from infecting others. Along with its academic partners, the company developed and tested an algorithm that was trained on past data to predict hotspots of EV-D68. The real proof of the approach came in 2018, when the algorithm alerted researchers to the emergence of EV-D68 that summer. Nationwide Children's Hospital in Columbus, Ohio, was one of the first places the algorithm identified with a possible uptick in cases of the virus; the team there confirmed the algorithm was right. As a result, the hospital implemented EV-D68 testing to catch cases early and prevent it from spreading.

A related surveillance platform that uses BioFire's PCR test collates data from different sites across the U.S. and other countries around the world on respiratory viruses such as influenza, rhinovirus and now coronavirus, as well as more than a dozen gastrointestinal pathogens. Unlike the cumbersome data-collection protocols of the past, surveillance systems that continuously collect data directly from connected PCR machines have the potential to be used to detect outbreaks, including those of foodborne disease.

In many ways, this approach—combination PCR tests that cast a wider net to look for more possible pathogens in a given sample—signals the future of PCR. "Their instruments are phoning home, which is totally cool," Greninger says of the BioFire disease-tracking platform, explaining that the broad net it casts could help show where unexpected outbreaks are occurring. The COVID pandemic has made it clear that testing people for viruses even if they are asymptomatic can help identify those who would not otherwise know they are infected, prompting them to isolate before they pass the pathogen unknowingly to others in their community.

Viral evolution can sometimes create a challenge for PCR. Because the primers and probes used in the tests are tailored to look for specific, telltale sequences within a virus, sometimes a new viral variant can evade detection because its sequence has evolved beyond what the test is looking for. Test developers have to constantly ensure the primers and probes are up-to-date. "You need to have a very good understanding of emerging genomes in populations throughout the globe if you're going to have a globally applicable and accurate diagnostic PCR-based test," explains Alexandra Valsamakis, head of clinical development and medical affairs at Roche Diagnostics Solutions.

Yet once scientists have identified new viral variants, they can use PCR testing to track the spread of those variants. This is a capability that the antigen-based testing methods—which look for proteins unique to a particular pathogen—cannot do. The emergence of the Omicron variant has shown how vital it is to track variants. The data pouring in from PCR tests revealed that Omicron was spreading like wildfire compared with the Delta variant that preceded it. As a result, some governments began updating their guidelines and pushing for more booster shots, and some people took the data as a cue to reconsider their social interactions and upgrade the efficacy of their masks.

Some experts worry that even if PCR testing capacity expands to make more of this kind of surveillance possible, it will be hampered by insurance companies that might be unwilling to pay for asymptomatic testing or that hesitate to reimburse tests for pathogens for which no drugs or treatment are yet available. In most cases, insurance companies "pay for vaccines and diagnostics based on individual benefit," says Dan Wattendorf, the Innovative Technology Solutions team director at the Bill & Melinda Gates Foundation. "But we don't really have payment schemes or reimbursement and coverage to find transmission in the community." The problem with coverage for PCR testing has already been a sticking point in the coronavirus pandemic. The U.S. government set up requirements for health insurers to cover PCR testing for COVID, but consumers both with and without coverage have still been left with surprise bills in the thousands of dollars. Whereas PCR technology itself is undoubtedly powerful for disease surveillance, the question of who will foot the bill remains largely unanswered.

HOW COVID IS SHAPING THE FUTURE OF DIAGNOSTICS

AS COVID CREATED DEMAND for more PCR testing everywhere, it also exposed how most of the technology relies on costly enzymes and single-use plastic parts for sample processing. After successfully setting up the fast-turnaround GeneXpert machines on Uganda's border in the spring of 2020, Ssengooba soon ran out of the cartridges and reagents the machines rely on. In those early months of the pandemic, Uganda requested 500,000 such cartridges from Cepheid, but Ssengooba says the company sent only 30,000. The test maker, he recalls, said that it was barred from sending more cartridges out of the U.S. "We spent the rest of 2020 without access to additional cartridges," Ssengooba says.

Modern PCR machines use plastic trays that traditionally have each contained 96 or 384 small wells to hold samples. To circumvent the need for expensive plastic "consumables" such as tubes and caps, U.K.-based company LGC replaces the tray with a long, flexible polymer tape. Only 0.3 millimeter thick, it can stretch up to 40 meters and has room for 106,368 reaction wells. "That allows you to do 100,000 to 150,000 tests per machine per day, which is 10 times more than any machine in the world at 10 times less cost," Wattendorf says, adding that the Gates foundation has partnered with LGC and Northwell Health, the largest health system in New York State, to try the tape-based method for COVID testing.

Another bottleneck with PCR is that "you have to get the sample very, very purified" before running the test, says biomedical engineer Nicholas Adams. PCR machines are calibrated to run reactions at specific temperatures, and impurities such as salts and proteins from patient samples and added preservatives can throw that off. Removing impurities is tough. To avoid that step, Adams and Frederick Haselton, both at Vanderbilt University, had the idea of adding DNA that is a mirror version of the target genetic sequence the PCR test is trying to detect. These mirror sequences are "left-handed"—meaning that they twist in the opposite direction of nat-

UNASSUMING MACHINES: GeneXpert modules use PCR technology to test for all kinds of infectious diseases, including COVID.

urally occurring DNA, which is right-handed—so they do not interfere with the detection process. By adding a specific amount of the left-handed DNA and tracking how much of it is copied, Adams can use it as a benchmark to calibrate and confirm that the PCR machine is running without worrying about many impurities. Adams says that by reducing the need for purification with the left-handed DNA—which costs about 11 cents per test—labs could save significant labor and material costs.

Now that COVID has shown how important it is for testing to be accessible, there is more enthusiasm for portable PCR devices. Avleo Technologies has designed a handheld molecular testing machine that gives results in 30 minutes. Another device, from Visby Medical, was initially developed to look for sexually transmitted infections such as chlamydia and gonorrhea (and received FDA clearance for those applications) and has since added testing for SARS-CoV-2. Anavasi Diagnostics' AscencioDx platform, originally developed to detect HIV and flu before the pandemic hit, is being used in trials as a rapid molecular COVID test. In November 2021 the National Institutes of Health awarded $14.9 million to Anavasi to support that initiative.

Diagnostics developers are continuing to tinker with PCR. German engineering company Solarkiosk Solutions is developing a version that runs on solar power, which it is piloting for COVID testing in a remote part of Sumatra where many residents lack access to electricity and diagnostics. Academic labs and start-ups such as Mammoth Biosciences in San Francisco are combining traditional PCR methods with CRISPR gene-editing technology to make the tests more efficient at detecting specific pathogen genes.

At Uganda's border crossings, Ssengooba says that testing, at this moment, anyway, is "very smooth." But nearly 40 years after the idea of PCR was born, the technology is evolving rapidly as a result of the pandemic, and Ssengooba is dreaming big. He is eager to try the handheld disease diagnostics because traditional PCR—including the printer-size machines at the border—still require hookups to the electricity grid and various sample-processing rooms. A portable version, akin to the one in development by Indian company Molbio, could bypass some of these requirements and open up fast-testing access to remote areas for the first time. "This is something that is incredible," he says.

Public health has always been stymied by the hours or days between collecting a sample and delivering the results to the patient; in the meantime, an infected person has left the clinic and gone back to the routines of their life, unwittingly exposing others and delaying treatments that are often more effective if started earlier. COVID, and the stunning transmissibility of Omicron in particular, has laid bare the consequences of that gap—for individual health, community transmission, overburdened hospitals, labor shortages, and so much more. Ssengooba is hopeful that the urgency for closing that gap will persist. When imagining a future where portable PCR tests with on-site results are commonplace, "all of these challenges," he says, "are going to be left behind."

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Global Health Institutions Reached Their Limits

The need to reinvent the World Health Organization has become abundantly clear

By Lawrence O. Gostin

Moments of existential crisis can turn into opportunities for bold reform. World War II led to the creation of transformative institutions—the United Nations in 1945 and the World Health Organization in 1948. The birth of the WHO came the same year that the U.N. adopted the Universal Declaration of Human Rights.

The COVID pandemic marks just such a moment of crisis. But instead of ushering in significant change, it has fractured global solidarity. That, in turn, has revealed deep-seated fragility in the WHO, the planet's health leader. The WHO's binding, governing framework for pandemic response—the International Health Regulations—has failed to serve its purpose in the face of widespread failures by national governments to comply.

But it is not too late to turn the corner. In fact, this is just the moment to ask what a bold new global public health architecture might look like.

As the U.N.'s first specialized agency, the WHO has a constitutional mandate to direct and coordinate international health, which includes advancing work to eradicate epidemic disease. No state acting alone can prevent the worldwide spread of infectious diseases. Only robust international institutions can set global norms, promote cooperation and share scientific information needed to respond to disease outbreaks. As a result, the WHO's role remains indispensable. With vast and growing global interdependency, intercontinental travel and mass migration, the realities of globalization and climate change have fueled a modern era of new diseases. The list includes three novel coronaviruses—SARS-CoV, MERS-CoV and SARS-CoV-2—and, of course, Ebola and Zika.

WHO director general Tedros Adhanom Ghebreyesus has been the world's conscience throughout the COVID crisis by urging global cooperation. But his pleas have largely been ignored by nationalistic leaders taking a stance of "my country first." Global dysfunction reached a pinnacle when President Donald Trump formally announced the U.S.'s intent to withdraw from the WHO. (President Joe Biden reversed this decision on his first day in office.) Yet Trump's was only one of many dysfunctional nationalistic responses, which ranged from near-total border closures to the hoarding by rich countries of personal protective equipment, oxygen and vaccines. The WHO was powerless to stop any of it. Even the agency's vaunted scientific expertise came into question, as it was embarrassingly late in recommending masks or acknowledging asymptomatic and aerosolized spread of the virus.

It is tempting to simply create an entirely new international health organization, but that would be a serious mistake. It took a world war to build political consensus to establish a global health agency with vast constitutional powers. Every country on Earth is a member except Liechtenstein and Taiwan (the latter left out because of the U.N.'s "One China" policy). The WHO helped to lead the efforts that brought about the eradication of smallpox and the near eradication of polio, among other crowning achievements. Instead of giving up on the agency, we should use this moment, and what political consensus we have, to prepare the organization for future pandemics—and what remains of the current one. This goal can be accomplished with robust funding and a bold new international agreement.

It has become painfully obvious that there is a major disconnect between what the world expects of the WHO and its capacities and powers. Consider its funding: The WHO's next Biennium Budget (for 2022 and 2023) is $6.12 billion, less than those of some large U.S. teaching hospitals and one fifth of the budget of the Centers for Disease Control and Prevention. As long ago as 2011, the WHO's report on the H1N1 influenza pandemic concluded that the agency's budget is "wholly incommensurate" with its global responsibilities. Yet the money it receives has remained roughly constant in inflation-adjusted dollars for the past three decades.

What is worse is that the WHO has control of less than 20 percent of its overall finances. That is the percentage of its budget that comes from so-called mandatory assessed contributions. The rest consists of voluntary contributions, which are mostly earmarked for donors' pet projects. The WHO cannot set global priorities or even hire for the long term, as voluntary funds disappear after a year. A donor then may just shift to another cause. Sustainable funding requires, at minimum, doubling the WHO's total budget over five years, with mandatory assessments making up at least 50 percent of its overall budget. Yet even these modest proposals might not pass muster, because member states insist on calling the shots as to how their contributions are used.

ITALIAN ARMY nurse helps a COVID patient at a camp hospital in Perugia that was opened to relieve the burden on nearby Santa Maria della Misericordia hospital. In December of 2020, the world continued to struggle with the pandemic's successive waves.

Tommaso Ausili/Contrasto/Redux Pictures

Beyond funding, the WHO must have enhanced powers to ensure governments work cooperatively in responding to global health emergencies. Yet the goal of enhancing the agency's powers involves several challenges. Most countries frowned on Trump's withdrawal from the WHO, but many agreed that he had a legitimate grievance. China's early reporting of COVID cases was disingenuous, causing a delay of weeks before the world was alerted, and the country later blocked an independent investigation of SARS-CoV-2's proximal origins. But what national leaders did not realize is that the WHO has no power to verify a nation's reports or gain entry to a state's territory for scientific investigations. These two structural weaknesses—and many more—are the subject of intense global negotiations to create a bold new pandemic treaty, perhaps taking advantage of the WHO's power to adopt broad-based, legally defined commitments such as the Framework Convention on Tobacco Control.

With crisis comes opportunity, and the new pandemic treaty has the potential to be transformative. It should introduce momentous reforms even beyond giving the WHO power to conduct independent investigations. These provisions should include adopting a "One Health" strategy (a collaborative and transdisciplinary approach to achieving optimal health outcomes) that recognizes the interconnection among people, animals, plants and their shared environments. The most likely origin of SARS-CoV-2 is a natural zoonotic spillover, the source of more than 60 percent of emerging diseases. Separating animal and human populations could prevent spillovers—a step that could be achieved through land management, reforestation and regulation of wild animal trade and markets.

Although SARS-CoV-2 most likely reached humans through natural means, a laboratory leak at the Wuhan Institute of Virology has been posed as an alternative theory for COVID's origins. Rigorous regulation and inspection of lab safety, as well as gain-of-function research, could help prevent the unintentional or deliberate release of novel pathogens.

Undoubtedly the rapid development of vaccines and therapeutics, including innovative messenger RNA technologies, was the greatest technological success in responding to the pandemic. But open access and sharing of data and tools, such as real-time virus samples, genomic sequencing, and results from clinical trials and other research, were often lacking. A new legal instrument negotiated under the auspices of the WHO's constitution could provide a pipeline for channeling significant research funding to where it is needed while promoting public-private partnerships and scientific cooperation.

Perhaps most important, the COVID pandemic revealed massive divides based on race, ethnicity, sex, disability and socioeconomic status at both international and national levels. High-income countries dominated global markets in diagnostics, protective equipment, therapeutics and, especially, vaccines. The WHO and its partners designed the Access to COVID-19 Tools (ACT) Accelerator to hasten the development and production of, and equitable access to, COVID resources. Yet COVAX (the ACT Accelerator's vaccine pillar) has badly underperformed. About 10 percent of Africa was fully vaccinated as of mid-January, compared with roughly 63 percent of the U.S. (the European Union had achieved even better coverage). COVAX could be transformative if it were properly funded and resourced and if its distribution channels were strengthened so that vaccines could be stored, transported and administered with speed and without waste.

President Biden has announced the investment of billions of dollars to expand mRNA-vaccine manufacturing, aiming for 100 million doses a month for domestic and global use. Yet this charitable-donation model is deeply flawed because donations always seem to come too little, too late. Any new international agreement must go beyond donations to plan for

Michael Nagle/Redux Pictures

REFRIGERATED TRAILERS served as makeshift morgues during New York City's first COVID wave in May 2020.

adequate and equitably distributed supplies of medical resources, including by securing supply chains, intellectual-property waivers, knowledge sharing and technology transfers.

I have delved into remaking global institutions, but it is obvious that we also must consider domestic public health capacities. The Global Health Security Index ranked the U.S. as most prepared for a pandemic, but the country was among the world's worst performers. There are many reasons for this lack of success, including a collapse of public trust and deep political polarization. But the CDC's guidance and actions—as well as those of state, local and tribal health departments—were, by any measure, weak. That agency and health departments at both state and local levels have lost considerable capacities (surveillance, labs and response) since the post-9/11 anthrax attacks. Buttressing domestic health system capacities is vital. But the CDC also erred badly in its health communications on topics ranging from asymptomatic and aerosolized spread to guidance on masks, vaccines and isolation. Its vaccine and mask recommendations, for example, changed three times in a matter of six weeks.

We are at a crucial junction in the COVID pandemic. We could simply return to the unvirtuous cycle of panic to neglect and back again. All too often, rather than building resilience during the pandemic response, we have blamed "the other," engaging in stereotyping of racial minorities and immersing ourselves in geostrategic battles. But we could transform this crisis into a historic opportunity for once-in-a-lifetime reforms of our national and global health systems based on science, equity and solidarity.

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We Didn't Get Serious about the Climate Crisis

Emergency managers are stuck reacting to a constant march of disasters

By Samantha Montano

DISASTER RESEARCHERS are used to seeing train wrecks coming. We study the worst moments in human history—their warning signs, failures, destruction, pain, corruption and injustice—so that we can lessen the hurt. But the scale of the pandemic, and the response to it, shook even the most practiced among us.

In the beginning, I spent hours gaming out scenarios with other researchers, trying to answer the question everyone was asking us: *How bad is this going to be?* Our debates ("if this happens, then that could happen") were frequently reappraised as we learned more about the how the virus was transmitted—and watched politicians mishandle the response. With every wrong or delayed decision made by the Trump administration, the scenarios narrowed until it was inevitable that hundreds of thousands of people in the U.S., if not more, would die. We have become haunted by the knowledge that the worst could have been prevented.

For decades the U.S. has built a network for responding to acute crises, with the Federal Emergency Management Agency at the top. Each state and territory has a matching agency. The real heart of the system, though, is the patchwork of local agencies. Our approach to disaster response depends on sharing resources: When one community is in crisis, help arrives from other parts of the country to back them up. But when the pandemic began, every part of this system activated for a response simultaneously for the first time ever. I held my breath. There was no

RECORD RAINFALL and deadly floods hit New Jersey in September 2021.

Tayfun Coskun/Anadolu Agency via Getty Images

plan for what happens when everyone is in crisis at once.

I witnessed so many local emergency managers move mountains to get their communities what they needed—ventilators, PPE, testing sites, vaccines—while navigating virulent political conditions that made their jobs harder. As the pandemic response dragged on, new disasters fueled by climate change piled up: From suburban wildfires in Colorado to back-to-back hurricanes in Louisiana to deadly rainstorms in the Northeast to heat waves that led to hundreds of deaths in the Pacific Northwest, the extraordinary has become ordinary.

This constant march of disaster has pushed emergency management to the brink and exhausted the people who make it run. Elected officials expect them not only to respond to increasingly severe disasters but to help lead multiyear recoveries—while preparing for tomorrow's crises at the same time. This is an insurmountable task for local agencies, many of which are staffed with a single, part-time emergency manager. Like healthcare workers, emergency managers are battling burnout as they fight to protect their communities without proper resources and support.

When you are surrounded by calamity, there is an impulse to look for the silver lining. We like to believe there are windows of opportunity that open in the aftermath of disasters, periods of reckoning during which time changes can be made to make people and places safer. Although most disasters do not lead to major policy updates, some—like 9/11 and the levee failure after Hurricane Katrina—do. Disaster researchers call these "focusing events," and while the question of whether the policy outcomes are "good" or "enough" is a second matter, they rattle the status quo.

In early 2020 some thought the pandemic would be just the sort of focusing event that wakes up world leaders to the risks of sleeping on the climate crisis. Maybe they would use this "window of opportunity" to draw obvious parallels, so that one global crisis inspired action on the other. Perhaps the U.S. Congress would finally admit the need to reform—and massively expand—our emergency management system to one that prioritizes risk reduction rather than reactionary measures. One that meets the needs of frontline and marginalized communities who experience disproportionate disaster impacts and are kept from accessing adequate aid.

None of this has happened. Not only is the government not applying the lessons of the pandemic response to other disasters, but even within the pandemic itself, many elected officials have failed to apply the lessons learned at the beginning. Inadequate COVID testing, for instance, was a significant problem early on; when the Omicron variant emerged, we saw a lack of access to testing yet again. Month after month officials have debated mask mandates and the need for hazard pay despite clear evidence that these types of public health policies minimize spread. For all its upheaval, the pandemic has not become a focusing event. Instead it is the latest in a long line of disasters for which the U.S. is unprepared.

For my entire career, I have argued that it does not have to be like this. We have the research and resources to manage disasters more effectively, efficiently and justly, if only policy makers would make that choice. I have always believed that at some point there will be a disaster so bad it will drive them to strengthen our emergency management system. Watching the protracted bungling of the pandemic response, however, has made me doubt there will ever be enough political will to do so—and that is what has scared me the most. If the government cannot effectively manage a single acute surge, I am at a loss for how the U.S. will be able to respond to the all-consuming effects of the climate crisis.

Samantha Montano is author of *Disasterology: Dispatches from the Frontlines of the Climate Crisis* (2021) and an assistant professor of emergency management at Massachusetts Maritime Academy.

Illustration by James Olstein

Lockdowns Showed the Promise of Cities with Fewer Cars

DURING COVID'S FIRST WAVE, the streets of New York and other major cities became eerily empty. Mournful sirens replaced the usual bustle and din. But urban dwellers also heard something new: an abundance of birdsong. During walks outside—the only safe respite beyond their apartments—they breathed cleaner air. Lockdowns had meant fewer cars on the roads, and the effects were unmissable. Levels of nitrogen dioxide—a by-product of fossil fuels burned in cars and in electricity generation—were 30 percent lower along the I-95 corridor from Washington, D.C., to Boston in March 2020 compared with previous years. Come summer, people sat at outdoor extensions of restaurants built in parking zones and moved around on newly added bike lanes. These incidental adaptations to the pandemic allowed residents to *experience* the benefits of shifting away from the "car is king" status quo in a way that policy proposals for climate-friendly infrastructure never could, explains Christian Brand, an environmental scientist with the Transport Studies Unit at the University of Oxford. Now, he says, "they know what's possible."

Some fought to keep it that way. Paris has been a leader of this sustainability shift nudged along by the pandemic. The French capital already had plans to tamp down car use and encourage cycling before COVID emerged, but in late spring 2020 some 50 kilometers of pop-up bike lanes, called *coronapistes*, were added literally overnight. They are now a permanent part of Paris's cycling network, with more in the works.

These strides, Brand says, came in no small part because of political will. Paris Mayor Anne Hidalgo made climate change a focus of her reelection campaign. Besides providing subsidies for purchasing and repairing bicycles, she emphasized the health benefits of reducing car emissions, calling pollutants and a contagious respiratory virus "a dangerous cocktail." In other cities, like New York, changes were more modest or temporary. Shutdowns may have revealed the possibility of safer, healthier streets—but it was often a fleeting vision.

Andrea Thompson is an associate editor at *Scientific American* who covers climate and sustainability.

Inequality Got Much Worse

The poor, no matter where they live, will suffer the greatest lasting toll

By Joseph E. Stiglitz

The coronavirus exposed and exacerbated the fragility and inequity of the global economic system. Many countries, including the U.S., proved unable to manufacture simple products such as face masks, let alone more complicated ones such as ventilators. Multiple supply chains broke. The resulting ordeal will almost surely lead to the creation of more onshore production facilities. An ugly nationalism displayed by countries that have hoarded vaccines and put profits over lives shows no sign of abating, despite its potentially devastating consequences for the world.

The pandemic's most significant outcome will be a worsening of inequality, both within the U.S. and between developed and developing countries. Global billionaire wealth grew by $4.4 trillion between 2020 and 2021, and at the same time more than 100 million people fell below the poverty line. Just how bad the situation will become depends on how long the disease rages and what policy makers do to control it and its consequences.

In part because of its huge income and wealth inequalities, the U.S. suffered the most COVID-attributed deaths of any country. SARS-CoV-2 went after those with poverty-related health conditions and with jobs that cannot be done in isolation. Surviving from paycheck to paycheck and not having even the most basic rights of health care and paid sick leave, many Americans lacked testing to know if they were infected and either went to work, spreading the virus, or sought help too late.

The poorest will also suffer the most from the pandemic's economic aftermath—in particular, from the loss of jobs, disproportionately concentrated in low-wage service sectors. Just as worrisome, poorer children have experienced terrible educational setbacks as schools moved online, presaging a potentially long-term aggravation of inequality and deprivation.

Still, a strong policy response in the U.S. has created a shallower economic downturn than elsewhere. President Joe Biden's American Rescue Plan *reduced* childhood poverty in 2021 by more than a third, demonstrating that the country's high level of poverty has always been a matter of choice. But the measures taken so far are temporary palliatives. The Build Back Better plan was designed to make these achievements more permanent and to reduce inequality in all its dimensions. If it fails to pass, we can expect an enduring increase in poverty. Matters will almost surely get even worse if the pandemic continues.

It was a triumph of scientific, political and economic organization that we were able to so quickly develop, produce and distribute billions of vaccine doses. But matching these enormous successes are colossal failures. Despite having the technology and the resources, we have failed to ramp up vaccine supply and distribute enough doses in poor countries.

Markets can solve most economic problems—a shortage of glass vials, for example. They cannot, however, overcome the legal barriers presented by intellectual-property rights that have given the current producers of vaccines monopoly power. Those pharmaceutical companies have an incentive to restrict manufacturing, allowing them to charge prices that are a multiple of the cost of production—although most of the original R&D, and even much of the initial productive capacity, was publicly financed.

The failure to bring the disease under control and the unequal burden of the disease are thus largely a failure of our economic and political systems. Had the vaccine intellectual-property waiver, which would allow any firm in the world to produce the vaccines after paying a fair royalty, been adopted when it was first proposed more than a year ago, we would almost surely have far greater supplies today. Hope may have arrived in the form of CORBEVAX, a vaccine that has no patent restrictions and is easy to make, circumventing national selfishness and corporate greed. If it proves sufficiently safe and effective, it could get the world inoculated, reducing the likelihood of a more deadly, more contagious or vaccine-resistant mutation.

The global inequities in vaccine distribution are matched by glaring inequities in responses to the economic downturn. Whereas the U.S. has spent a quarter of its gross domestic product (GDP) to keep the economy going, poor countries could spend but a mere fraction of that amount. Some countries have seen a drop in GDP of 10 percent or more, with especially adverse effects on the poorest. And although the U.S. can manage the large increase in debt, poor countries will find it difficult to do so.

Unfortunately, then, the economic shock of the pandemic most likely will linger. It will be those at the bottom—poorer Americans and most people in poorer countries—who will still suffer the consequences years from now. Not doing everything we can to control the disease and its economic aftermath *everywhere* is shortsighted. Dithering and dawdling will allow COVID to rage on, with further supply chain disruptions contributing to shortages, postponing a robust global recovery and entrenching unconscionable levels of inequality.

Joseph E. Stiglitz is a University Professor at Columbia University and chief economist at the Roosevelt Institute. He received the Nobel Prize in economics in 2001. Stiglitz chaired President Bill Clinton's Council of Economic Advisers from 1995 to 1997 and served as the chief economist and senior vice president of the World Bank from 1997 to 2000. He chaired the Sarkozy Commission (2008–2009) and an expert group (2013–2019) at the OECD for devising measures for well-being and sustainability.

Illustration by Samantha Mash

Messenger RNA Therapies Finally Arrived

Instructing our cells to make specific proteins could control influenza, autoimmune diseases, even cancer

By Drew Weissman

IN JUST 17 YEARS, MESSENGER RNA therapies have gone from proof of concept to global salvation. The Pfizer-BioNTech and Moderna vaccines for COVID-19 have been given to hundreds of millions of people, saving countless lives.

In 2005 Katalin Karikó and I created a way to make mRNA molecules that would not cause dangerous inflammation when injected into an animal's tissue. In 2017 Norbert Pardi and I demonstrated that modified mRNA, carried into human cells by a fatlike nanoparticle, protected the mRNA from being broken down by the body and prompted the immune system to generate antibodies that neutralize an invading virus more effectively than the immune system could do on its own. The Pfizer-BioNTech and Moderna vaccines both use this mRNA-liquid-nanoparticle "platform"—known as mRNA-LNP. In large clinical trials, it prevented more than 90 percent of the people who received the vaccines from becoming ill.

These extremely promising trials, and massive studies of people who have since received the vaccines, have finally given us sufficient information about the safety and efficacy of mRNA vaccines in humans. The platform outperformed more conventional approaches, in which vaccines are grown in laboratory cell cultures or chicken eggs. The rapid development also accelerated investment in further research that is now underway. And because the U.S. Food and Drug Administration and similar regulatory agencies are now familiar with the technology, assessment of new therapeutics should come readily.

Messenger RNA vaccines instruct cells to create proteins that induce an immune response to an invader such as the SARS-CoV-2 virus, training the immune system to attack future infections of the actual pathogen. They are easier to produce in large quantities than conventional protein therapies (genetically engineered versions of natural human or pathogen proteins) and monoclonal antibody therapies (lab-produced molecules that attack viruses in the same way that human antibodies do). And once a reliable manufacturing facility is built, it can quickly switch to a new mRNA vaccine or drug—unlike protein or monoclonal facilities, which must reengineer production from the ground up for each new therapy.

Success has inspired researchers, companies and government labs to pursue mRNA therapies for many infectious diseases, including influenza, cytomegalovirus, herpes simplex virus 2, norovirus, rabies, malaria, tuberculosis, dengue, Zika, HIV, hepatitis C and the entire family of coronaviruses. In each case, researchers are determining exactly how mRNA-LNP vaccines induce potent antibody responses.

Drew Weissman is a professor of vaccine research at the University of Pennsylvania. The nucleoside-modified mRNA-lipid-nanoparticle vaccine platform his laboratory created is used in COVID-19 vaccines made by Pfizer-BioNTech and Moderna. Weissman receives royalties from a patent for nucleoside-modified mRNA that is licensed by those two companies.

Illustration by Thomas Fuchs

Work on mRNA vaccines is also expanding to certain cancers, food and environmental allergies, and autoimmune diseases. Positive results against ATTR amyloidosis, a fatal condition that involves the liver, have already been produced in a phase 1 clinical trial. Although protein-based medications for certain illnesses are expanding quickly, large doses are typically required, and production is often difficult and expensive; mRNA delivery of therapeutic proteins could help. The approach has already worked in animals for issues as disparate as bone repair and asthma, and human clinical trials are underway.

The Defense Advanced Research Projects Agency is even experimenting with mRNA delivery of monoclonal antibodies that could be tailored for previously unidentified infectious diseases, with the goal of supplying reliable manufacturing of such remedies within 60 days.

The concentrated COVID-19 work has also helped make mRNA a leader in nucleic acid therapeutics—approaches that can produce nearly any protein made by a specific cell. The technique is starting to be applied, and it could fight diseases in more convenient, less invasive and less expensive ways. For example, the FDA has approved gene therapy for sickle cell anemia, and it is working in the U.S., although it requires marrow to be extracted from a person's bone, treated and reinserted; mRNA therapy could be delivered to marrow with a straightforward injection into a person's arm. If that works, sickle cell treatment could be greatly expanded in countries where the condition is widespread.

In similar fashion, mRNA therapeutics could revolutionize treatment of many infectious diseases in developing countries, greatly improving health-care equity. I am collaborating with labs around the world. Thai investigators at the vaccine center at Chulalongkorn in Bangkok and I have made a Thai COVID vaccine and established a quality manufacturing center to produce it for Thailand and seven surrounding low- and middle-income countries. I am doing similar work in Africa and eastern Europe; South America will be next.

Plenty of hurdles remain, including the creation of a better supply chain for delivering raw mRNA vaccine and materials needed for its production worldwide, as well as improvements that could reduce the dosage a person needs to receive. Yet the ease of mRNA production should enable most countries to make their own medications, as long as they can attract and retain researchers who can develop subsequent therapeutics that in turn keep domestic, high-quality manufacturing sites operating.

Illustration by James Olstein

Billionaire Space Tourists Became Insufferable

LAST SUMMER, at a time when the pandemic had strained many people's finances, inflation was rising and unemployment was still high, the sight of the richest man in the world joyriding in space hit a nerve. On July 20 Amazon founder Jeff Bezos rode to the edge of space onboard a rocket built by his company Blue Origin. A few weeks earlier ProPublica had revealed that he did not pay any income taxes for two years, and in other years he paid a tax rate of just 0.98 percent. To many watching, it rang hollow when Bezos thanked Amazon's workers, whose low-paid labor had enriched him enough to start his own rocket company, even though Amazon had quashed workers' efforts to unionize several months before. The fact that another billionaire, Richard Branson, had also launched himself onboard his own company's rocket just a week earlier did not help.

COVID changed many people's willingness to shrug off the excesses of the rich. The pandemic drew an impossible-to-ignore distinction between those who can literally escape our world and the rest of us stuck on the ground confronting the ills of Earth: racism, climate change, global diseases. Even several members of Congress expressed their disapproval of Bezos. "Space travel isn't a tax-free holiday for the wealthy," said Representative Earl Blumenauer of Oregon. Bezos and Branson putting the spotlight on themselves as passengers served to downplay the work that hundreds of scientists and engineers at Blue Origin and Virgin Galactic had put into designing, building and testing their spacecraft. It also masked the reality that advances in private spaceflight really could eventually pay off in greater access to space for all and more opportunities for scientific research that could benefit everyone. All their flights did was give the impression that space—historically seen as a brave pursuit for the good of all humankind—has just become another playground for the 0.0000001 percent.

Clara Moskowitz is a senior editor at *Scientific American* who covers space and physics.

Long Haulers Called Attention to Chronic Illnesses

But society is not prepared for the growing crisis of long COVID *By Meghan O'Rourke*

When the first wave of coronavirus infections hit the U.S. in March 2020, what kept me up at night was not only the tragedy of the acute crisis but also the idea that we might soon be facing a second crisis—a pandemic of chronic illness triggered by the virus. I had just finished reporting and writing a book about infection-associated syndromes and contested chronic illnesses, long an underresearched and dismissed area of medicine. Medical science has increasingly understood that infections can trigger ongoing physical symptoms in a subset of people, yet the medical establishment has typically ignored the experiences of those people. Such conditions include myalgic encephalomyelitis/chronic fatigue syndrome (ME/CFS), so-called chronic Lyme disease, and more.

Sure enough, later that spring a cohort of patients who had caught the coronavirus in March began reporting that they were still not better. In online message boards, patients began sharing stories of what they called long COVID. Groups of "long haulers" banded together to call for more attention and research into their plight.

The clamor, combined with the scope of the problem, had a clear impact on medical attitudes, making long COVID visible in ways that ME/CFS had struggled for decades to become. In a matter of months centers dedicated to treating long COVID sprang up at respected research hospitals, such as the Center for Post-COVID Care at Mount Sinai in New York City. In itself, this is a hopeful development: when I got sick with a similar condition a decade ago, I longed for such a place.

The effects on research, too, have been dramatic, with scientists at numerous academic medical centers working to understand what long COVID is, how to measure it and how best to treat or manage it. Akiko Iwasaki, an immunologist and head of a laboratory at the Yale School of Medicine, is one of them. "I used to focus mainly on acute infectious diseases, but with long COVID on the rise, a big chunk of my lab now focuses on long COVID and other postacute infection syndromes," she says. David Putrino, director of rehabilitation innovation for the Mount Sinai Health System, says he is "seeing a sharp increase in interested researchers," in part because funding agencies such as the National Institutes of Health "have begun allocating increased resources to long COVID."

Two years into the pandemic, long COVID remains one of the biggest threats it poses. Early estimates suggest that anywhere from 10 to 50 percent of unvaccinated people infected with the virus develop long-term symptoms. Vaccines may reduce the risk by as much as 50 percent, but according to Putrino, they do not eliminate it.

Yet long COVID was rarely discussed in public health messaging during the Delta and Omicron waves; officials focused on acute severe disease and death and largely ignored the debilitating—and life-altering—long-term effects that the virus has on so many people. We've had even fewer conversations about the societal responsibilities we have toward a growing generation of sick people, many of whom are between the ages of 30 and 50.

This lack of concern is even more surprising considering that we still understand little about the condition, including what causes it. Some theories suggest that the virus triggers rampant inflammation or autoimmune disease, others that the virus itself may persist in tissues in the body. What we do know is that millions of people are seeking care for a staggering array

of symptoms that include fatigue, brain fog, racing hearts, breathlessness, pain, and more. The task of treating all these patients is exposing some of medicine's enduring weaknesses.

Modern medicine is based on replicability. Since the advent of germ theory in the 19th century, the field has taken an "if you can't measure it, it doesn't exist" view, as Harvard University researcher Susan D. Block put it to me. Medicine has a long history of stigmatizing diseases it does not understand and cannot yet readily measure. Clinicians like to be able to treat diseases that resolve. When patients present with chronic conditions or an array of systemic symptoms that are hard to quantify, doctors do not have quick fixes to offer. These patients are often dismissed as malingerers or as suffering from a psychosomatic condition—and so it still is with long COVID.

Some patients have reported seeing doctors who want to help but lack the skills and bandwidth to do so. Early in the pandemic, staff at the Center for Post-COVID Care at Mount Sinai would spend hours with patients during their intake sessions. Compare that with the silo-based U.S. health-care system, which is designed to maximize efficiency: its basic building block is a 15-minute visit with a clinician. To treat long COVID effectively, then, Putrino thinks medicine needs more than just an infusion of interest and money. Additional funding, he says, will not "lead to a meaningful cultural change in the research and clinical world" until research centers start "actively involving people with these conditions" in the decision-making process.

The potential for transformation goes far beyond long COVID. Understanding what causes this condition might illuminate treatments for ME/CFS, tick-borne illness and other diseases that involve dysfunction of the immune system, many of which are on the rise. "I believe understanding the pathogenesis of long COVID not only will help reveal parallel mechanisms for ME/CFS but also may hold a key to understanding autoimmune diseases, as many autoimmune diseases occur postinfection," Iwasaki says.

It is time for medical researchers to investigate these long-contested illnesses with the full force of science's power and for medical educators to train doctors in how to effectively *care* for chronically ill patients. If they do not, they will be failing not only this generation of patients but many millions more to come.

Meghan O'Rourke is editor of the *Yale Review*. Her essays, criticism and poetry have appeared in the *Atlantic*, the *New Yorker* and many other publications. Her latest book is *The Invisible Kingdom: Reimagining Chronic Illness* (Riverhead Books, 2022).

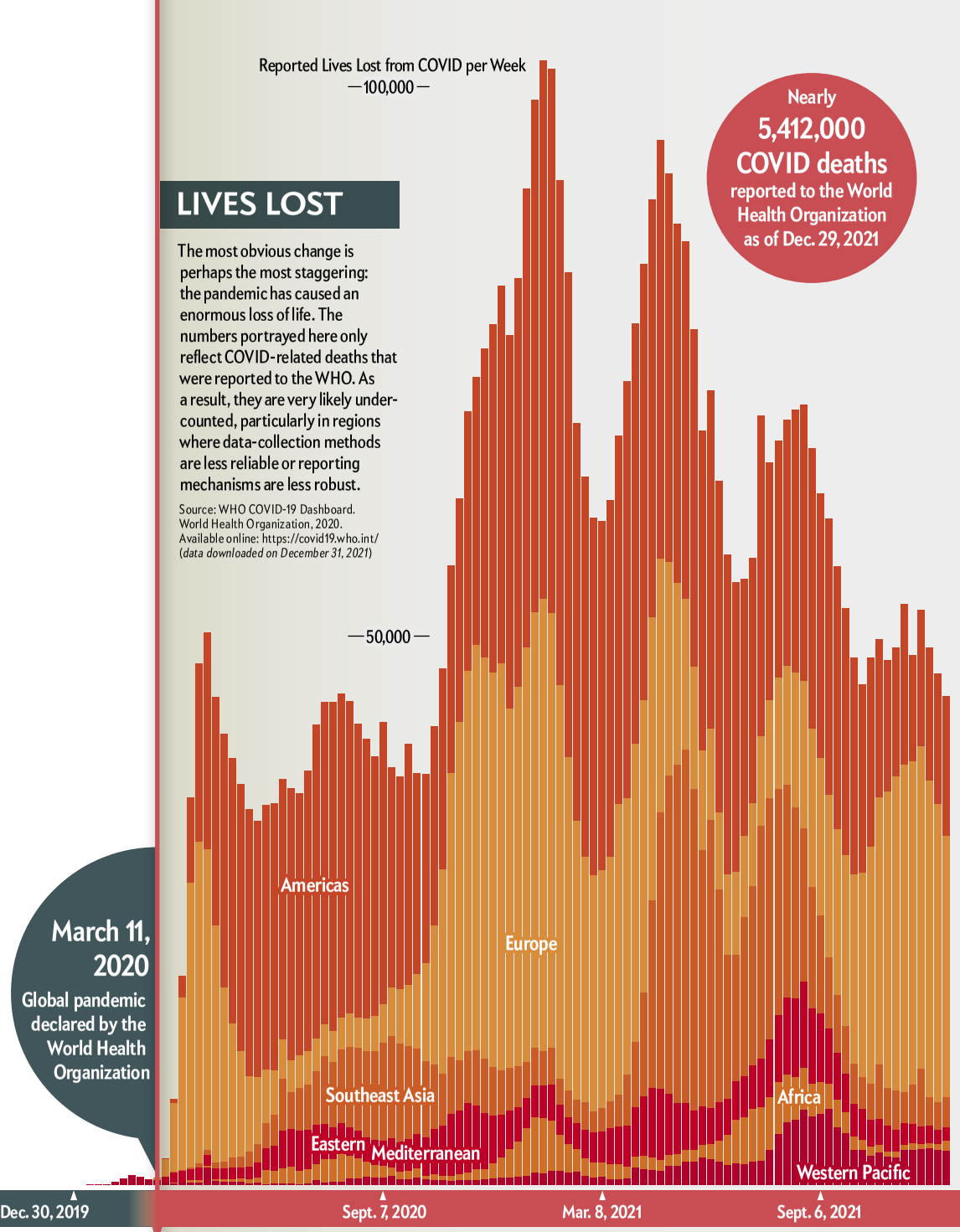
Illustration by Thomas Fuchs

Data Captured COVID's Uneven Toll

Visualizing ongoing stories of loss, adaptation and inequality

By Amanda Montañez and Jen Christiansen, with research by Sabine Devins, Mariana Surillo and Ashley P. Taylor

By telling the story of COVID-19 in real time, data visualization has taken on new importance in our daily lives. Early in the pandemic, we watched circles multiply and swell on a map as the virus spread around the globe. We saw lines on time-series charts turn nearly vertical during surges in cases. These numbers and their pictorial signifiers have been critical for informing our behaviors over the past two years, but they hardly capture the full significance of the crisis and its many snowball effects. Much of the fallout—from personal and collective traumas to profound economic disruption—can also be measured to help us tell a fuller story of how COVID has changed the world. The visualizations that follow focus on the emergence of potential trends, sudden pivots and troubling setbacks; we also explore the consequences of some dramatic, if temporary, blips. Because no story can be captured by data alone, context and caveats are provided throughout.



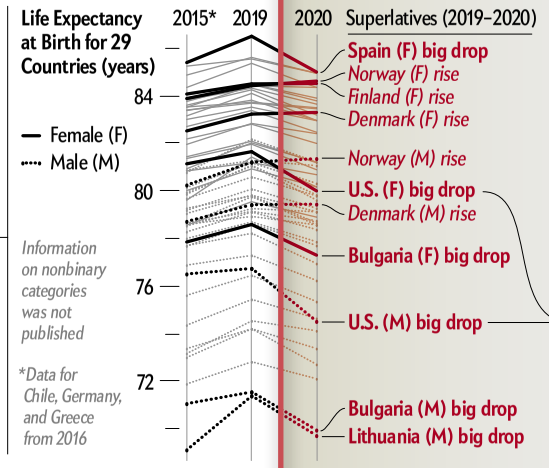
HEALTH

Globally, COVID has changed people's health in ways that go far beyond the acute impact of the disease. Efforts to limit the virus's spread, as well as the death toll itself, have generated widespread fear, isolation and economic hardship, the effects of which will be felt for generations.

Life Expectancy

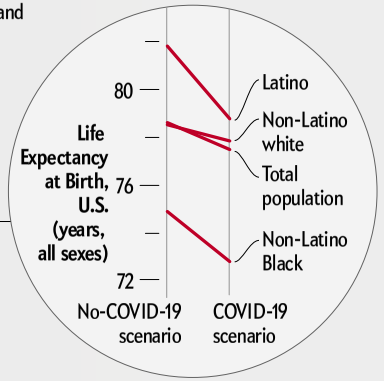
A useful measure of population health and longevity, the indicator known as "life expectancy at birth" has been on the rise in most places for the past century. In a recent study of 29 countries, COVID single-handedly reversed that trend in 27 of them. Life expectancy is typically measured separately for males and females; overall, the pandemic's toll was greater among males.

Source: "Quantifying Impacts of the COVID-19 Pandemic through Life-Expectancy Losses: A Population-Level Study of 29 Countries," by José Manuel Aburto et al., in *International Journal of Epidemiology*; September 26, 2021 (*data*)



Overall life expectancy in the U.S. has plummeted, but some populations suffered more than others. The pandemic's disproportionate impact on communities of color underscores the serious health effects of racial and ethnic inequality.

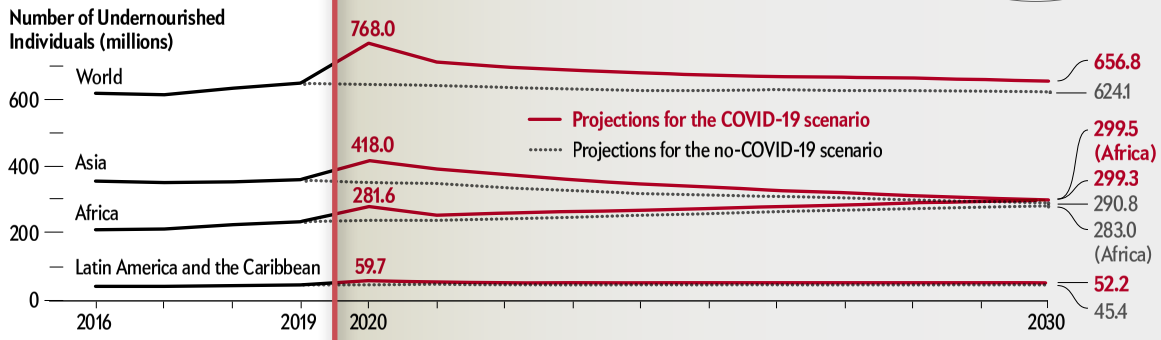
Source: "Reductions in 2020 U.S. Life Expectancy Due to COVID-19 and the Disproportionate Impact on the Black and Latino Populations," by Theresa Andrasfay and Noreen Goldman, in *PNAS*, Vol. 118; February 2, 2021 (*data*)



Food Insecurity

Factors such as climate change and pervasive inequality were already contributing to high rates of food insecurity. A recent report found that the pandemic caused an immediate spike in undernourishment both globally and regionally in 2020, primarily related to people losing their jobs or experiencing a reduction in work hours amid lockdowns. It also compared projected numbers of undernourished people over the next decade with what those values would be without COVID. The data suggest that these seemingly acute disruptions will have a long tail: COVID scenario projections largely exceed no-COVID ones as far out as 2030.

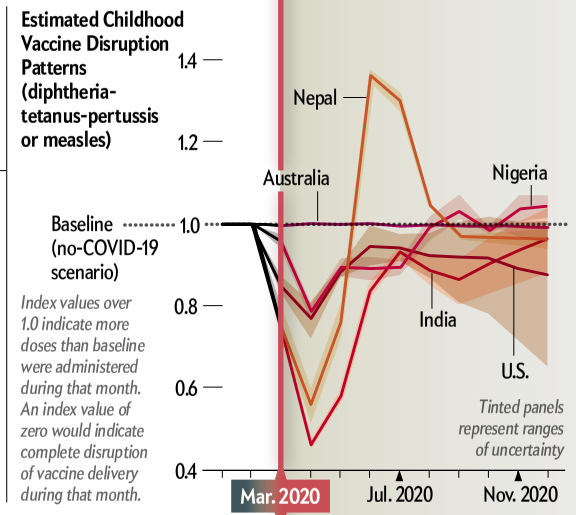
Source: *The State of Food Security and Nutrition in the World 2021.* "Transforming Food Systems for Food Security Improved Nutrition and Affordable Healthy Diets for All," by FAO, IFAD, UNICEF, WFP and WHO, 2021



Childhood Vaccinations

Despite ubiquitous talk of vaccines, rates of immunization against diseases *other* than COVID have recently fallen. A study tracking children due for their third dose of the diphtheria-tetanus-pertussis vaccine and their first dose of the measles vaccine estimated that between eight million and nine million more doses of each vaccine were missed globally compared with what was expected, with coverage dipping lowest in April 2020. Numbers have improved since then, but in some countries, coverage remains lower than it would be without COVID.

Source: "Estimating Global and Regional Disruptions to Routine Childhood Vaccine Coverage during the COVID-19 Pandemic in 2020: A Modelling Study," by Kate Causey et al., in *Lancet*, Vol. 398; July 14, 2021 (*data*)



Birth Rates • Globally, COVID's impact on birth rates has been mixed. In many high-income nations, people had fewer babies than expected in 2020, perhaps because of high levels of stress and financial uncertainty. But in low- and middle-income countries, pandemic restrictions disrupted access to contraceptives for an estimated 12 million women, resulting in nearly 1.4 million unintended pregnancies.

Loss of Caregivers • In October 2021 the CDC reported that one in four COVID deaths in the U.S. deprived a child of a primary or secondary caregiver. From April 2020 to June 2021, this amounted to 140,000 children affected, a disproportionate number of whom were kids of color.

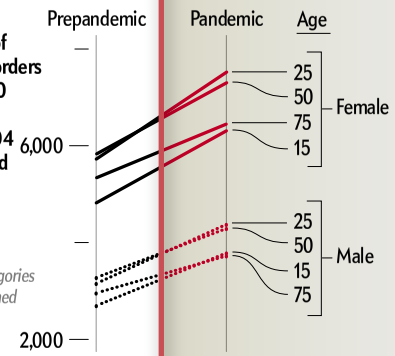
Mental Health

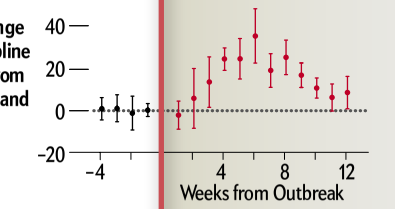
The global prevalence of depressive disorders grew by nearly 28 percent in 2020, and anxiety disorders rose by almost 26 percent, according to a study in the *Lancet*. This explosion of cases was linked to pandemic-related factors such as high infection rates and decreased mobility during lockdowns.

Source: "Global Prevalence and Burden of Depressive and Anxiety Disorders in 204 Countries and Territories in 2020 Due to the COVID-19 Pandemic," by Damian Santomauro et al., in *Lancet*, Vol. 398; October 8, 2021 (*data*)

One study in *Nature* evaluated mental health effects by tracking calls to helplines in 19 countries. Call volume was up 35 percent compared with prepandemic levels, with more callers than usual expressing feelings of fear and loneliness.

Source: "Mental Health Concerns during the COVID-19 Pandemic as Revealed by Helpline Calls," by Marius Brülhart et al., in *Nature*, Vol. 600; November 17, 2021 (*data*)





Substance Use

Cigarette Sales • In 2020 cigarette sales in the U.S. increased for the first time in nearly 20 years.

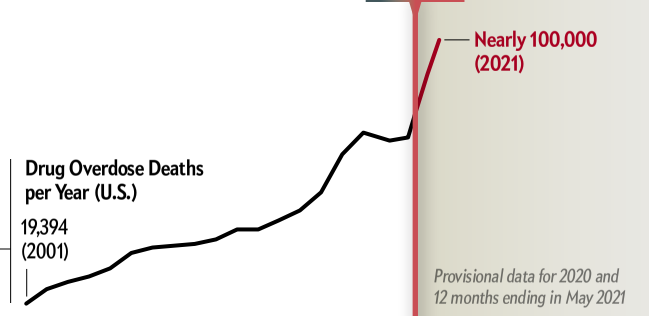
Source: *Federal Trade Commission Cigarette Report for 2020*, published October 2021 (*data*)

Alcohol Sales • From March to September 2020, retail sales of alcoholic beverages in the U.S. jumped by 20.4 percent compared with the same period in 2019. This change was accompanied by a decrease in sales at restaurants and bars, so it is hard to say whether the pandemic prompted people to consume more alcohol overall. But drinking at home certainly became more prevalent.

Source: "The Concerning Increasing Trend of Alcohol Beverage Sales in the U.S. during the COVID-19 Pandemic," by João M. Castaldelli-Maia et al., in *Alcohol*, Vol. 96; November 2021 (*data*)

Drug Overdose Deaths • People in the U.S. died from drug overdoses in unprecedented numbers following the onset of the pandemic, according to CDC data. The period from April 2020 to April 2021 represented the first time over 100,000 overdose deaths were reported in a single year. Many of these deaths were attributed to fentanyl, the powerful synthetic opioid that has flooded the illegal drug market following a surge in prescription opioid addiction in recent years.

Source: National Center for Health Statistics, Centers for Disease Control and Prevention (*data*)



Changes in mental health disorders do not capture the full picture of loss, stress and isolation

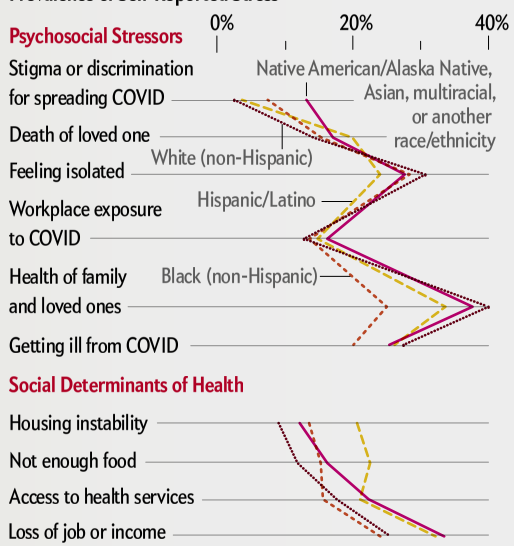
"The mental health consequences of COVID could lead to long-term losses in well-being, diminished economic productivity and increasing health-care costs. Unfortunately, the existing U.S. mental health system is sorely lacking a public focus: it engages largely with those who are already mentally ill and often only those who are able to pay for treatment."

—Psychiatry residents Sofia Noori and Isobel Rosenthal, in Scientific American, *June 2020*

COVID caused new types of stress

A CDC survey conducted in April and May of 2020 evaluated prevalence of depression, suicidal ideation and the initiation of substance abuse, along with specific pandemic-associated stressors and social determinants of health. Rates of these issues varied across racial and ethnic groups. For example, Hispanics reported outsize rates of both housing instability and suicidal ideation. Meanwhile those identifying as Native American/Alaska Native, Asian, multiracial, or another race or ethnicity not listed separately in the survey reported the highest rates of stigma around viral spread, job or income loss and lack of access to health services.

Source: "Racial and Ethnic Disparities in the Prevalence of Stress and Worry, Mental Health Conditions, and Increased Substance Use among Adults during the COVID-19 Pandemic—United States, April and May 2020," by Lela R. McKnight-Eily et al., in *Morbidity and Mortality Weekly Report*, Vol. 70; February 5, 2021 (*data*)



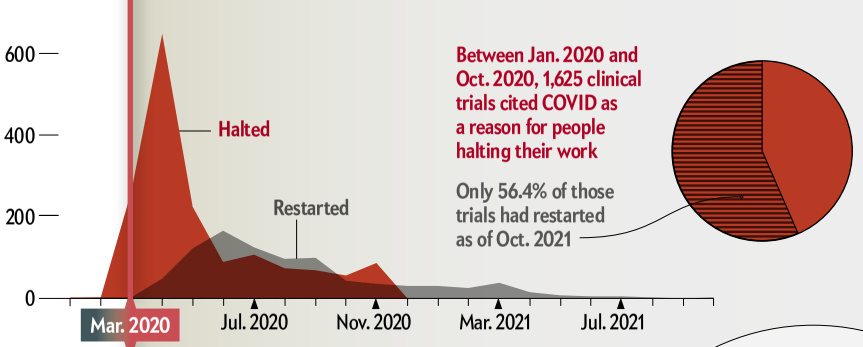
SCIENTIFIC RESEARCH

Beginning in March 2020, some research projects screeched to a halt, whereas others suddenly ramped up. An urgency to understand COVID—and the underlying public health issues it has revealed—may have prompted a reevaluation of priorities in scientific research.

Clinical Trials

During the period of December 2019 through January 2021, 2,043 clinical trials globally were suspended or paused because of COVID-19. Some of those have subsequently restarted, but many have not.

Source: Data from ClinicalTrials.gov, processed by Benjamin Gregory Carlisle (*unpublished analysis*)



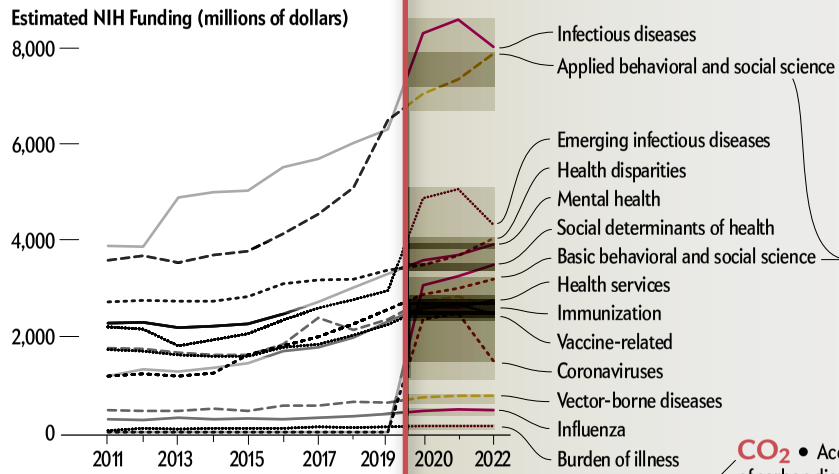
Between Jan. 2020 and Oct. 2020, 1,625 clinical trials cited COVID as a reason for people halting their work

Only 56.4% of those trials had restarted as of Oct. 2021

Funding by the National Institutes of Health

Out of a total of 200 broad research areas, certain categories of NIH funding experienced especially large increases from 2019 to 2022 (which is a projected budget). Some seem clearly linked to the pandemic: social determinants of health, for example, are related to COVID's disproportionate impact on certain populations. Other areas, such as influenza and vector-borne disease, received relatively little investment.

Source: National Institutes of Health, June 25, 2021 (*data downloaded from https://report.nih.gov*)



Behavioral science research is on the rise

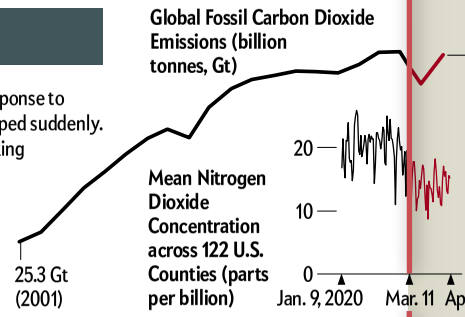
Reflecting on how misinformation exacerbated COVID's impacts in the U.S., outgoing NIH director Francis Collins told PBS *NewsHour:* "I wish we had more insights from behavioral social science research into how this has come to pass and why it could have gotten so completely widespread. I want to call this out as one of my most major concerns as I stepped down from the NIH, of looking at the situation in our nation." The NIH's increased investment in the field in 2022 reflects Collins's concerns.

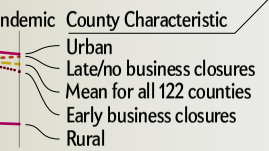
EMISSIONS

When governments issued lockdowns and other restrictions in response to COVID, transportation and commercial energy consumption dropped suddenly. The result was a striking decrease in air pollution. But studies tracking changes in carbon dioxide, nitrogen dioxide and fine particulates also show a rebound toward prepandemic levels.

Reducing emissions is possible—but how we get there matters

The pandemic's immediate impact on emissions proves that collective behavioral changes can produce swift results. But there is little about the painful conditions of the pandemic that anyone desires to replicate. One exception is the shift to remote work for millions of people who formerly commuted by car. Policies that support telecommuting could help sustain a decrease in emissions.





CO_2 • According to CarbonMonitor.org, global emissions of carbon dioxide, the greenhouse gas responsible for the majority of global warming, fell by a considerable 5.4 percent in 2020 but have since rebounded to levels approximating those of 2019.

Source: Global Carbon Project

NO_2 • Nitrogen dioxide is emitted through the burning of fossil fuels and is associated with human respiratory problems. In the first several weeks of pandemic lockdowns in the U.S., levels of this gas dropped by more than 25 percent relative to the same period in the previous three years.

Source: "Changes in U.S. Air Pollution during the COVID-19 Pandemic," by Jesse D. Berman and Keita Ebisu, in *Science of the Total Environment*, Vol. 739; October 2020 (*data*)

Fine Particulates • Following lockdowns in the U.S., fine particulate matter (PM2.5) stayed relatively close to prepandemic levels overall. Researchers did find, however, significant decreases in urban areas and those where nonessential businesses closed early.

Source: "Changes in U.S. Air Pollution during the COVID-19 Pandemic," by Jesse D. Berman and Keita Ebisu, in *Science of the Total Environment*, Vol. 739; October 2020 (*data*)

ECONOMY

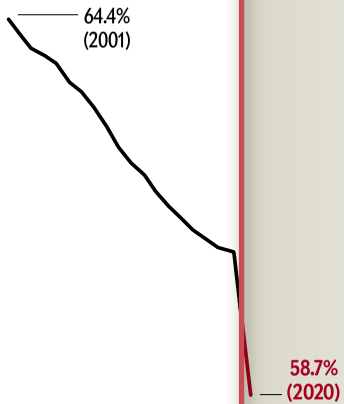
COVID's economic impacts are as varied as they are significant. From a distance, it is easy to identify clear winners and losers: air travel and hospitality industries suffered, for example, whereas video calling and online shopping skyrocketed. But a closer look at the data reveals a more granular picture because different people experienced these changes in varying ways.

Labor Force Participation

The worldwide share of people in the labor force—defined by the World Bank as those aged 15 or older who supply labor for the production of goods and services—has been gradually falling in recent decades (although trends have varied by country). Since 1990 the typical annual fluctuations were around 0.1 percent. From 2019 to 2020 the global rate fell from around 61 percent of the population to less than 59—a sudden, steep drop.

Source: International Labor Organization, ILOSTAT database; data retrieved on June 15, 2021, and presented by the World Bank

Global Labor Force Participation Rate (percent of total population, ages 15 and up)

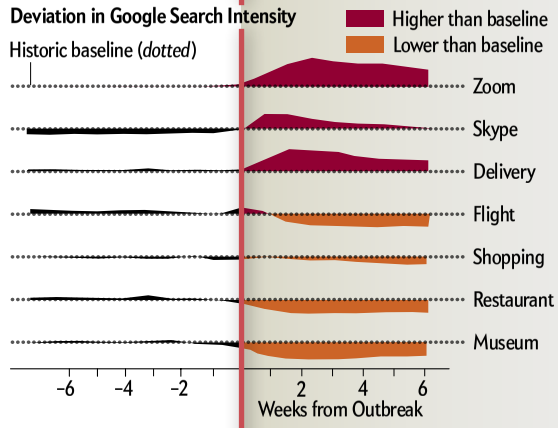


Industry Ups and Downs

A look at worldwide trends of Google search terms reveals clear industry winners and losers. When lockdowns put an abrupt stop to nonessential travel, searches including words like "hotel" and "airport" became scarce. Meanwhile remote workers sent "Zoom" skyrocketing, and people avoiding the grocery store performed abundant searches for "delivery."

Source: "Winners and Losers from COVID-19: Global Evidence from Google Search," by Kibrom A. Abay at al. Policy Research Working Paper 9268, World Bank Group, Development Economics Development Research Group, June 2020

Deviation in Google Search Intensity



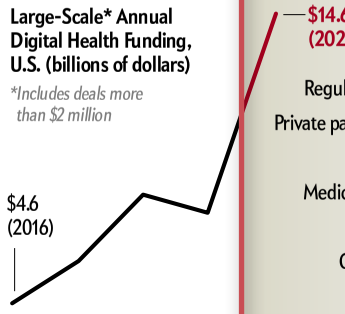
Telehealth Investments

Telehealth uses certain technologies to provide health care at a distance. Examples range from sensors that allow for remote tracking of vital signs to consultations with a medical professional by phone or computer. It is not a new concept, but global investments—in terms of number of investors and scale of contributions—jumped up in 2020 and continued to break records in 2021. The chart here shows one measure: cumulative investments in digital health companies.

Source: Rock Health Funding Database, as published on July 6, 2021, by rockhealth.org (*data*)

Large-Scale* Annual Digital Health Funding, U.S. (billions of dollars)

**Includes deals more than $2 million*



Mar. 2020

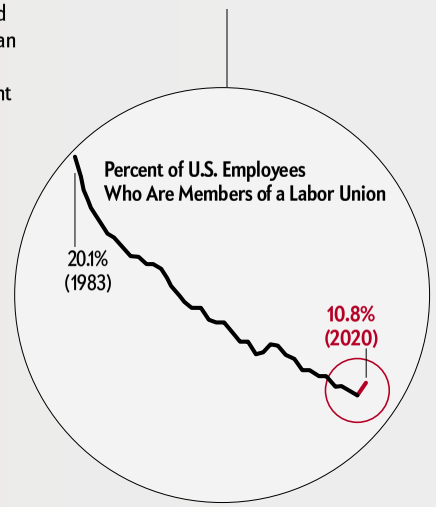
The burden of job loss is not shared evenly

In mid-2021 the International Labor Organization reported that although men's global employment had returned to prepandemic levels, there were still 13 million fewer women in the workforce than in 2019. People in low-paying jobs were also affected disproportionately, in part because their roles may not be compatible with remote work. The U.S.-based Brookings Institution reported that "before COVID-19, nearly half of all working women … worked in jobs paying low wages, with median earnings of only $10.93 per hour." Hispanic and Latina women represent an outsize share of these workers, compared with white women.

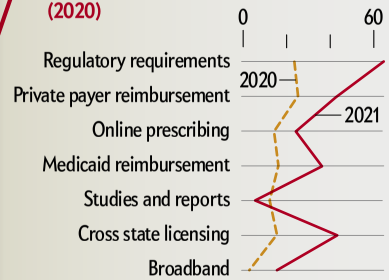
Unions are on the rise

People who were put in the category of "essential worker" in 2020 found that their roles had become both newly dangerous and indispensable. Yet many did not feel their employers responded adequately to keep them safe and fairly compensated. Perhaps in response to these developments, the U.S. has seen a recent uptick in unionized workers as a percent of its total workforce.

Source: Bureau of Labor Statistics



Telehealth-Related Bills Passed



Telehealth Policy

In the U.S., federal and state laws control the type and extent of telehealth services available to patients. During the COVID public health emergency, regulations shifted quickly, making the option of remote care more accessible to more people. Advocates are pushing for continued—and expanded—access, even as the acute need wanes.

Source: Center for Connected Health Policy (*data*)

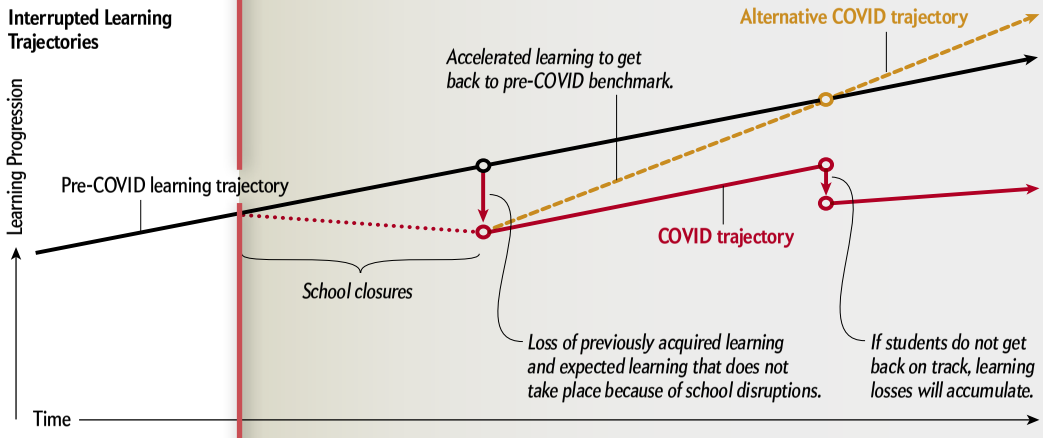
EDUCATION

A report from the World Bank, UNESCO and UNICEF warns that COVID-related disruptions caused "the worst education crisis on record." Children in low- and middle-income countries have suffered the biggest losses because of school closures and will likely experience longer-lasting effects than those in high-income nations. "Affected cohorts of children end up with lower educational attainment, as well as lower earnings and higher unemployment in adulthood."

Disrupted Learning Trajectories

According to the World Bank, some evidence shows that a portion of the long-term losses "are attributable to slower learning once children return to school." If educators and administrators are given the resources and support to respond to pandemic-related setbacks with an "accelerated learning trajectory," students may still catch up. But that would require immediate, sweeping changes to education systems, including consolidating the curriculum, increasing instructional time and tutoring students in small groups.

Source: *The State of the Global Education Crisis: A Path to Recovery,* World Bank, UNESCO and UNICEF (2021)



TRUST

The success of any democracy depends largely on the degree to which the public trusts its institutions to act in its best interest. In many countries, political responses to COVID appear to have shifted public perceptions of corruption in government—some for better, others for worse.

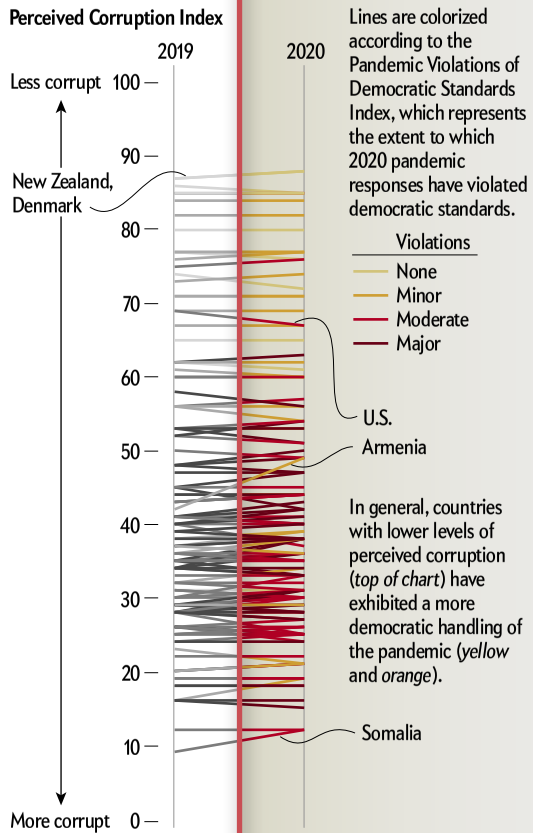
Perceived Corruption (Global)

According to the organization Transparency International, the corrosive effects of corruption are amplified during emergencies, which can in turn exacerbate the emergency. Some of the key factors in this spiral of harm are diversion of funds from essential services, opaque government spending, and breaches of human rights in the management of the crisis. All these issues arose during the pandemic, and people all over the world suffered and died as a result.

Sources: Transparency International (*Corruption Perception Index values*), and Pandemic Backsliding Project, Varieties of Democracy Institute (*Pandemic Violations of Democratic Standards Index values*)

Successes and failures

In New Zealand, which famously handled COVID quite well, levels of public trust started out high in 2019 and improved in 2020 as the government maintained democratic standards throughout its response. In the U.S., however, violations of democratic standards seem to have worsened perceptions of corruption at the same time the country has suffered devastating losses during the pandemic.



New rules require interpersonal trust

"The problem is that for the recommendations or regulations to work, we need to trust our fellow citizens as well as the government institutions that are issuing them. If people do not believe that most others are going to play by these novel and restrictive rules, they are unlikely to adhere to them themselves."

—Political scientist Bo Rothstein, in Scientific American, *March 2020*

MOVING FORWARD

The story of COVID and its myriad impacts is far from over. As we enter year three of the pandemic, data will continue to play a key role in quantifying the waves of change that ripple through society. Some of these data will help us make personal risk assessments in our daily lives, whereas others might inform policy decisions. Charts and graphics can also highlight emerging trends that might otherwise get lost as we navigate the daily noise of an ongoing crisis.

Work Changed Forever

People realized their jobs don't have to be that way

By Christina Maslach and Michael P. Leiter

HARDLY ANYONE has made it through the pandemic with their work life unchanged. Millions of people have lost jobs, been placed on furlough or switched to working from home. Essential workers have continued in place but often with major changes to their workloads, including additional safety procedures and an awareness of infectious disease as a new workplace hazard. According to the Bureau of Labor Statistics, employment dropped by 20.5 million people in the U.S. alone in April 2020. Service providers were hit most intensely: 7.7 million jobs were lost in the leisure and hospitality sector, with 5.5 million of them in food service or drinking establishments.

The shift to remote work led to the complete collapse of the work-home boundary, especially for parents juggling child care and homeschooling with job demands. Poorly timed or endless Zoom meetings interfered with people's ability to get work done and sometimes harmed relationships with colleagues. Essential workers often discovered that their employers' only strategy to bridge the gap created by increased demand was for them to work harder—reinforcements were not on the way. Many employees had to deal with inadequate personal protective equipment while feeling unfairly treated. And it became more difficult for everyone to relax and recover from their ongoing exhaustion as entertainment and fitness facilities closed. Because of these changes, workers experienced more stressful exhaustion, became more negative and cynical about the workplace and felt an erosion of self-confidence—the triple markers of burnout.

At the same time, other people—especially those with comfortable home offices and few parental responsibilities—found benefits in working remotely. Being on their own gave them greater control with fewer distractions. The absence of commuting gave people more time and energy while saving them

Illustration by James Yang

money. People who had been working in unpleasant or hostile workplaces were now free from disrespectful encounters.

The pandemic has taught many people that the job does not have to be the way it was. This realization may be one reason that many are not going back to their old jobs. At the end of 2021, the service provider and hospitality sectors were facing major challenges in enticing people back to these low-paid, heavy-demand jobs, with many positions remaining empty. At the same time, 4.5 million Americans (3 percent of the workforce) voluntarily quit their jobs in November, reflecting both discontent with their current positions and the desire to find better ones. But solving the burnout problem cannot fall to individual workers. The workplace must change. People burn out because their employers have not successfully managed chronic job stressors. We must place a stronger focus on modifying or redesigning workplace conditions. How can job environments be places that help people thrive rather than wearing them down?

People whose work lives got better over the past two years can generally thank personal resources—a comfortable room of one's own—rather than foresight from their employers. But employers can learn a lot from attending to what helped people be more productive and satisfied during this time. For example, workers were less distracted by pointless meetings and open office settings and were able to focus on meaningful tasks rather than being burdened by busywork. Some companies are trying to entice workers with higher pay or time off. Improving job conditions has even more potential for enduring impact.

Work takes up a lot of people's time, talent and potential—and workers are increasingly demanding that it offer a sustainable and rewarding quality of life in return.

Christina Maslach is a professor of psychology at the University of California, Berkeley, and creator of the Maslach Burnout Inventory, a widely used psychological instrument. She and Leiter co-authored the forthcoming book *The Burnout Challenge* (Harvard University Press, 2022).

Michael P. Leiter is an organizational psychologist and president of Michael Leiter & Associates, a consulting firm in Nova Scotia.

Illustration by James Olstein

Nasal Spray Preventives Went into Development

COVID IS CREDITED WITH propelling clinical innovation. But for a disease that seems to start in people's noses, none of the available drugs or vaccines are delivered intranasally. Killing the virus before it travels into our lower airways could prevent serious illness. An intranasal vaccine could do this by stimulating the immune system in the mucus of our noses. And intranasal treatments, such as antibodies or small-molecule antivirals, could stop the virus before it infects enough cells to cause disease. Vaccinated health-care workers, for instance, could take a puff of a virus-killing nasal spray after exposure to protect against breakthrough infection.

So why aren't intranasal pharmaceuticals here yet? Drugmakers default to injectable vaccines and treatments for a few reasons. Our muscles have lots of blood vessels, so injections in arms are perhaps the fastest way to get immune-stimulating vaccines and therapeutic antibodies into the bloodstream. From there these molecules can work their way to the respiratory system (and other systems), where the COVID virus is doing its dirty work. Similarly, pills get absorbed into our circulation quickly. To make existing drugs or vaccines work intranasally may require reformulation and retesting. But a nasal spray might have benefits that injectables and pills do not: direct delivery to the earliest site of infection.

Several nasal vaccines are now in clinical trials. Intranasals for prevention and treatment are also in development. A scientist at the University of Houston, for example, has shown in animal models of COVID that an intranasal antibody spray seems to reduce viral load; the biotech company he cofounded is working toward clinical trials. Depending on how these methods perform, we may get new tools for living amid this pervasive disease.

Megha Satyanarayana is chief opinion editor at *Scientific American* and has reported on COVID-related technologies.

Fault Lines in American Society Got Deeper

The pandemic energized the Black Lives Matter movement—and provoked a dangerous backlash

By Aldon Morris

In 2020, as the bodies piled up, it became clear that people of color were dying at far higher rates than white people. They had the jobs that exposed them to infections, the comorbidities that made them more likely to get very sick, and less ability to access quality health care than white Americans. The toll revealed in very stark ways that racial disparities and racism were alive and well in the U.S.

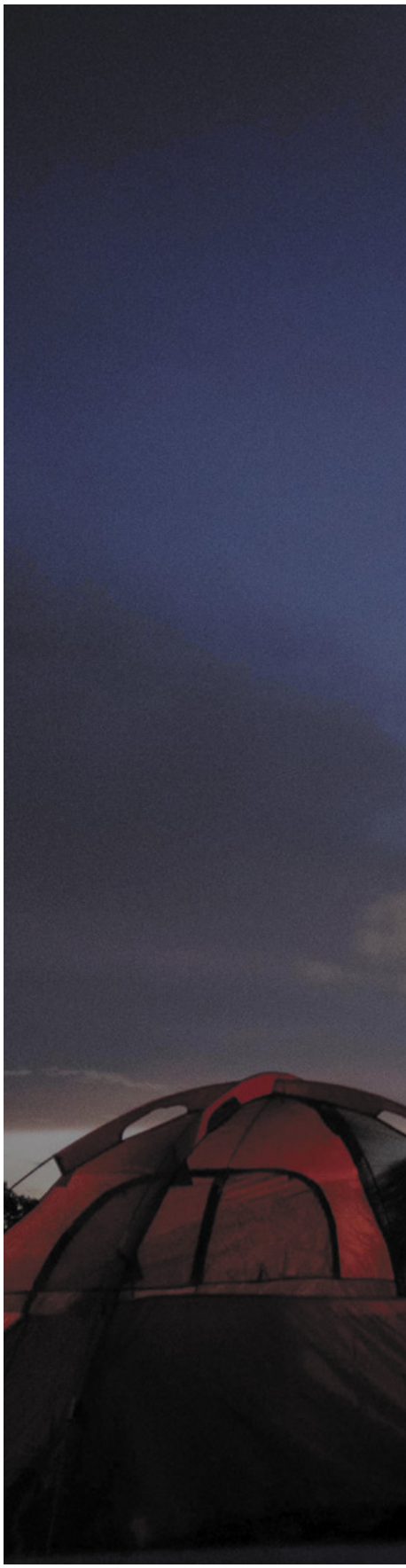
At the same time, police were attacking Black people, and those attacks were being disseminated far and wide via new visual technologies. Just as COVID laid bare the racial disparities, the murder of George Floyd unfolded in front of millions of eyes in a way that made racial oppression undeniable. Not only was the structural racism in American society displayed in all its hideousness, but people were dissecting and debating it across social media in a way that had never been possible before.

For social justice movements to erupt, you need a diagnosis of the problem. No matter how much suffering there is, oppression, inequality and injustice can be thought of as natural. The Bible says, for example, that the poor will always be among us. Some people see it that way—it is just fate. Or defective genes or culture. A real diagnosis was finally on the table, being discussed not only by a few scholars and activists but by Americans at large.

Understanding the depth of the injustice made people angry, and they came out in the streets in unprecedented numbers. In this manner, the pandemic dovetailed with police oppression and technology to energize the Black Lives Matter (BLM) movement. In addition, the pandemic nearly shut down the economy, giving many more people opportunities to protest. During the Civil Rights Movement (CRM), college students were especially available for sit-ins and other protests on so-called T-days—Tuesdays and Thursdays—when they had no classes. But at the height of the pandemic, far more people had the time to join the BLM and other protests. And there was another breakthrough: for the first time in American history, people of diverse classes, races and ethnicities joined a movement against racial oppression.

These protests led to important gains. For the first time, there is serious public deliberation on the disparities in health, schooling, access to universities and wealth that persist along racial lines. The police are more aware of the possibility of being held accountable. And a debate over reparations for slavery has sprung up—something hitherto unthinkable. More broadly, the intersection of the pandemic, police brutality and modern technology has spurred a very vibrant progressive movement in the country and the world.

How lasting the gains will be is far from clear. Worryingly, the massive social justice movements energized countermovements that are determined to halt any progressive changes to American society. The political right has



Carlos Bernate/Redux Pictures

CELEBRATING JUNETEENTH, a day that marks the end of U.S. slavery, residents of Richmond, Va., gathered on June 21, 2020, at a Confederate monument that they have reclaimed. The memorial now honors victims of police brutality and is called Marcus-David Peters Circle, after a man who was shot dead by Richmond police in 2018.

FAR-RIGHT PROTESTERS, including members of the Proud Boys, a neofascist group, marched against COVID vaccine mandates in Manhattan last November. More than two dozen Proud Boys members have been indicted in connection with the attack on the U.S. Capitol on January 6, 2021.

Mark Peterson/Redux Pictures

gathered new strength, to the extent that it threatens to set us back to an era before the Civil Rights Movement. Among the great achievements of the CRM were the 1964 Civil Rights Act and the 1965 Voting Rights Act. What is under attack now? It is precisely the right to vote. Multiple states now have laws restricting the rights of what they call "minority voters," by which they mean voters of color.

The recent Kyle Rittenhouse case, in which a vigilante who shot white people participating in largely Black protests was completely exonerated, is also alarming. In the 1960s segregationists attacked white participants in the CRM, describing them as race traitors. Rittenhouse's assault has similar overtones. Now white people know that not only can conservatives attack them if they participate in protests, but the courts may also side with the attackers. Going forward, will they be willing to risk their lives for a cause that is not directly theirs? And how can we ignore the insurrection of January 6, 2021, when a predominantly white armed mob sought to annul the outcome of the presidential election?

As I see it, a very serious clash is taking place between progressive and conservative forces, between people who are fighting for equality and people who are fighting to maintain the status quo. It is not clear who will triumph. What is clear is that America is at its highest level of polarization in modern history. I can imagine it must have looked something like this prior to the Civil War. We are at a cusp, and we could fall on either side—into the chasm of fascism or into a more hopeful, democratic world.

Aldon Morris is Leon Forrest Professor of Sociology and African American Studies at Northwestern University and a previous president of the American Sociological Association. His landmark books include *The Origins of the Civil Rights Movement* (1986) and *The Scholar Denied: W.E.B. Du Bois and the Birth of Modern Sociology* (2015).

Vaccine Inequality Shut Vulnerable People Out of Plans to Save the Planet

Those with the most at stake were heard the least

By Nnimmo Bassey

For decades a global economic system based on the conversion of nature into profit has been accelerating inequality, environmental destruction and climate change. Hundreds of millions of people are vulnerable to (seemingly) natural disasters, including pandemics caused by the emergence of novel pathogens. By exacerbating xenophobic nationalism and precipitating vaccine apartheid, COVID-19 has intensified these dangerous trends.

People from the Global South have always been underrepresented at international conferences where road maps for the future are etched. Now the barriers to participation are prohibitive. With the voices of those worst impacted by biodiversity loss and climate change being muffled by COVID-related constraints, corporate and other winners of the neoliberal order are seizing decision-making processes on these crucial and urgent issues, to the detriment of people and the biosphere.

The one major event since the pandemic began that was not impacted by COVID-related restrictions was the United Nations Food Systems Summit, held on September 23, 2021. That is because it was shunned by more than 300 civil-society groups representing scientists, farmers and Indigenous peoples for being at best indifferent, and at worst hostile, to their views. As the Alliance for Food Sovereignty in Africa (AFSA), which represents more than 200 million African food producers and others, observed, the summit had been structured to give undue influence over global agricultural systems to multinational corporations and their allies. As such, the summit was bound to "echo the business-as-usual, quick-technofix policy prescriptions of the agribusiness agenda," AFSA argued. The boycott, along with an alternative summit that focused on food sovereignty, may have fended off what many observers feared was an attempt by global capital to control the future of agriculture.

But COVID constraints ensured that civil society was barely represented at the U.N. Biodiversity Conference last October, where delegates from 195 nation-states and the European Union met to discuss a plan to protect 30 percent of the planet by 2030. Many Indigenous groups, who have ample reason to fear violent eviction from and dispossession of the ecosystems they protect as nation-states use "30 by 30" as an excuse to seize their territories, opposed the plan. But with their participation limited to brief online appearances, they were unable to explain their concerns or provide their alternative visions for biodiversity conservation.

Most disastrously impacted by the pandemic was COP26, the 26th Conference of Parties to the U.N. Framework Convention on Climate Change, held in Glasgow, Scotland, last October–November. Climate activists condemned the conference as the most exclusionary COP ever, with delegates facing severe COVID-related restrictions for entering the U.K. and accessing the venue. The COP26 Coalition, representing grassroots activists from around the world, announced as the conference began that two thirds of the thousands of delegates it represented had given up on attending it.

It was double trouble for delegates from nations red-listed for COVID, who had to quarantine in hotels for days on arrival in the U.K. After passing the hurdles of obtaining visas and covering expensive travel costs, many negotiators were excluded from the conference halls and had to watch the proceedings from screens in their rooms—which they could just as well have done from their home countries. COVID protocols required some side events to have only panelists speaking before

Nnimmo Bassey is director of the Health of Mother Earth Foundation, based in Nigeria. His books include *To Cook a Continent: Destructive Extraction and the Climate Crisis in Africa* (Pambazuka Press, 2012).

Illustration by Hanna Barczyk

cameras, excluding the possibility of discussion. And with only two seats assigned for national delegates in each negotiating room, officials were denied access to needed technical backup.

All told, the fossil-fuels sector had an outsize influence on a conference that should have been about curtailing its damaging activities. There were a whopping 503 representatives of fossil-fuel companies, more than any nation's delegation, and no participants at all from 11 out of 14 Pacific Island states, which are the worst affected by climate change. The voices of those living in sacrifice zones and demanding real climate action—keeping fossil fuels in the ground—were shut out. The outcome was a lot of hot air, which did not even include a pledge to phase out coal.

Disproportionately impacting those who already suffer the most and will continue to suffer the most, pandemic-era exclusions mean that multilateral events can no longer be counted on to solve the existential challenges confronting the world. Instead COVID is enabling the entrenchment of exploitative and false solutions to impending catastrophes.

Illustration by James Olstein

Oxygen Shortages Delayed Rocket Launches

WHEN FLORIDA had a COVID surge, it caused a shortage of liquid oxygen for people in intensive care. Part of the supply chain for liquid oxygen was moved over to compensate for it, and that impacted about half a dozen rocket launches. Florida was the source of the need for oxygen, but it pulled resources from the entire country.

We [United Launch Alliance] had a planned launch going off the West Coast, out of Vandenberg Space Force Base in California. We had seen the issue starting in Florida, and we stocked up on liquid oxygen ahead of time. But we were surprised when we could not get liquid nitrogen. By then all the trucks that could move cryogenic liquids, and the people who could drive them, had gone to Florida.

It was kind of a funny opportunity for SpaceX and us to almost help each other. I did not have any nitrogen on the West Coast, and they had a shortage of liquid oxygen on the East Coast. I think Gwynne Shotwell [president and chief operating officer of SpaceX] and I had a conference somewhere together, and I said, "Hey, I've got this giant tank of liquid oxygen that was for a launch several months away. I'd be happy to make that available to you." She replied, "Well, I've got a bunch of nitrogen out on the West Coast that I could loan you." We were arranging to trade this material when our respective teams solved the problems locally, so we ended up not having to do it. I was actually a little disappointed because it would have been fun.

I doubt we will face a crisis quite that acute again, but it did reveal the weak links in that supply chain. We had a shortage of drivers with the special training and certification to drive liquid cryogenics around. Now that we understand that this is a vulnerability, we have more people certified than are needed at any time.

Tory Bruno is an aerospace engineer and chief executive officer of United Launch Alliance, one of the world's largest space launch companies.

Conspiracy Theories Made It Harder for Scientists to Seek the Truth

Virus-origin stories have always been prone to disinformation, and the "lab-leak hypothesis" threatens research—and lives

By Stephan Lewandowsky, Peter Jacobs and Stuart Neil

WHENEVER SCIENTIFIC FINDINGS threaten people's sense of control over their lives, conspiracy theories are never far behind. The emergence of novel viruses is no exception. New pathogens have always been accompanied by conspiracy theories about their origin. These claims are often exploited and amplified—and sometimes even created—by political actors. In the 1980s the Soviet KGB mounted a massive disinformation campaign about AIDS, claimitng that the U.S. Central Intelligence Agency had created HIV as part of a biological weapons research program. This campaign benefited from a "scientific" article written by two East German scientists that ostensibly ruled out a natural, African origin of the virus, an explanation favored by Western scientists that has since been unambiguously established. In African countries, where many scientists and politicians considered the hypothesis of an African origin of AIDS to be racist, the disinformation campaign fell on fertile ground. Ultimately the conspiracy theory was picked up by Western media and became firmly entrenched in the U.S. Similarly, when the Zika virus was spreading in 2016 and 2017, social media was awash in claims that it had been designed as a bioweapon.

From the beginning, the genomic evidence led most virologists who were investigating SARS-CoV-2 to favor a zoonotic origin involving a jump of the virus from bats to humans, possibly with the help of an intermediate host animal. But considering the anxiety-provoking upheavals of the pandemic, it came as no surprise that the virus inspired conspiratorial thinking. Some of these theories—such as the idea that 5G broadband rather than a virus causes COVID or that the pandemic is a hoax—are so absurd that they are easily dismissed. But some theories came with a patina of plausibility. Speculation that the SARS-CoV-2 virus was engineered in the Wuhan Institute of Virology (WIV) in China was facilitated by the physical location of the institute: it is right across the Yangtze River from the Huanan market where many of the earliest cases of COVID were detected. The Chinese government's denial that markets sold live wild animals also roused suspicion, even though such wares were always suspected and have since been confirmed.

The so-called lab-leak hypothesis gained sufficient rhetorical and political force that President Joe Biden instructed the U.S. intelligence services to investigate it. Although the interagency intelligence report update, declassified in October 2021, dismissed several popular laboratory-origin claims—including that the virus was a bioweapon and that the Chinese government knew about the virus before the pandemic—it was unable to unequivocally resolve the origin question.

Does this mean that proponents of the lab-leak hypothesis uncovered a genuine conspiracy that will be revealed by persistent examination? Or is the lab-leak rhetoric rooted in conspiracy theories fueled by anxiety over China's increasing prominence on the world stage or in preexisting hostility to biotechnology and fear over biosecurity? And what is it about the conditions of the past two years that made it so difficult to know?

ZOONOTIC ORIGINS

THE OSTENSIBLE LAB-LEAK hypothesis is not a single identifiable theory but a loose constellation of diverse possibilities held together by the common theme that Chinese science institutions—be it the WIV or some other arm of the Chinese government—are to blame for the pandemic. At one end is the straightforward possibility of WIV lab personnel being infected during fieldwork or while culturing viruses in the lab. Scientifically, this possibility is challenging to disentangle from a zoonotic origin that followed other

GREATER HORSESHOE BAT (*Rhinolophus ferrumequinum*). Research shows a clear zoonotic path between bats and the SARS-CoV-2 virus.

Stephen Dalton/Minden Pictures

FEAR AND BLAME: A table of T-shirts with antimask slogans accompanied a protest outside the Jet Blue headquarters in Queens, N.Y., on October 27, 2021. Protesters were pushing back against the airline's COVID vaccine mandate and mask policies. The instability created by the pandemic is fertile ground for conspiracy theories.

pathways and is therefore difficult to rule out or confirm. At the other extreme are the assertions that SARS-CoV-2 was designed and engineered by the WIV, perhaps as a bioweapon, and was released either accidentally or as a biological attack. This possibility necessarily entails a conspiracy among WIV scientists—and potentially many others—to first engineer a virus and then cover up its release. Scientific investigation of the genomic and phylogenetic evidence *can* help us determine whether SARS-CoV-2 was genetically engineered.

SARS-CoV-2 is a member of a subgenus of the betacoronaviruses called the sarbecoviruses, named after their prototype member, SARS-CoV-1, which caused the SARS epidemic in 2002 and 2003. The zoonotic origin of SARS-CoV-1 has been firmly established by research that also showed that the bat sarbecoviruses pose a clear and present danger of pandemic overspill from bats to humans.

One key feature of sarbecoviruses is that they undergo extensive amounts of recombination. Parts of their genomes are being regularly swapped at a rate that implies a vast ecosystem of these viruses is circulating, most of which have not been discovered. The area of the genome that is most likely to recombine is also the area that encodes the "spike" proteins—the very proteins that play a crucial role in initiating an infection. Many sarbecoviruses encode spike proteins that can bind to a wide range of mammalian cells, suggesting that these viruses can easily move back and forth between different species of mammals, including humans.

SARS-CoV-2 is not as virulent as SARS-CoV-1, but it is transmitted far more easily between people. Two of the most prominent features of the SARS-CoV-2 spike are its receptor-binding domain (RBD), which binds very tightly to human ACE2, the protein that allows it to enter lung cells, and the so-called furin cleavage site (FCS). This site divides the spike protein into subunits. The FCS is present in many other coronaviruses, but so far SARS-CoV-2 is the only sarbecovirus known to include it. It allows the viral spike protein to be cut in half during its release from an infected cell, priming the virus to spread to new cells more efficiently.

The RBD and FCS are central to initial virological arguments by expert proponents of the lab-leak hypothesis. Such arguments are based on the supposition that neither the RBD nor the FCS "appears natural" and therefore that they can only be the product of lab-based engineering or selection. Nobel laureate David Baltimore, an early proponent of the lab-leak hypothesis, referred to the FCS as a "smoking gun" that points to a lab origin.

Although an unusual feature of a virus can legitimately stimulate further inquiry, this argument is reminiscent of the creationist claim that humans must have been "intelligently designed" because we are seemingly too complex to have evolved by natural selection alone. This logic is fundamentally flawed because complexity does not license dismissal of the overwhelming evidence for natural selection and, by itself, does not mandate any design, intelligent or otherwise. Likewise, labeling the RBD or the FCS "unnatural" does not mandate lab-based engineering, and, critical-

Mark Peterson/Redux Pictures

ly, it does not license the dismissal of the growing evidence for a zoonotic origin.

Recently, for example, bat colonies on the border between Laos and China were discovered to carry sarbecoviruses that have RBDs almost identical to those of SARS-CoV-2 in both sequence and ability to enter human cells. This finding refutes the claim that SARS-CoV-2's binding affinity in humans is unlikely to have a natural origin.

Similarly, although some lab-leak proponents contend that the lack of an FCS in the closest relatives of SARS-CoV-2 is indicative of its manual insertion in a lab, very recent evidence from SARS-CoV-2 population sequencing suggests that the insertion of new sequences from human genes next to the FCS can be detected. Moreover, the closest relative of the SARS-CoV-2 spike in the Laotian bat viruses would require the addition of only a single amino acid to generate a putative FCS. Thus, in a species where it would have a major selective advantage, it would probably be very easy for some of these bat coronaviruses to rapidly evolve an FCS.

This research sketches a clear zoonotic path to the emergence of the RBD and FCS. Although some evolutionary gaps along this path persist, their number and size have been dwindling. A detailed analysis in late 2021 further strengthened the link to the Huanan markets as the point of origin of the virus and the initial source of community transmission. This rapidly growing body of evidence for a zoonotic origin of SARS-CoV-2 creates increasing difficulties for the lab-engineering hypothesis.

CONSPIRATORIAL COGNITION

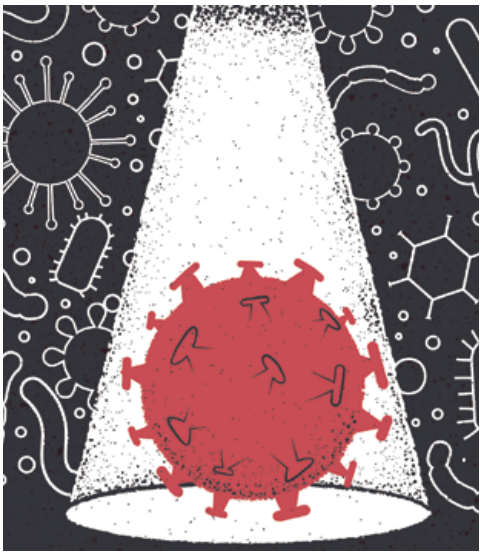
IN NORMAL SCIENTIFIC INQUIRY, as evidence emerges, the remaining space for plausible hypotheses narrows. Some facets continue to be supported, and others are contradicted and eventually precluded altogether. Some of the strongest advocates for a lab origin for SARS-CoV-2 changed their views as they learned more. Baltimore, for instance, withdrew his "smoking gun" comment when challenged by additional evidence, conceding that a natural origin was also possible. Revising or rejecting failed hypotheses in light of refuting evidence is central to the scientific process. Not so with conspiracy theories and pseudoscience. One of their hallmarks is that they are self-sealing: as more evidence against the conspiracy emerges, adherents keep the theory alive by dismissing contrary evidence as further proof of the conspiracy, creating an ever more elaborate and complicated theory.

There is perhaps no better example of self-sealing cognition than the contortions of climate change denial that erupted after the 2009 "Climategate" controversy. At that time thousands of documents and e-mails were stolen from the Climatic Research Unit of the University of East Anglia in England and made public right before the United Nations climate conference in Copenhagen. The e-mails were cherry-picked by deniers for sound bites that, when taken out of context, seemed to point to malfeasance by scientists. Ultimately nine independent inquiries around the world cleared the scientists of misconduct, and nine of the warmest years ever measured have occurred in the 11 years since Climategate.

Undeterred by the exonerations, climate deniers—including at least one U.S. congressperson—branded the inquiries as a "whitewash." The volume of activity on skeptics' Web sites relating to the hacked e-mails continued to increase for at least four years, long after the public had lost all interest in the confected scandal. It was only in late 2021 that one of the principals making unfounded accusations against the scientists apologized for his role.

The e-mails were publicly misrepresented as a result of an unsolved hack, but top scientists and health officials also have seen their correspondence become public through Freedom of Information Act (FOIA) requests by groups with long histories of attacking scien-

Illustration by James Olstein



Pandemic-Era Research Paid Off—and Will for Years

AFTER COVID APPEARED, a huge number of virologists, biochemists, cell biologists and immunologists shifted their work to the coronavirus, and because of that, the world got what it was desperately hoping for: a vaccine, in record time. Everything worked out better than we could have dreamed—several parallel vaccines, all with high efficacy. We are seeing antiviral treatments roll out, too.

Scientists can leverage all this effort to better understand other viruses and diseases. Never before have we been able to simultaneously test multiple vaccine platforms, head-to-head, in massive global clinical trials. Usually you are lucky if you get one vaccine to trial, and if it fails, you will not really know whether the concept or just the one platform failed.

I anticipate that scientists will use all the COVID research infrastructure to build more vaccines against other pathogens, such as cytomegalovirus and respiratory syncytial virus, and to create mRNA vaccines for flu. Furthermore, most of the coronavirus research has been collaborative. That will stick with people. It will make future work pay off more than if all those individuals went back to just their own niches.

This is not going to be the last spillover pandemic we see. It is not going to be the last public health crisis. I hope that COVID has given the public a sense of how important it is to have sustained investment in science. We don't know what discovery we will stumble on that will be the lifesaver the next time.

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tists. The anti-GMO organization U.S. Right to Know honed its FOIA tactics against food scientists before turning its sights on virologists. Despite e-mails clearly showing virologists considering but ultimately rejecting various claims about SARS-CoV-2 being engineered, lab-leak proponents tend to selectively quote messages. They cast virologists as either never having given lab scenarios fair consideration or—on the other extreme—believing in a lab origin all along and deliberately lying about it. People who push conspiracy theories often toggle between opposing claims as the rhetorical need arises.

Another e-mail-centered theory turned on the idea that the WIV had originally housed viruses closely related to SARS-CoV-2, presumably including the natural virus from which it had been engineered. The theory further held that the WIV suspiciously delayed publication of a paper that had been submitted in October 2019 until 2020. At some point after the paper's submission with the "true" sequences, the argument went, the WIV halted its publication and altered the sequence information in furtherance of the cover-up.

Another FOIA effort was marshaled to reveal the discrepancy between the "real" sequences submitted to the journal and those that were pawned off on the unsuspecting public. Unfortunately for this conspiracy claim, the FOIA results revealed that the submitted paper's sequences were exactly what the scientists publicly said they were. The self-sealing nature of conspiratorial reasoning being what it is, however, some proponents of the lab-leak hypothesis remain undeterred and believe the "real" sequences must exist in some as yet undocumented draft created before the submitted version.

The self-sealing dynamic can produce even more elaborate epicycles to resist falsification. Until earlier this year, the closest known relative of SARS-CoV-2 was a virus called RaTG13, which is known to have been held by the WIV in a collection of bat swab samples. RaTG13 is more than 96 percent identical to SARS-CoV-2. It is likely that this virus genome was sequenced from a swab taken in 2013 from bats in an abandoned mine shaft in Mojiang, a county in China's Yunnan province. RaTG13's centrality to many lab-leak claims stemmed from its putative role as the "backbone" from which SARS-CoV-2 was allegedly engineered.

Being closely related to SARS-CoV-2 and being present in the lab at the WIV made RaTG13 a perfect candidate for a precursor that was engineered into SARS-CoV-2. In the short time since the pandemic took hold, however, several related viruses have been discovered that are closer in sequence to SARS-CoV-2 over much of the genome. Moreover, despite being related to SARS-CoV-2, RaTG13 has been found to occupy a separate phylogenetic branch. SARS-CoV-2 is not descended from RaTG13; rather the viruses share a common ancestor from which they diverged an estimated 40 to 70 years ago, meaning it could not have served as a backbone for an engineered SARS-CoV-2.

Rather than accepting this contrary evidence, some lab-leak advocates resorted to self-sealing reasoning that deviates from standard scientific practice: They began to argue that RaTG13 was not a natural virus itself but rather had been edited or in some way fabricated in an effort to hide the "true" backbone of SARS-CoV-2 and thus its engineered nature. The virus from Laos showing that SARS-CoV-2's RBD and the efficiency of its binding to human receptors are not unique—providing strong support for a zoonotic origin—is thus reinterpreted to mean that the WIV obtained and used a similar but so far secret virus from Laos to design SARS-CoV-2. This ad hoc hypothesis is accompanied by the expectation that the burden is on the WIV to prove it did not have that secret virus—a reversal of the expected burden of proof that runs counter to conventional scientific reasoning.

Such pivots are potentially immune to further evidence. Just as there are effectively unlimited "gaps" between transitional fossils that are exploited by creationists, so, too, are there effectively unlimited potential natural viruses from which SARS-CoV-2 must have been engineered that have been kept hidden by the WIV. Or else unnatural viruses the WIV might have engineered to make SARS-CoV-2's features seem naturally evolved.

More and more relatives and antecedents of SARS-CoV-2 are bound to be discovered, and adherents of the lab-leak hypothesis will face a stark choice. They can abandon, or at least qualify, their belief in genetic engineering, or they must generate an ever increasing number of claims that these relatives and antecedents, too, have been fabricated or engineered. It is likely that at least some people will follow the latter path of motivated reasoning, insisting that secretive Chinese machinations or an unnatural manipulation of biology is responsible for the virus's origin.

Motivated reasoning based on blaming an "other" is a powerful force against scientific evidence. Some politicians—most notably former President Donald Trump and his entourage—still push the lab-leak hypothesis and blame China in broad daylight. When Trump baldly pointed the finger at China in the earliest days of the pandemic, unfortunate consequences followed. The proliferation of xenophobic rhetoric has been linked to a striking increase in anti-Asian hate crimes. It has also led to a vilification of the WIV and some of its Western collaborators, as well as partisan attempts to defund certain types of research (such as "gain of function" research) that are linked with the presumed engineering of SARS-CoV-2. There are legitimate arguments about the regulation, acceptability and safety of doing gain-of-function research with pathogens. But conflating these concerns with the fevered discussion of the origins of SARS-CoV-2 is unhelpful. These examples show how a relatively narrow conspiracy

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IN THE LAB: The Wuhan Institute of Virology in China, shown here in a 2017 photograph, has been a leader in infectious disease research for many years. Some scientists identified with COVID research have been harassed by proponents of SARS-CoV-2 conspiracy theories.

Feature China/Barcroft Media via Getty Images

theory can expand to endanger entire groups of people and categories of scientific research—jeopardizing both lives and lifesaving science.

A LONG TAIL

SCIENTISTS NO LONGER DEBATE the fact that greenhouse gas emissions from the burning of fossil fuels are changing Earth's climate. Although this scientific consensus on climate change was established 20 years ago, it has never stopped influential politicians from calling climate change a hoax. Climate denial is a well-organized disinformation campaign to confuse the public in pursuit of a clear policy goal—namely, to delay climate mitigation.

The markers of conspiratorial cognition are universal, whether the subject is climate denial, antivaccination propaganda or conspiracies surrounding the origin of SARS-CoV-2. It is critical to help the media and the public identify those markers. Unlike the overwhelming evidence for climate change, however, a zoonotic origin of SARS-CoV-2 is likely but not yet conclusive. This is not a sign of nefarious activity and is, in fact, entirely unsurprising: It took 10 years to pin down the zoonotic source of SARS-CoV-1. The Zaire Ebola virus has never been isolated from bats, despite strong serological evidence that they are the likely reservoir.

Plausible routes for a lab origin *do* exist—but they differ from the engineering-based hypotheses that most lab-leak rhetoric relies on. The lab in Wuhan could be a relay point in a zoonotic chain in which a worker became infected while sampling in the field or being accidentally contaminated during an attempt to isolate the virus from a sample. Evidence for these possibilities may yet emerge and represents a legitimate line of inquiry that proponents of a natural origin and lab-leak theorists should be able to agree on. But support for those claims will not be found in self-sealing reasoning, quote mining of e-mails or baseless suggestions. Ironically the xenophobic instrumentalization of the lab-leak hypothesis may have made it harder for reasonable scientific voices to suggest and explore theories because so much time and effort has gone into containing the fallout from conspiratorial rhetoric.

Lessons from climate science show that failure to demarcate conspiratorial reasoning from scientific investigation results in public confusion, insufficient action from leadership, and the harassment of scientists. It even has the potential to impact research itself, as scientists are diverted into knocking back incorrect claims and, in the process, potentially ceding them more legitimacy than warranted.

We must anticipate that this type of dangerous distraction will continue. Scientists identified with COVID research are suffering abuse, including death threats. When the Omicron variant emerged, so did nonsensical conspiracy theories that it, too, was an escaped, human-altered virus, originating from the lab in South Africa that first reported it. One can only assume that further variants may likewise be blamed on whichever research lab is closest to the location of discovery. We are not doomed to keep repeating the mistakes of past intersections of science and conspiracy should we choose to learn from them instead.

FINDING HAPPINESS in the after times.

Photograph by Peter Turnley

COVID Is Here to Stay

How do we live with it?

By Christine Crudo Blackburn

COVID-19 WILL CONTINUE IN PANDEMIC FORM, surging in one or more regions and disrupting daily life, until the world reaches herd immunity. With that, most scientists say, the SARS-CoV-2 virus will become endemic—always present but transmitted among people at modest, predictable rates. After several years the infamous 1918 influenza pandemic made that transition, and the virus is still circulating, 104 years later, in mutated strains. Almost all influenza A infections since 1918 have descended from that strain.

As the endemic stage arrives, people of all ages will be eligible for the COVID vaccine, and hospitals and pharmacies will be well supplied with effective treatments for infection. At that point, it might be wise for public health officials to treat COVID as a respiratory disease that is more dangerous than a cold, similar to how we handle influenza and cytomegalovirus (CMV)—by evaluating distribution of a seasonal vaccine, tracking hospitalization rates and educating the public about current risk. We don't yet know if COVID will lead to higher rates of long-term complications than those diseases do, so other precautions may be necessary.

In this future, routine testing might become part of everyday life. People with imperceptible symptoms who test positive would know to wear masks and isolate from others. If we could develop similar tests for influenza and CMV and make them cheaply available to everyone, everywhere, society could end up even safer against infectious respiratory diseases than it was before COVID arrived.

Even if COVID cases declined significantly, it's unlikely the virus would burn out. As long as it was still spreading in animals, it could spill over into humans at another time. Nature is always surprising us. A future, reemergent SARS-CoV-2 could be either less or more transmissible, less or more lethal. The Omicron variant that spread this winter taught us to expect the unexpected. Our world still has much to do to become better prepared for new variants—as well as whatever novel virus emerges next.

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NONFICTION

Tending Our Musical Planet

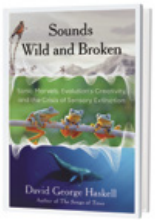
What do we lose when the diversity of Earth's noise is drowned out by humans?

By Kathleen Dean Moore

In the beginning was silence. The big bang made not a whimper, let alone a bang. That is because the universe was born in a sea of nothingness without the space and time where sound can exist. In the end, the universe will be reduced again to silence, either collapsed into a singularity or expanded into cold, flat uniformity. But now, suspended between the beginning and the end, Earth sings and rings and warbles: a musical planet, maybe the only one in the universe. As David George Haskell tells it in his captivating new book, *Sounds Wild and Broken,* it is astonishing good fortune—and a fearsome responsibility—to be given this music and the ears to hear it with.

At first stone, water, lightning and wind sang alone. After 3.5 billion years came the tremolo of cilia on the earliest cells. Eventually insects joined the swelling chorus, with "rasping mouthparts, wheezing air tubes, drumming abdomens, and wings shaped to crackle and snap as they fly." Lacking a syrinx, dinosaurs could not exactly sing, but they still shook the Cretaceous forests with rubbing scales, snapping jaws, whip-cracking tails and a sound like the "strangled belch of ruddy ducks." The asteroid that brought that cacophony to a cataclysmic end made room for the expansion of fluting birds. "In birdsong," Haskell writes, "we hear the evolutionary legacy of renewal after great loss." And what a renewal it was: roaring whales, bellowing elephants, tootling children and moaning freight trains. The whole Earth shimmered with sound.

The science stories in *Sounds Wild and Broken* offer one delight after another. What a joy to know that elephants can "hear" with special sensory pads on their feet, picking up the rumbling voices in the ground, and that birds in cities sing at pitches higher than those of their country cousins, choosing frequencies less masked by the city's dull roar. Humans' teeth, which once met in a predator's vise, slid into an overbite as people turned to the softer foods that agriculture provided, shaping sounds such as "farm," "vivid," "fulvous" and "favorite." We hear Earth's sounds with ears that evolved from repurposed fish gill bone, sometimes in theaters designed to match the acoustic properties of forests. But why don't worms sing? "Predation is a powerful silencer," Haskell explains. "Animals whose lives are sedentary or slow and whose bodies lack weaponry are voiceless."



Sounds Wild and Broken: Sonic Marvels, Evolution's Creativity, and the Crisis of Sensory Extinction
by David George Haskell. Viking, 2022 ($29)

Earth's musical variety show testifies to the boundless creativity of evolution. As with improvisational jazz, order, narrative, complexity and beauty emerge from the interacting voices of Earth and its creatures. Here, in the bittern's croak, in the turtle's cluck and whine, in Miles Davis's trumpet, is "evolution drunk on its own aesthetic energies." Music returns us to direct experience—a time before language, before tools, before humans began to imagine themselves as separate from Earth's community and outside its limits. We are enticed by beauty to listen to the sounds that remind us of our membership in the intricate, interactive orchestras.

As the book develops, it becomes clear that all this sonic science is not merely reporting. It is bearing witness to a terrible moral and ecological crisis. With lives powered by sequential explosions of gas and oil, humans make deafening noise. In our industrial empires, we are constantly assaulted by whirring tires, booming woofers, pounding engines and "a smeared canopy of airline noise." The burden of noise pollution in cities is unjustly distributed, reinforcing race, class and gender inequities. The cacophonies indirectly and directly harm animals, of course, interfering with their reproductive patterns, reducing their habitats, fragmenting their communities and sometimes killing them outright. Haskell cites the U.S. Navy's high-intensity sonar blasts, which panic whales: "Sound bleeds them to death from within."

Reckless human enterprise is killing Earth's wild songmakers at alarming rates, using poisons, bulldozers, forest-clearing fires and industrial-scale pillage of prey species. Readers who are at least 50 years old live in a world that is less than half as song-graced as when they were born. In that half a century, a third of North American songbirds have disappeared. Ninety percent of large fish are gone. Sixty percent of bellowing, squeaking mammals are extinct. All lost, in our lifetimes, on our watch.

What do we lose when we lose their songs? Listening to the song stories of other species can make us better members of life's community, Haskell argues. They signal interdependence and resilience, deep kinship, shared beginnings and likely a shared fate. So they are the "foundations not only of delight," he writes, "but of wise ethical discernment."

Illustration by London Ladd

NONFICTION

Secrets of Bird Scent

A delightfully meandering account of a scientist's curiosities

By Ryan Mandelbaum

The Secret Perfume of Birds: Uncovering the Science of Avian Scent
by Danielle J. Whittaker.
Johns Hopkins University Press, 2022 ($27.95)

Vultures and albatrosses find food using scent cues. Scent influences the mating behaviors of dark-eyed juncos. But when a scientist offhandedly told Danielle J. Whittaker that "birds can't smell," she discovered that most ornithology textbooks rarely mention avian olfaction and that this misconception was a common one. The realization changed the course of her life.

Unexpected changes are a regular occurrence for Whittaker, who has "never been particularly good at long-term planning." In *The Secret Perfume of Birds,* Whittaker humorously recounts her own journey from office worker to primatology Ph.D. student to postdoc studying bird behavior to Roller-Derby-ing managing director of a National Science Foundation Science and Technology Center. One constant throughout the book is that things rarely happen as she expects them to, at times making her question everything she already knows.

After all, the study of avian olfaction is not straightforward. Birds daily cover their feathers in a substance called preen oil taken from a gland at the base of their tail. This oil contains odorous compounds—in the case of the dark-eyed junco, it smells like leaf litter and soil. Studying how this odor arises and its purpose in bird behavior combines the chemistry of smelly compounds, the biology of bacteria and even the genetics of human immune systems. In turn, scientists study this topic with a funhouse of experiments that involve capturing juncos in the Appalachians, sequencing DNA and surveying human women after they smell men's worn T-shirts. Most of these experiments, in Whittaker's view, have yielded as many questions as answers.

Though not a birder herself, Whittaker presents a new lens for bird lovers to view common species, and she had me wondering what some of my favorite birds smell like. But the book's greatest success is how it depicts the reality of doing science. Experiments are difficult and do not always return clean answers. Scientists carry biases that can influence their results; for example, focusing on the stereotypically flashier male birds instead of the females can lead researchers to overlook important details. It takes a diverse group of perspectives—and the humility to reconsider our biases—to truly understand our world.

mwalker973/Getty Images

IN BRIEF

Animal Revolution
by Ron Broglio.
University of Minnesota Press, 2022 ($88)

In a chapter appropriately entitled "Manifesto," English professor Ron Broglio begins his book of speculative nonfiction by proclaiming that the animal revolution, while it "will not be televised, mediated, or co-opted by our representation systems," is nonetheless afoot. The following chapters present a compelling argument that pairs "untold incidents of animals in revolt" with theoretical frameworks that reveal their revolutionary power: Kantian subjectivism explicates the hordes of jellyfish that choke nuclear reactors, Derridean radical hospitality unpacks the sheep that commando roll over cattle grates. Broglio calls for all comrades to join the revolution. *—Dana Dunham*

Journey of the Mind: How Thinking Emerged from Chaos
by Ogi Ogas and Sai Gaddam.
W. W. Norton, 2022 ($30)

Questions of consciousness often veer into philosophical territory that cannot be resolved, let alone approached by science. *Journey of the Mind* is a more unusual take. The co-authors' backgrounds in computational neuroscience and machine learning inform their premise that behaviors can be broken down into modules of sensors and doers in the same way proteins are made of peptides and amino acids. The stars of the book are its illustrated diagrams of minds, beginning with "Archie" the haloarcheon and progressing to "Captain Buzz" the fruit fly and eventually to frogs, monkeys and humans. *—Maggie Brenner*

The Kaiju Preservation Society
by John Scalzi. Tor, 2022 ($26.99)

John Scalzi's stand-alone adventure novel is a fun throwback to Michael Crichton's 1990s sci-fi thrillers. When the first COVID wave hits New York City, a food-delivery driver named Jamie Gray joins a team of scientists at a secret facility in Greenland, where they travel to an alternative version of Earth populated by mountain-sized creatures called Kaiju, like those familiar from Japanese films. But other people with less scientific goals have found their way there as well. In an author's note, Scalzi describes the book as a "pop song," and he's right—there are no cerebral messages about animal rights or nuclear proliferation. Written with the brisk pace of a screenplay, it's as quippy as a Marvel movie and as awe-inspiring as *Jurassic Park. —Adam Morgan*

Healthy Skepticism

Popular notions, such as a woman's fertility dropping at age 30, are overblown

By Naomi Oreskes

Why do fitness device makers claim you need to take 10,000 steps every day? Do you also really need to drink eight glasses of water daily? The scientific basis for popular health claims is often thin. A piece in the *New York Times,* for example, notes that the idea of 10,000 steps was based more on marketing—it was the name of an early pedometer—than science. Data point to clear benefits from moderate exercise—perhaps 7,000 steps or so but not necessarily more.

Often popular wisdom turns out to be only sort of true. The emphasis on so many steps is one instance. Glasses of water is another. If you let yourself get too thirsty, you may be tempted to reach for sodas or sugary coffee drinks, and that's not good. But a scientific review in 2002 found "no scientific studies" that support the eight-glass claim for healthy adults in a temperate climate. That doesn't mean it's wrong, but it does mean we probably shouldn't worry if we drink only six.

It's worthwhile to dig a bit into often heard health maxims before accepting them literally. You can sometimes find a nugget of truth that has become seriously exaggerated, or you discover that a claim stems from outdated and poorly applied evidence. The latter is what happened with a famous and specious claim about female fertility.

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).

For decades women have heard distressing warnings about their "biological clocks." We have been repeatedly told that fertility drops dramatically after age 30, so people who want children either need to get moving or else freeze their eggs. Embryo freezing is now a big business, and discussions of it are commonplace among young professional women. Pregnancy, and age-linked anxiety about it, also occurs among transgender and nonbinary people.

But, as Jean M. Twenge reported in 2013 in the *Atlantic,* the claim is based on very sparse data, much of them of dubious quality or relevance. The notion stems largely from a 2004 paper based on records from 1670 through 1830. Many things have changed since then, including medical care and nutrition. In wealthier nations, people are now healthier overall and likely to be more fertile for longer periods of their lives. Systematic data collected by the National Center for Health Statistics demonstrate that from 1980 to 2002 fertility rates for women aged 30 and older were going up. It is also worth noting that when infertility treatments started to become more common and more clinics began opening in the 1980s and 1990s, alarms over biological clocks were being sounded by this growing industry with a self-interest in the matter.

Despite the importance of childbearing to so many people—and although infertility treatments are costly, have only modest success rates and are not risk-free—the sad fact is that robust studies of age-dependent infertility are scant. The data we do have tend to show that although fertility does decline slightly at older ages, most women continue to be fertile well into their 30s, and for many people that is a good time to have children. There's a long-standing cultural tendency to blame infertility on women, but when a couple is infertile it is equally likely that the cause can be traced to the man. Male infertility also declines with age, but how often do you hear warnings about the male biological clock?

Like the female clock or the 10,000 steps, many health beliefs have shallow and flimsy roots. But sometimes the wisdom of the crowd is supported by facts: most of us do need around eight hours of sleep a night, for instance. So where does this leave someone trying to make sense of what they hear or read?

Well, for one thing, people should be skeptical of any large claim based on one study. Good science requires building a multifaceted and detailed case, which takes time and is almost never achieved in a single piece of research. The online medical library PubMed.gov enables people to find out if a subject is well studied or not. And the National Institutes of Health has a medical consensus program that has published more than 160 statements on various diseases and their treatments. Some of them are actually readable, and none relies solely on data from more than a century ago. 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

MARCH

1972 Surprise: Mars Volcano

"Mars continues to surprise the investigators associated with Mariner 9, which has been in orbit around the planet since November 13. Perhaps the most spectacular feature is a volcanic cone at least 300 miles in diameter at the base, making it larger than any comparable feature on the earth. Close-ups of the sides of the volcano show a lineated texture almost certainly produced by the flow of lava. The volcano coincides with a circular feature identified on maps since 1879 as Nix Olympica. In pictures returned by Mariner 6 and Mariner 7 it appeared to be a giant crater about 300 miles in diameter; now it is seen to be a cone at least four miles high."

1972

1922

1872

Computer Logic

"In a major effort to build a computer that is easier to work with, the Fairchild Camera and Instrument Corporation has designed a new computer system in which a large fraction of the programming tasks normally assigned to software are handled by hardware, that is, by logic incorporated directly into the computer. Fairchild calls the new system SYMBOL, which signifies direct hardware symbolic addressing. The system will handle many critical areas of memory management from 10 to 100 times more efficiently than it is now handled by software. The first prototype of the new Fairchild system, SYMBOL IIR, is undergoing tests at Iowa State University."

1922 Human Aura Is Ultraviolet

"Each person is enveloped by a haze invisible under ordinary circumstances. This halo, shown in old pictures, has for a long time been manifest to certain 'clairvoyants' possessing a specially gifted sight. The unquestionable evidence of Walter J. Kilner, electrical expert of St. Thomas' Hospital, London, as given in his book, *The Human Atmosphere,* should at once set aside any belief that this is a byproduct of occultism or charlatanism. Professor Kilner says, "Although at present it is impossible to say exactly of what the aura consists, I feel positive that we are dealing with an ultra-violet phenomenon. The physical aura [also] can be influenced by external forces such as electricity and chemical action."

Holly Tea

"A species of holly, growing riotously over 40,000 square miles in the South Atlantic and Gulf States, may in the not remote future be converted into a beverage in quantity production. George F. Mitchell, tea specialist of the Bureau of Chemistry, has correctly appraised the value of this native plant, sometimes called cassina, as a stimulating drink similar to imported teas and coffees. This shrubbery has wide appeal for decorative purposes and as Christmas trees during the festive season. Samples of the leaves analyzed by chemists evidenced as high as 1.65 percent of caffeine. Laboratory experiments and reinforced observations in the South during the past summer seem to indicate that a delicious drink can be produced. The tea as now being concocted in the bureau's laboratory is of two colors, one being dark and the other of a greenish hue."

1872 Lead Head Is Dead

"With but few exceptions, all the concoctions sold for the purpose of 'restoring' the color of the hair, or for dyeing the hair, contain the salts of lead, a deadly poison, highly injurious to the health when applied to the scalp or other portions of the body, even in minute quantities. Professor Charles F. Chandler of Columbia College has examined a variety of these preparations and, in each fluid ounce of many popular articles, finds lead."

Nature Enchants

"Everything in nature indulges in amusement of some kind. The lightnings play, the winds whistle, the thunders roll, the snow flies, the rills and cascades sing and dance, the waves leap, the fields smile, the vines creep and run, the buds shoot, and the hills have tops to play with. But some of them have their seasons of melancholy. The tempests moan, the zephyrs sigh, the brooks murmur, and the mountains look blue."

1972: "Paleolithic portraits of bears include the engraved image of a cave bear, characterized by its domed forehead. The 20-inch-long likeness is one of the many Ice Age animal images at La Combarelle, near Les Eyzies in France."

Scientific American, Vol. 226, No. 3; March 1972

Text and Graphic by Katie Peek

The Great Monarch Odyssey

Citizen science data reveal where and when the famously itinerant butterflies travel

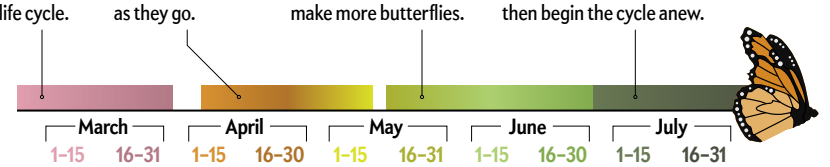
It's spring, and monarchs are on the move. Every year the butterflies leave their dense winter clusters near Mexico City and head for northern latitudes. It will take four months and three generations to get there. Once they arrive, the butterflies will get busy boosting their company enough to survive next year's winter. It's a Sisyphean task—eastern monarch numbers have dropped 80 percent in the past 20 years because of habitat degradation (including fewer flowers)—throughout their range, says Iman Momeni-Dehaghi, a biologist at Carleton University in Ottawa. Enter citizen scientists, who have been building databases such as Journey North, which Momeni-Dehaghi recently used to identify where the overwintering generation hatches. The data could help researchers devise more targeted interventions for a species in rapid decline.

The Old Guard
In March the monarchs that wintered in Mexico move north. In northern Mexico and the southern U.S., they lay the eggs that will be the first generation of the next life cycle.

First Generation
The spring eggs gestate for a month or so. By late April first-generation monarchs emerge and begin to fly north, laying eggs as they go.

Second Generation
In late May and early June the second generation hatches. The South will soon be too hot for monarchs, so those born there move north. Their objective: make more butterflies.

Third and Fourth Generations
In late summer the last generations emerge in the northern part of the monarch range. These are the butterflies that will make the trek south again, starting in September. They will spend November through March in the mountains of Michoacán, then begin the cycle anew.



March 1–15 | March 16–31 | April 1–15 | April 16–30 | May 1–15 | May 16–31 | June 1–15 | June 16–30 | July 1–15 | July 16–31

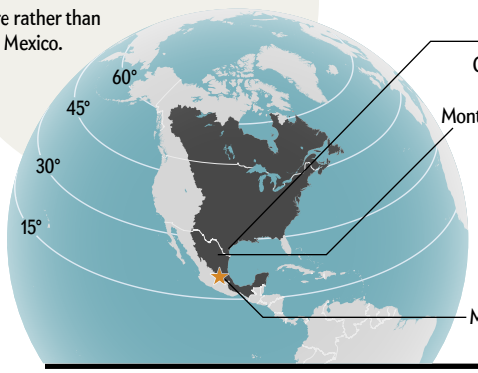
2,266 | 4,482 | 5,229 | 4,164 | 4,031 | 9,218 | 7,776 | 5,524 | 9,050 | 11,893 observations

Latitude: 60°, 50°, 40°, 30°, 20°

Edmonton, Alta.
Calgary, Alta.
Winnipeg, Man.
Thunder Bay, Ont.
Quebec City
Montreal
Minneapolis
Toronto
Chicago
New York
Washington
St. Louis
Nashville
Atlanta
Dallas
Houston
Corpus Christi, Tex.
Monterrey, N.L.
Monarch wintering grounds
Mexico City

HOW TO READ THIS GRAPHIC
Each shape represents sightings of eastern monarchs—eggs, larvae and adult butterflies—logged in the Journey North database between 2012 and 2021 (more than 66,000 data points). For each shape, width represents the number of sightings during that half month, corrected by the human population at that latitude.

Area Included
Monarchs from wintering grounds in Mexico (*orange star*) spread through North America east of the Rockies. Florida is excluded because its monarchs overwinter there rather than in Mexico.



Sources: Monarch Sightings from Journey North Citizen Science Data (*journeynorth.org*); Population Data from Columbia University's Socioeconomic Data and Applications Center (SEDAC)

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