MIT Technology Review

The progress issue

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"Progress." We take for granted that it's a good thing. We constantly invoke it to justify change. But all the ways in which society is measured—from economic indicators to health and education metrics to markers of political development and technological sophistication—rely on long-held assumptions about what progress is. As the economic and political shocks of this still newish century have shown, growing numbers of people are, or feel, excluded by the progress they were told would benefit everyone. And many of the countries that score best on traditional measures of progress have done worst in coping with the covid-19 pandemic, the clearest sign possible that these measures are missing something.

This issue contains MIT Technology Review's annual list of 10 technological breakthroughs we think will change the world—in other words, leading examples of progress that we predict will lead to … even more progress! So I thought it behooved us, on the 20th anniversary of starting that list, to take a harder look at what progress means.

David Rotman sets the stage with a review of the technological changes we've seen since 2001, and a survey of some economists' attempts to come up with measures of progress that better capture what matters to people (page 10). He draws a surprising conclusion: if there's a reason to be optimistic about the next decade, it's less because of new technologies than because of more equitable ideas about how to measure progress that will better guide us in using these advances.

For many, these changes may come too late. Susie Cagle reflects on how American capitalism's promise of progress "stopped with our [millennial] generation," why things look set to worsen still further, and what that will mean for her newborn child (page 17). Brian Alexander writes about the pockets of America that the progress of the past few decades has simply left behind (page 58). Chelsea Sheasley looks at how the digital divide, coupled with the pandemic, could further widen the economic gap between white and non-white Americans in the years to come (page 64).

Elsewhere, Amy Nordrum asks people from various fields what progress means to them (page 18), while James Temple asks other experts what would be the single best way to help the world make progress on climate change (page 21). David Vintiner, with his sometimes unsettling photographs of biohackers and body-augmentation researchers (page 72), raises the question of whether cyborg humans are a form of progress or a deviation from it.

IAN ALLEN

Gideon Lichfield is editor in chief of MIT Technology Review.

We also pick apart some myths about how progress is made. Carl Benedikt Frey examines how tech giants that began life as the vanguards of progress have become obstacles to it (page 15). John Markoff argues that the rise of tech hubs like Silicon Valley owes much more to serendipity than their boosters like to admit (page 79). Adam Piore examines why brilliant ideas that should succeed sometimes get stuck, and how a crisis like covid-19 may help break the logjam (page 68). J. Benjamin Hurlbut debunks the view that He Jiankui, the creator of the "CRISPR babies," was a scientist gone rogue, arguing instead that his ambition represents a form of progress within science that the establishment prefers to underplay (page 82). And Leah Stokes questions the idea that we need more technology to fight climate change (page 85).

And finally, we have the 10 breakthrough technologies themselves, starting on page 26. As always, three things are true of our list. It is eclectic; some of the innovations on it are clearly making an impact now, while some have yet to do so; and many of them have the potential to do harm as well as good. Whether or not they come to represent progress 20 years from now depends on how they're used—and, of course, on how we're defining progress by then.

Contents

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THE PROGRESS ISSUE

Edited by David Rotman and Amy Nordrum

10 BREAKTHROUGH TECHNOLOGIES 2021

FEATURES

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Are you ready to be a techno-optimist again?

IN 2001, WE PICKED OUR FIRST ANNUAL SET OF 10 BREAKTHROUGH TECHNOLOGIES. HERE'S WHAT THEIR FATES TELL US ABOUT PROGRESS OVER THE LAST TWO DECADES.

BY DAVID ROTMAN

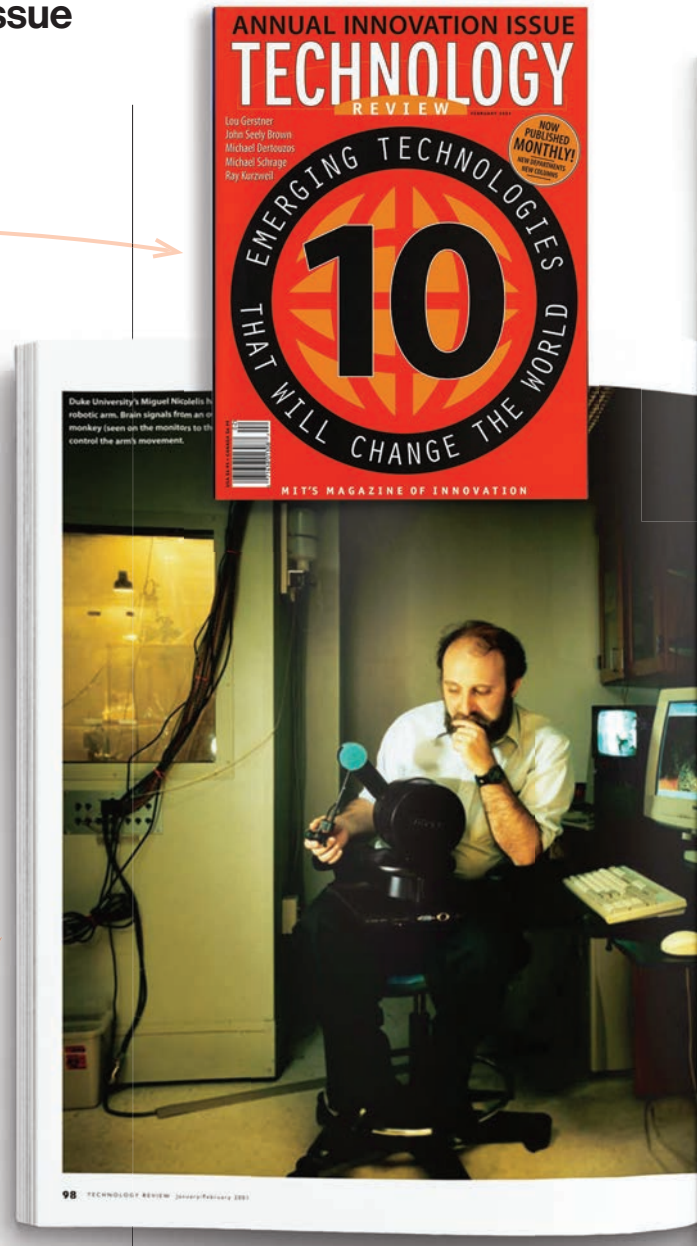
Twenty years ago, MIT Technology Review picked 10 emerging areas of innovation that we promised would "change the world." It was a time of peak techno-optimism. Yes, the dot-com boom was in the midst of imploding; some insiders were already fretting about the end of Moore's Law. (They still are, though the industry keeps finding ways to make computers more powerful.) But in many ways it was a glorious time for science and technology.

A working draft of the human genome was published in February of 2001—a genetic blueprint that promised to reveal our deepest biological secrets. There was great excitement over recent breakthroughs in nanotechnology. Early advances in quantum and molecular computing portended a new, post–Moore's Law era of computation. And then there was that amazing search engine with the funny name, rapidly gaining users and changing how they surfed the web and accessed information. Feeling lucky?

So it's worthwhile to look back at the initial "TR10," as we now call our annual list, for clues to just how much progress we've made.

First, let's acknowledge that it was a thoughtful list. We eschewed robotic exoskeletons and human cloning, as well as molecular nanomanufacturing and the dreaded gray goo of the nano doomsayers—all hot topics of the day. Instead we focused on fundamental advances in information technology, materials, and biotech. Most of the technologies are still familiar: data mining, natural-language processing, microfluidics, brain-machine interfaces, biometrics (like facial recognition), and robot design.

So how well did these technologies fulfill the dreams we had for them two decades ago? Here are a few lessons from the 2001 list.



LESSON 1: Progress is often slow

Our first selection, brain-machine interfaces, begins with a description of the neuroscientist Miguel Nicolelis recording the electric signals from the brain of a very cute owl monkey named Belle as she thinks about how to get a few drops of apple juice. Flash forward to late summer 2020, as Elon Musk shows off the brain signals from a very cute pig named Gertrude, gaining oohs and ahhs from adoring fans attending the demonstration for Neuralink, his brain-machine startup.

An observer at Musk's event might have been forgiven for wondering whether 20 years had really passed since Nicolelis's experiment. Both men had similar visions for directly connecting the brain to computing devices via implanted chips. As our biomedicine editor, Antonio Regalado,

MIGUEL NICOLELIS

Brain-Machine Interfaces

Belle, a nocturnal owl monkey small enough to fit comfortably in a coat pocket, blinks her outsized eyes as a technician plugs four connectors into sockets installed in the top of her skull. In the next room, measurements of the electrical signals from some 90 neurons in Belle's brain pulse across a computer screen. Recorded from four separate areas of Belle's cerebral cortex, the signals provide a window into what her brain is doing as she reaches to touch one of four assigned buttons to earn her reward—a few drops of apple juice. Miguel Nicolelis, a Duke University neurobiologist who is pioneering the use of neural implants to study the brain, points proudly to the captured data on the computer monitor and says: "This readout is one of a kind in the world."

The same might be said of Nicolelis, who is a leader in a competitive and highly significant field. Only about a half-dozen teams around the world are pursuing the same goals: gaining a better understanding of how the mind works and then using that knowledge to build implant systems that would make brain control of computers and other machines possible. Nicolelis terms such systems "hybrid brain-machine interfaces" or HBMIs. Recently, working with the Laboratory for Human and Machine Haptics at MIT, he scored an important first on the HBMI front, sending signals from individual neurons in Belle's brain to a robot, which used the data to mimic the monkey's arm movements in real time.

In the long run, Nicolelis predicts that HBMIs will allow human brains to control artificial devices designed to restore lost sensory and motor functions. Paralysis sufferers, for example, might gain control over a motorized wheelchair or a prosthetic arm—perhaps even regain control over their own limbs. "Imagine," says Nicolelis, "if someone could do for the brain what the pacemaker did for the heart." And, in much the same way that a musician grows to feel that her instrument is a part of her own body, Nicolelis believes the brain will prove capable of readily assimilating human-made devices.

Ongoing experiments in other labs are showing that this idea is credible. At Emory University, neurologist Phillip Kennedy has helped severely paralyzed people communicate via a brain implant that allows them to move a cursor on a computer screen (*see "Mind Over Muscles," TR March/April 2000*). And implants may also shed light on some of the brain's unresolved mysteries. Nicolelis and other neuroscientists still know relatively little about how the electrical and chemical signals emitted by the brain's millions of neurons let us perceive color and smell, or give rise to the precise movements of Brazilian soccer players—whose photos adorn the walls of the São Paolo native's office. "We don't have a finished model of how the brain works," says Nicolelis. "All we have are first impressions."

Others in Brain-Machine Interfaces

Organization	Project
Andy Schwartz (Arizona State University)	Neural control of robotic arm
John Donoghue (Brown University)	Brain representation of movement
Richard Andersen (Caltech)	Improved neuroelectrode systems
Phillip Kennedy, Roy Bakay (Emory University)	Communication systems for paralyzed patients

Nicolelis' latest experiments, however, show that by tapping into multiple neurons in different parts of the brain, it is possible to glean enough information to get a general idea of what the brain is up to. In Belle's case, it's enough information to detect the monkey's intention of making a specific movement a few tenths of a second before it actually happens. And it was Nicolelis' team's success at reliably measuring tens of neurons simultaneously over many months—previously a key technological barrier—that enabled the remarkable demonstration with the robot arm.

Still, numerous stumbling blocks remain to be overcome before human brains can interface reliably and comfortably with artificial devices, making mind-controlled prosthetic limbs or computers more than just lab curiosities. Among the key challenges is developing electrode devices and surgical methods that will allow safe, long-term recording of neuronal activities. Nicolelis says he's begun working with Duke's biomedical engineering department to develop a telemetry

TECHNOLOGY REVIEW January/February 2001 99

skeptical of Atick's vision of a biometric-enabled wireless Web can't deny his ingenuity and ambition. At the age of 15, while living in Israel, Atick dropped out of school to write a 400-page physics textbook entitled *Introduction to Modern Physics*. "I was bored in school. I wanted to show the establishment I was [illegible]

value to this process," says Atick. In 1994, he and colleagues Paul Griffin and Norman Redlich founded Visionics.

Based in Jersey City, N.J., Visionics develops and markets pattern-recognition software called FaceIt. In contrast to the main competing technology, which relies on data from the entire face, FaceIt verifies [illegible] a set of

Data Mining

wrote in 2001, "Nicolelis sees the effort as part of the impending revolution that could eventually make [brain interfaces] as common as Palm Pilots."

That claim has come true, but thanks only to the demise of Palm Pilots, not the popularity of brain-machine interfaces. Despite some encouraging human experiments over the years, such interfaces remain a scientific and medical oddity. As it turns out, neuroscience is very difficult. There has been success in shrinking the electronics and making the implants wireless, but progress in the science has been slower, hindering the visions Nicolelis and Musk hoped to realize. (A footnote to lesson one: success often depends on whether a series of advances can all come together. Making brain interfaces practical requires advances in both the science and the gadgetry.)

LESSON 2:

Sometimes it takes a crisis

We chose microfluidics in 2001 because of some remarkable advances in moving tiny amounts of biological samples around on a small device—a so-called lab-on-a-chip. These promised quick diagnostic tests and the ability to automate drug and genomic experiments.

Since then, microfluidics has found valuable uses in biology research. Clever advances continued, such as ultra-cheap and easy-to-use paper diagnostic tests ("Paper Diagnostics" was a TR10 in 2009). But the field has fallen short of its promise of transforming testing. There simply wasn't an overwhelming demand for the technology. It's fair to say that microfluidics became a scientific backwater.

Covid-19 ended that. Conventional tests rely on multistep procedures done in an analytical lab; this is expensive and slow. Suddenly, there is an appetite for a fast and cheap lab-on-a-chip solution. It took a few months for researchers to dust off the technology, but now covid-19 diagnostics using microfluidics are appearing. These techniques, including one that uses CRISPR gene editing, promise to make covid tests far more accessible and widely used.

LESSON 3:

Be careful what you wish for

In 2001, Joseph Atick, one of the pioneers of biometrics, saw facial recognition as a way for people to interface with their gadgets and computers more securely and easily. It would give the cell phones and personal digital assistants that were increasingly popular a way to recognize their owners, spelling the end of PINs and passwords. Part of that vision eventually came true with such applications as Apple's FaceID. But facial recognition also took a turn that Atick now says "shocks me."

In 2001, facial-recognition algorithms were limited. They required instructions from humans, in mathematical form, on how to identify the distinguishing features of a face. And every face in the database of faces to be recognized had to be laboriously scanned into the software.

Then came the boom in social media. Whereas in the early days, Atick says, he would have been thrilled with 100,000 images in facial-recognition databases, suddenly machine-learning algorithms could be trained on billions of faces, scraped from Facebook, LinkedIn, and other sites. There were now hundreds of these algorithms, and they trained themselves, simply by ingesting and comparing images—no expert human help required.

But that remarkable advance came with a trade-off: no one really understands the reasoning the machines use. And that's a problem now that facial recognition is increasingly relied on for sensitive tasks like identifying criminal suspects. "I did not envision a world where these machines would take over and make decisions for us," says Atick.

LESSON 4:

The trajectory of progress matters

"Hello again, Sidney P. Manyclicks. We have recommendations for you. Customers who bought this also bought …"

The recommendation engines described in this, the opening of our 2001 article on data mining, seemed impressive at the time. Another potential use of data mining circa 2001 also sounded thrilling: computer-searchable video libraries. Today, it all seems utterly mundane.

Thanks to ever increasing computational power, the exploding size of databases, and closely related advances in artificial intelligence, data mining (the term is now often interchangeable with AI) rules the business world. It's the lifeblood of big tech companies, from Google and its subsidiary YouTube to Amazon and Facebook. It powers advertising and, yes, sales of everything from shoes to insurance, using personalized recommendation engines.

Yet these great successes mask an underlying failure that became particularly evident during the pandemic. We have not exploited the power of big data in areas that matter most.

At almost every step, from the first signs of the virus to testing and hospitalization to the rollout of vaccines, we've missed many opportunities to gather data and mine it for critical information. We could have learned so much more about how the virus spreads, how it evolves, how to treat it, and how to allocate resources, potentially saving countless lives. We didn't seem to have a clue about how to collect the data we needed.

Overall, then, the 10 technologies we picked in 2001 are still relevant; none has been forsaken; and some have been remarkable, even world-changing, successes. But the real test of progress is more difficult: Have these technologies made our lives not just more convenient, but better in ways that we care about? How do we measure that progress?

What makes you happy?

The common way to gauge economic progress is by measuring gross domestic product (GDP). It was formulated in the 1930s in the US to help us understand how well the economy was recovering from the Great Depression. And though one of its chief architects, Simon Kuznets, warned that GDP shouldn't be mistaken for a measure of the country's well-being and the prosperity of its people, generations of economists and politicians have done just that, scrutinizing GDP numbers for clues to the health of the economy and even the pace of technological progress.

Economists can tease out what they call total factor productivity (TFP) from GDP statistics; it's basically a measure of how much innovation contributes to growth. In theory, new inventions should increase productivity and cause the economy to grow faster. Yet the picture has not been great over the last two decades. Since around the mid-2000s—shortly after our first TR10 list—growth in TFP has been sluggish and disappointing, especially given the flood of new technologies coming from places like Silicon Valley.

Some economists think the explanation may be that our innovations are not as far-reaching as we think. But it's also possible that GDP, which was designed to measure the industrial production of the mid-20th century, does not account for the economic benefits of digital products, especially when they're free to use, like search engines and social media.

Stanford economist Erik Brynjolfsson and his colleagues have created a new measure to try to capture the contribution of these digital goods. Called GDP-B (the "B" is for benefits), it is calculated by using online surveys to ask people just how much they value various digital services. What would you have to be paid, for example, to live a month without Facebook?

The calculations suggest that US consumers have gained some $225 billion in uncounted value from Facebook alone since 2004. Wikipedia added $42 billion. Whether GDP-B could fully account for the seeming slowdown in productivity is uncertain, but it does provide evidence that many economists and policymakers may have undervalued the digital revolution. And that, says Brynjolfsson, has important implications for how much we should invest in digital infrastructure and prioritize certain areas of innovation.

GDP-B is one of a larger set of efforts to find statistics that more accurately reflect the changes we care about. The idea is not to throw out GDP, but to complement it with other metrics that more broadly reflect what we might call "progress."

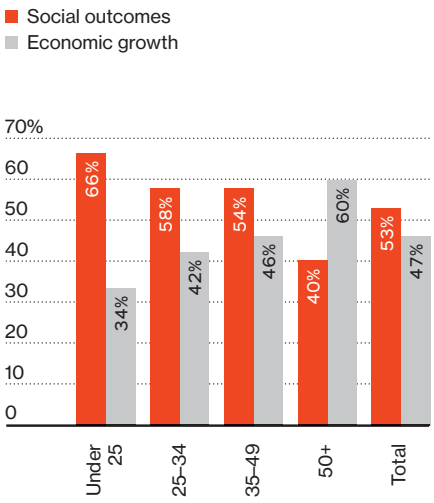
Another such measure is the Social Progress Index, which was created by a pair of economists, MIT's Scott Stern and Harvard's Michael Porter. It collects data from 163 countries on factors including environmental quality, access to health care and education, traffic deaths, and crime. While wealthier countries, unsurprisingly, tend to do better on this index, Stern says the idea is to look at where social progress diverges from GDP per capita. That shows how some countries, even poor ones, are better than others at turning economic growth into valued social changes.

THE 2001 LIST

- Brain-machine interfaces
- Flexible transistors
- Data mining
- Digital rights management
- Biometrics
- Natural-language processing
- Microphotonics
- Untangling code
- Robot design
- Microfluidics

SURVEY FROM 13 COUNTRIES SHOWS GENERATION GAP

"Imagining when the covid-19 pandemic is over ... which should your country prioritize more?"



SOURCE: IPSOS/SOCIAL PROGRESS IMPERATIVE

The US, with one of the world's highest levels of GDP per capita, is 28th in the index, and is one of only four countries whose scores have declined since 2014. Norway, which is similarly wealthy, was ranked first in 2020 (see chart). Some poorer countries also outperform.

"Very often the decisions about innovation and technology are about its economic impact," says Stern. "There's nothing wrong with that. But are we directing the economic rewards to areas that will advance social progress?"

A similar thought lies behind another alternative to GDP, developed by Diane Coyle and her colleagues at the Bennett Institute for Public Policy in Cambridge, UK. Their measure of what they call the wealth economy is based on what they define as the assets of a society, including its human capital (the health and skills of its people), natural capital (its resources and the health of the environment), and social capital (trust and social cohesion).

It's a hugely ambitious project that attempts to create a couple of key measurements for each asset. Those numbers, says Coyle, are meant to inform better decisions about technology and innovation, including decisions on the priorities for government investment. She says the approach allows you to ask, "What is the technology doing for people?"

The value of these various alternatives to GDP is that they provide a broader picture of how our lives are changing as a result of technology. Had they been in place 20 years ago, they might have shined light on crises we were late in seeing, such as the growth of income inequality and the rapid deterioration of our climate. If 20 years ago was a time of peak techno-optimism, it might have prompted us to ask, "Optimism about what?"

2020 SOCIAL PROGRESS INDEX RANKINGS

Unless you like the cold, New Zealand might be your best bet for happiness.

Rank	Country	Score
1	**Norway**	92.73
2	**Denmark**	92.11
3	**Finland**	91.89
4	**New Zealand**	91.64
5	**Sweden**	91.62
6	**Switzerland**	91.42
7	**Canada**	91.40
8	**Australia**	91.29
9	**Iceland**	91.09
10	**Netherlands**	91.06
28	**United States**	85.71

SOURCE: SOCIAL PROGRESS IMPERATIVE

Born-again hope

About a decade ago, the techno-optimist narrative began to fall apart.

In 2011 Tyler Cowen, an economist at George Mason University in Virginia, wrote *The Great Stagnation*, arguing that the technologies that seemed so impressive at the time—especially social media and smartphone apps—were doing little to stimulate economic growth and improve people's lives. *The Rise and Fall of American Growth,* a 2016 bestseller by Robert Gordon, another prominent economist, ran to more than 700 pages, detailing the reasons for the slowdown in TFP after 2004. The temporary boom from the internet, he declared, was over.

The books helped kick off an era of techno-pessimism, at least among economists. And in the last few years, problems like misinformation on social media, the precarious livelihoods of gig-economy workers, and the creepier uses of data mining have fueled a broader pessimist outlook—a sense that Big Tech not only isn't making society better but is making it worse.

These days, however, Cowen is returning to the optimist camp. He's calling for more research to explain progress and how to create it, but he says it's "a more positive story" than it was a few years ago. The apparent success of covid vaccines based on messenger RNA has him excited. So do breakthroughs in using AI to predict protein folding, the powerful gene-editing tool CRISPR, new types of batteries for electric vehicles, and advances in solar power.

An anticipated boom in funding from both governments and businesses could amplify the impact of these new technologies. President Joe Biden has pledged hundreds of billions in infrastructure spending, including more than $300 billion over the next four years for R&D. The EU has its own massive stimulus bill. And there are signs of a new round of venture capital investments, especially targeting green tech.

If the techno-optimists are right, then our 10 breakthrough technologies for 2021 could have a bright future. The science behind mRNA vaccines (page 28) could open a new era of medicine in which we manipulate our immune system to transform cancer treatment, among other things. Lithium-metal batteries (page 38) could finally make electric cars palatable for millions of consumers. Green hydrogen (page 54) could help replace fossil fuels. The advances that made GPT-3 possible (page 34) could lead to literate computers as the next big step in artificial intelligence.

Still, the fate of the technologies on the 2001 list tells us that progress won't happen just because of the breakthroughs themselves. We will need new infrastructure for green hydrogen and electric cars; new urgency for mRNA science; and new thinking around AI and the opportunities it presents in solving social problems. In short, we need political will.

But the most important lesson from the 2001 list is the simplest: Whether these breakthroughs fulfill their potential depends on how we choose to use them. And perhaps that's the greatest reason for renewed optimism, because by developing new ways of measuring progress, as economists like Coyle are doing, we can also create new aspirations for these brilliant new technologies. If we can see beyond conventional economic growth and start measuring how innovations improve the lives of as many people as possible, we have a much greater chance of creating a better world. ■

David Rotman is MIT Technology Review's editor at large.

RE
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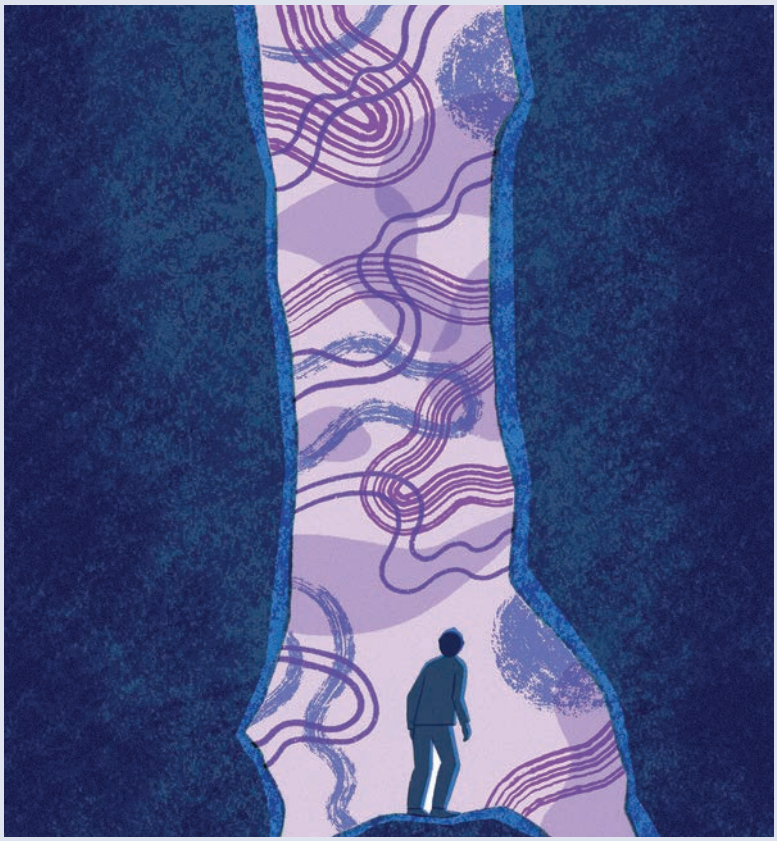
Get up to speed on the key themes, big ideas, and major players discussed in this issue.



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DISPATCHES

The many paths of progress

Decisions made long ago created the reality we live in today. Now, it's our turn to invent the future.

Why care about progress? The simplest answer is because our lives depend on it. Though more often talked about on a macro scale, progress is also deeply personal. Progress—or the lack of it—affects our health, our wages, our well-being, and even our life spans. Many of our biggest personal decisions are influenced by how well we think things are going in the world. We also all help direct future progress through the choices we make. The following contributors reflect on the forces that have shaped the progress we see today and what gaps still remain. —*Amy Nordrum*

OUR BEHEMOTH PROBLEM

Large corporations are essential for progress, but only when they let the startups roam free. Lately the giants have gotten better at edging out smaller companies—a terrible omen for the future of progress.

CARL BENEDIKT FREY is the director of the Future of Work program at the Oxford Martin School at Oxford University and author of *The Technology Trap: Capital, Labor, and Power in the Age of Automation.*

The coronavirus has shattered many people's lives, but most of us held on to one bit of optimism from the outset: the belief that we'd eventually invent a vaccine, that we would find a way to move beyond the pandemic. But it's important to remember that, just like the vaccine, the belief in constant progress itself had to be invented. We can't just presume it will continue.

Progress these days hinges on the interaction between larger incumbent companies and nimbler startups. The big, established companies focus more on improving efficiency and protecting their positions, while the smaller, fast-moving startups are more likely to provide the breakthrough inventions.

The problem is that over the past few decades the larger companies have, with the help of regulators, gotten better at edging out startups. The pandemic has in some ways worsened this trend. It is even harder for many cash-strapped young firms to

Proportion of e-waste that's recycled globally **17.4%**

Gap in years between the countries with the lowest and highest life expectancy **31**

Proportion of people in the world with internet access **51.4%**

survive. And that doesn't portend well for innovation.

One recent study from researchers at the University of Chicago and Northwestern University shows that breakthrough inventions are more likely to come from individual inventors or smaller teams. Corporations excel at bringing about incremental improvements, like those that make the production process more efficient. But major leaps in technology tend to come from newer, smaller firms. You can make a better horse carriage, but eventually it takes a radical innovation to make a motorcar—otherwise progress stalls.

Covid-19 has caused more churn of companies entering and exiting the marketplace than any other event since World War II, but we can't read that to mean we'll see a faster rate of technological progress. Instead, we've seen the opposite: restrictions on immigration, plummeting travel, and the isolation of knowledge workers in home offices have made the kinds of interactions that drive innovation less likely to happen.

Besides this, there's evidence that venture capitalists have devoted more of their energies to guiding companies already in their portfolios through the pandemic, rather than looking outward for new investments. As a result, the prime beneficiaries from the pandemic have been incumbents with deep pockets. Giants like Apple, Alphabet, Amazon, Facebook, and Microsoft collectively hold more than $570 billion in gross cash.

As covid-19 solidifies the market position of behemoths, it also increases their political clout, which tends to stifle the kind of dynamic environment in which nimble startups take risks and create bold new innovations.

To take the most immediate example, without progress we would have no vaccines—nor would we be capable of mass-producing them.

The British historian Eric Hobsbawm once wrote, "It is often assumed that an economy of private enterprise has an automatic bias towards innovation, but this is not so. It has a bias only towards profit." He was right.

In the early stages of a product's life cycle, a company will focus on innovation. But once a prototype has been established, that company's efforts shift toward incremental improvements in production to cut costs. At a certain point a company finds that it's more cost-efficient to focus on political lobbying to protect itself from competition than to spend money on innovating. And that's ultimately terrible for the state of progress: research from the National Bureau of Economic Research shows that companies with more political connections tend to be less innovative and apply for fewer patents.

The economy had been trending in this direction since before the pandemic. The French economist Thomas Philippon has documented how business dynamism has declined dramatically in the US since the 2000s, while business spending on lobbying has skyrocketed. In a separate study, Philippon and Germán Gutiérrez show that recent regulations "have a negative impact on small firms, especially in industries with high lobbying expenditures." In other words, powerful firms encourage regulations that hinder the competition and boost their own profits. This is a path toward stagnation, not progress.

One way of halting this economic equivalent of atherosclerosis is to encourage more free trade and global competition. But thanks in part to covid-19, we're moving in the opposite direction. As the pandemic took off in the first 10 months of 2020, G20 members undertook 1,371 policy interventions, of which 1,067 harmed trading partners, according to a recent report by the Centre for Economic Policy Research.

Should we worry that we're slowing the speed of progress? Absolutely. To take the most immediate example, without progress we would have no vaccines—nor would we be capable of mass-producing them. What's more, innovation is a prerequisite for sustained growth, and an economy that isn't growing becomes a zero-sum game. When growth is static and resources are limited, that leads to greater competition for those resources, which helps explain why violence was more pervasive before modern growth began, as Steven Pinker has shown.

Number of refugees worldwide in 2019

26 MILLION

Proportion of people in OECD countries who say they trust their national government

43%

Much has been written about the political power of the top 1% in the US, but the vast majority of campaign contributions come from business lobbying groups rather than wealthy individuals. If innovation has been stifled and people somehow sense that democracy is rigged, the solutions might have less to do with restraining the billionaires and more with reining in the corporate behemoths.

GENERATIONAL CHANGE

What my pandemic baby taught me about America's future.

SUSIE CAGLE covers climate change and inequality in California.

The morning my first child was born, I was mostly thinking of death.

It was the week before Thanksgiving as my husband and I hunkered down with our newborn in Berkeley, California, learning from cable news that hospitals—like the one where we were—would soon be overrun by covid-19 patients.

I had learned I was pregnant in March, just one week before California issued its first stay-at-home order to curb the spread of the coronavirus. My husband's business was closed indefinitely. I lost my job as a climate reporter a few months later, just before our state's worst fire season in history. Our world was mired in crisis at the same time that our lives were being joyously upended.

We had waited years for the perfect time to have a baby—until we had a stable home, income, and health care. Like other millennials, we'd put it off far longer than our parents had before us.

If there are motivators for this social change, they would seem to have more to do with necessity than choice. We graduated into the Great Recession, burdened with debt and rewarded with stagnant wages, and endured the slowest economic growth faced by any generation in US history. Millennials control less than 6% of US wealth. At the same age, baby boomers controlled more than 20%.

The American capitalist promise—that members of each generation can work hard and expect to give their children a life better than their own—was broken. By this measure, progress had stopped with our generation. And owing at least in part to these economic burdens, millions fewer millennials are giving birth, and those who do have children are doing it later.

Nearly a year into this pandemic, the baby bust is only worsening. The psychological and economic stresses of the pandemic appear to be pushing families in the other direction as young people have borne the brunt of a shuttered economy. In a survey by the company Modern Fertility, 30% of respondents said they were changing their family planning decisions because of covid-19. Of those, roughly three-quarters said they would delay having children—or reconsider having them at all.

The Brookings Institution has predicted that the pandemic could result in 300,000 to 500,000 fewer births in 2021, a drop of 10% or more. What's less clear is whether this dip reflects the anxieties of struggling would-be parents, their concerns for the future prospects of their potential children, or both.

This compounded covid baby bust will no doubt further depress the US birthrate, already the lowest it's been in over three decades. And by many traditional measures of progress, a falling birth rate is an indicator of failure.

Ours was one of the last babies conceived in the hopeful naïveté of early 2020, before I knew of this specific devastation to come. But after years spent reporting on the collapse of ecosystems at human hands, I could sense the contours of what lay ahead.

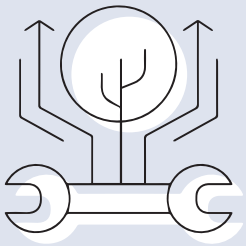
Year after year, I've watched my California neighbors burned out of their homes by ever larger, faster-moving wildfires—and I've watched them rebuild in the very same places. Even in the face of chaos, our collective willingness to change seems questionable.

So many of my peers have decided not to consign another young life to inheriting this mess, and I can't say they're wrong. Choosing to have children is an inherently optimistic act—either because one already has hope for the world or because, having created and committed to caring for part of a new generation, one must find some.

The morning my first child was born, I thought that if there were a perfect time to have a baby, this wouldn't be it. I thought about the future pandemics he would endure, along with the fires and the economic crashes. Still, somehow, I am confident that he will thrive. The task before him, along with all the other pandemic babies, will be to redefine progress in an age of crisis, like that which marked their very first days.

This piece was supported by the Economic Hardship Reporting Project.

WIKIMEDIA COMMONS



DEFINING TERMS

MAKING PROGRESS CAN MEAN MANY DIFFERENT THINGS.

What do we mean when we talk about progress? In general terms, to make progress means to move toward something and away from something else. But where we're headed and what we're leaving behind are key questions that drive political movements, shape international treaties, and define our own sense of personal growth.

Our notions of individual or collective progress reflect our values and our hopes for the future. Knowing what we're trying to achieve can also help us see what role technology could or should play. To help us explore those possibilities, the following experts responded to a deceptively simple prompt: What does progress mean to you? —*Amy Nordrum*

Ratio of CEO pay to an average worker's compensation across 350 top US firms

320:1

OPPORTUNITY

Shivani Siroya

Founder and CEO, Tala (United States)

I grew up between India and the United States, and so for a long time my idea of progress was shaped by the difference between these two places—the developing and the developed, the emerging and the established. Progress was about closing the gap, catching one place up to the systems and standards set by another.

But for the past decade, I've come to think about who has the power to name and measure progress, and how we can shift more of that power to people most in need of it.

There's some arrogance in thinking we can define what progress looks like for someone else. That's why I'm focused on creating the systems and tools that let people pursue whatever matters most to them. And it's also why I've stopped looking to the existing systems for answers.

The bottom line: progress isn't about closing a gap. It's about opening a door.

NHUNG LE

Gap in mean per capita income between wealthy and poor countries

$42,800

Proportion of people in the world with access to electricity

89%

JUSTICE
Jillian York

Director for international freedom of expression, Electronic Frontier Foundation (Germany)

Progress, to me, is not found in the growth of companies or even the development of new technologies, but in justice and equality and human rights. Technological "progress" means nothing if it holds some of us back. And yet companies from Silicon Valley to Shenzhen continue to move forward with limited diversity, recognition of harm, and consideration for human rights.

TEAMWORK
Bárbara Paes

Activist and cofounder, Minas Programam (Brazil)

For too long, progress in technology has meant advancement at any cost. Forward is good, staying still is bad, and looking backward is worse. But true progress can only happen when we reflect on the risks and consequences of the choices we make.

Meaningful progress is about using our abilities and resources to create a world where anyone can thrive. This involves questioning our own assumptions, acknowledging how different technologies may harm communities that have long faced oppression, and sometimes deciding to stop developing technologies that may cause harm.

Progress comes when we move toward a just and equitable future, and not when we just make shiny new things.

INNOVATION
Yariv Bash

Cofounder, SpaceIL and Flytrex (Israel)

Progress means actively fostering innovation. Within the drone industry, progress has come in the form of regulatory evolution. US regulators didn't just accept that drone delivery will become an industry standard but helped figure out the best way to ensure that it happens. Unlike conventional wisdom regarding regulation—which often sees it as a barrier to progress—the Federal Aviation Administration's forward-thinking approach is accelerating safety and ushering in a new era of on-demand delivery. When regulation drives innovation, then true progress takes place, regardless of the industry.

NADINE BARIŠIC (YORK); COURTESY PHOTO (PAES, BASH); GETTY (DRONE)

Number of people who suffer from hunger **690 MILLION**

Metric tons of e-waste generated globally in 2019 **53.6 MILLION**

Year that renewables are expected to beat out coal to become the world's primary source of electricity generation **2025**

OPTIMISM
Matthew Slaboch

Visiting assistant professor of political science, Denison University (United States)

Almost universally, people think that their societies and the world are in bad shape. But the widespread belief that we aren't now making progress isn't necessarily a rejection of the idea of progress itself: the idea that humanity can make lasting advances still holds currency, even in a dispirited age.

Is our expectation that the future will be better than the past a helpful one? The dogmatic insistence on a "better" future led prior regimes (such as the Nazis and the Soviets) to inflict tremendous pain on millions of people. But if the idea of progress loses its way, we might also lose the spirit of innovation that makes problem-solving possible.

WELL-BEING
Farhana Sultana

Associate professor of geography, Syracuse University (United States)

Progress is often measured as economic growth only. But real progress would involve growth that doesn't externalize social or environmental costs.

Progress is often measured in incremental gains such as the US Civil Rights Act. But limiting the idea of progress to only that act would miss the widespread structural racism that remains unaddressed. Similarly, climate agreements are indeed progress, but there aren't enough concrete actions to halt the climate crisis, while marginalized groups pay the biggest price.

Progress must be measured by how well those at the bottom are doing, not only those at the top.

QUALITY OF LIFE
Danny Dorling

Professor of geography, University of Oxford (United Kingdom)

Progress for me is about what actually matters most in life: health, job satisfaction, housing quality, living standards, and real education. Finland, for example, has one of the lowest rates of infant mortality in the world and the highest proportions of workers satisfied with their lives and the flexibility of their jobs. More workers can choose which hours they work in Finland than in any other country. Finland also has the world's lowest homelessness rate (the US has one of the highest) and is renowned for its education system. And Finland has greater income equality than the US, and a much lower carbon footprint. Not surprisingly, its people are happier.

HUMILITY
Vera Keller

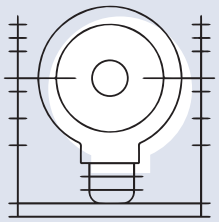
Associate professor of history, University of Oregon (United States)

To me, behind progress lurks another word. Progress comes from a Latin word meaning "movement forward." It suggests a collective march into the future. But often, when we hear of progress, what's really discussed is a project.

"Project" comes from a word meaning "thrown forward." Those hurtled into the future have little say in its design, and nobody can assume success. When we present risky projects as assured progress, we use what technology studies scholar Sheila Jasanoff identified as modern "technologies of hubris"—that is, ways of presenting expertise that conceal doubts.

We need to rediscover "technologies of humility." At the end of my book, I included one such technology common in the 17th century: a list identifying everything I wish I knew about my subject. Transparency about our ignorance makes the knowledge we communicate more trustworthy and extends a hand to others.

JAMIE HALE, DENISON UNIVERSITY (SLABOCH); COURTESY PHOTO (SULTANA); EDMUND BLOK (DORLING); NHUNG LE /SOURCE: MARTY MOORE (KELLER)



10 BIG IDEAS TO ACHIEVE REAL CLIMATE PROGRESS

By James Temple

Despite decades of warnings and increasingly devastating disasters, we've still made little progress in slowing climate change.

Clean energy alternatives have secured just a fraction of the marketplace today, with renewables generating around 10% of global electricity and electric vehicles accounting for about 3% of new sales. Meanwhile, greenhouse-gas emissions have continued to climb year after year, aside from the occasional recession or pandemic.

Given the lack of momentum, how do we make faster, more significant progress? We asked 10 experts across a variety of disciplines, including climate scientists, economists, physicists, and policy experts, a single question:

"If you could invent, invest in, or implement one thing that you believe would do the most to reduce the risks of climate change, what would it be and why?"

Here's what they had to say.

NHUNG LE

Proportion of the world's coral reefs expected to perish if global temperatures increase by 1.5 °C from preindustrial levels

70%

BILL GATES

Cofounder of Microsoft and chairman of Breakthrough Energy (US)

Right now, I'm investing a lot in nuclear fission. Our company [TerraPower] … just got a huge US government contract to develop that reactor, which we call Natrium.

A lot of people would say a storage miracle and some people would say super-cheap, clean hydrogen. The nice thing about super-cheap, clean hydrogen—forget about whether it ever competes in passenger cars; it probably doesn't—is it potentially solves a lot of problems (see "Green hydrogen," page 54).

It requires the cheapest electricity in the world and the cheapest capital cost in the world, if you're going to do it through electrolyzers cracking water.

That could work—we should try—but we can't count on it. You can't just focus on one thing, because you may hit a dead end, just like we may not get fusion or [next-generation] fission or the storage miracle.

Rise in global average surface temperature since the late 1800s

1.18 °C

Number of new annual deaths per 100,000 people that climate change could cause by 2100 if left unchecked

85

Centimeters of sea-level rise in the past century.

20

SALLY BENSON

Director of the Global Climate & Energy Project, Stanford University (US)

Wise, inclusive, courageous, and decisive leadership.

Wise because the stakes are so high and solving the climate problem is so complex. Inclusive because we need everyone work ing to solve the climate problem. Courageous because many tough decisions need to be made, and most of them are sure to make some people unhappy. Decisive because we don t have a moment to waste.

ELIZABETH KOLBERT

Staff writer at the New Yorker and author of Under a White Sky: The Nature of the Future (US)

I would impose an economy wide car bon tax that would increase year by year. I d use some of the proceeds to offset the regressive impact of the tax on low income families and the rest to invest in low carbon infrastructure.

Although I don t believe in putting too much faith in economic models, I have to believe economists are cor rect in saying this would be the most efficient way to bring carbon emis sions down. And we just don t have time for inefficiency at this point.

RHIANA GUNN-WRIGHT

Director of climate policy, Roosevelt Institute, and one of the architects of the Green New Deal (US)

Let☒ be clear: the covid-19 recession and climate change are not happening in isolation from one another. Our government is trying to rebuild our economy at the same time—and in the same places—as fires rage, waters rise, and homes are destroyed. To underestimate the depth of this recession and the impending threat of climate disaster would be a costly mistake—and, unfortunately, one that we have made before.

That is why if I could implement one thing to reduce the risks of climate change, I would ensure that stimulus policies designed to respond to the current economic crisis are also designed to create sustainable, long-term growth. To get these kinds of green stimulus policies off the ground fast, we can use existing programs meant to alleviate energy poverty and aging infrastructure and provide relief funding to encourage a permanent transition to a low-carbon economy.

I would also redirect resources toward rapidly scaling up production of key goods and services, and transitioning workers into different sectors crucial to decarbonization.

JOHN DABIRI

Professor of aeronautics and mechanical engineering, California Institute of Technology (US)

I would invest in a moonshot and a hedge.

The moonshot would be modular nuclear fusion. It would provide on demand power with unlimited fuel, no long lived waste, and limited risk of weapons proliferation. If achieved in a sufficiently small footprint, it could be accessible to developing countries, where energy demand will increase most significantly.

No other carbon free energy source checks all these boxes.

As a hedge, I would leverage our immense and ever increasing computational powers to develop a high resolution Earth model that can predict extreme weather events weeks in advance. Some of the most acute cli mate risks flooding and fires, for example are especially dangerous because they re currently unpredictable. If we can extend weather pre diction even further, from weeks to months in advance, perhaps even seasonal droughts could become a nuisance rather than an existential threat.

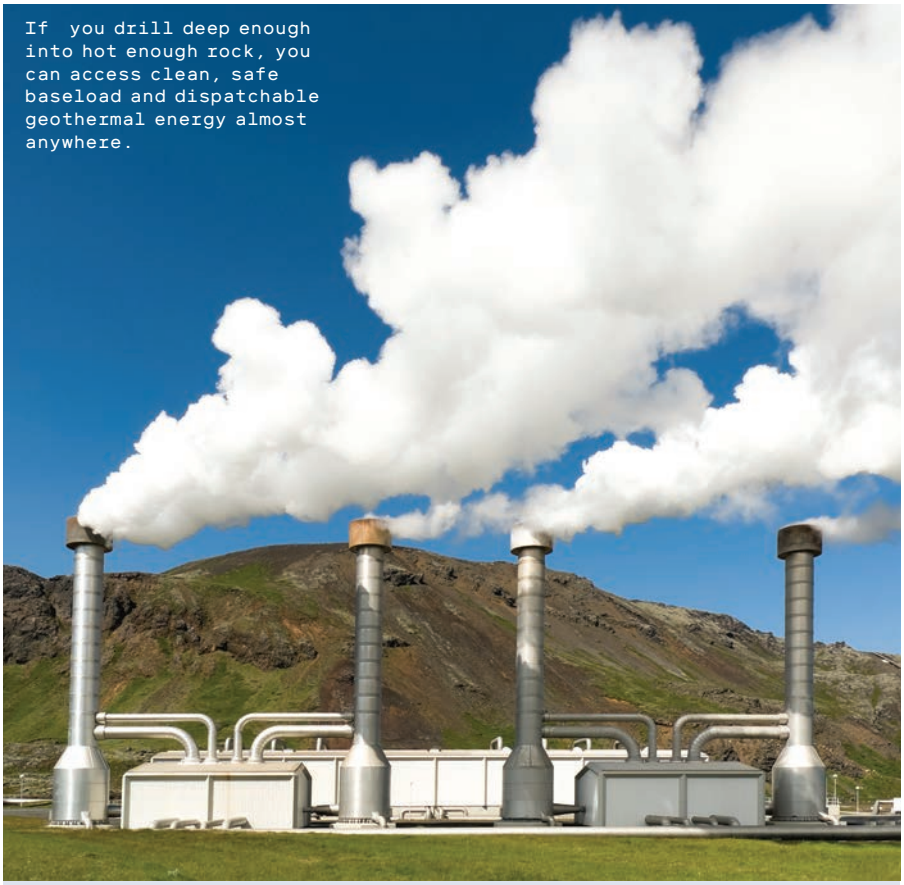
NHUNG LE (GUNN-WRIGHT); ALAN VIDALI (DABIRI); STEVE CASTILLO (BENSON); COURTESY PHOTO (KOLBERT)

Highest estimate for the number of people whom climate change could drive into poverty by 2030, in a worst-case scenario

122 MILLION

Global economic losses from wildfires in 2020

$19 BILLION



ADAM MARBLESTONE

Innovation fellow, Schmidt Futures (US)

Fortunately, it turns out that if you drill deep enough into hot enough rock, you can access clean, safe baseload and dispatchable geothermal energy almost anywhere in principle. A large scale expansion of geothermal energy availability would fill a key gap due to the intermittency of renewables, notwithstanding a hoped for gigantic rollout of next generation storage and transmission technologies.

While geothermal needn t supersede other options in the long term pipeline for baseload and dispatchable energy like novel compact fusion approaches leveraging high temperature superconductors, or small modular fission reactors it has the advantage of using more pedestrian technology and building on existing oil and gas talent and supply chains.

“The US will need to build enough storage of all types to provide 10,000 gigawatts of backup electricity.”

STEVEN CHU

Former US energy secretary and professor of physics, Stanford University (US)

At the top of my list would be low cost, long duration energy storage.

Most lithium ion battery systems being installed today are used to improve the stability of the power system, storing a few hours of energy each day during periods of peak electricity generation and releasing it during the peak demand. For example, the peak of solar generation is at noon but the peak demand for electricity occurs at roughly 4 p.m. For renewable sources to provide 80% of the electricity on the grid, given the huge seasonal dips in solar and wind output, we ll need technologies capable of storing as much as 100 hours of energy, a recent Joule study estimated.

Storage also needs to get much cheaper. Ultimately, the US will need to build enough storage of all types to provide 10,000 gigawatts of backup electricity, up from only around 25 gigawatts today.

GETTY (GEOTHERMAL); COURTESY PHOTO (MARBLESTONE); STEVE FISCH (CHU)

Projected increase in the rate of group conflicts like civil wars in many parts of the world if global temperatures rise 2 ˚C

50%

Year by which extreme hot zones like the Sahara could expand from covering 0.8% of Earth's surface (as they do today) to 19%

2070

A simple, non gameable fee for extracting fossil fuels from the ground, which would increase by a fixed percentage each year.

KEN CALDEIRA

Senior advisor on climate science, Gates Ventures, and senior staff scientist emeritus, Carnegie Global Ecology (US)

If I could only implement one thing to reduce the risks of climate change, it would be a simple, non gameable fee for extracting fossil fuels from the ground, which would increase by a fixed percentage each year. This would send a clear signal to the markets that every technology emitting carbon dioxide from fossil fuels will eventually become more expensive than any alternative.

Accurately measuring the carbon removed is relatively easy to do and not easy to game, unlike with the increasingly popular carbon offset programs that climate polluters are relying upon to balance out their emissions by paying for tree planting and similar efforts.

NADIA S. OUEDRAOGO

Economic affairs officer, United Nations Economic Commission for Africa (Ethiopia)

The Paris agreement calls for keeping the global temperature rise to no more than 1.5 ˚C above preindustrial levels. Renewables alone won't get us there. Around 44% of the emission reductions needed to meet the Paris [threshold] will come from energy efficiency, with another 36% from switching to renewables. By implementing energy efficient measures and nothing else, we could lower greenhouse gas emissions 12% by 2040. The right efficiency policies could enable the world to achieve a significant portion of the emissions cuts needed to reach its climate goals without any new technology.

NAVROZ DUBASH

Professor at the Centre for Policy Research (India)

There is a lot of talk about the fact that country pledges don't add up to emissions reductions required by science. We should be talking as much, or more, about the absence of governance mechanisms that translate visions into policies. Durable national institutions are a missing piece in our collective response to climate mitigation and adaptation. They are needed to lay out a strategic vision and set targets, coordinate implementation across sectors, and mediate politics. But approaches to climate governance have to suit national context; when countries get ahead of their climate politics, the policies, goals, or systems that result can become unstable or unachievable.

GETTY (RIG); COURTESY PHOTOS

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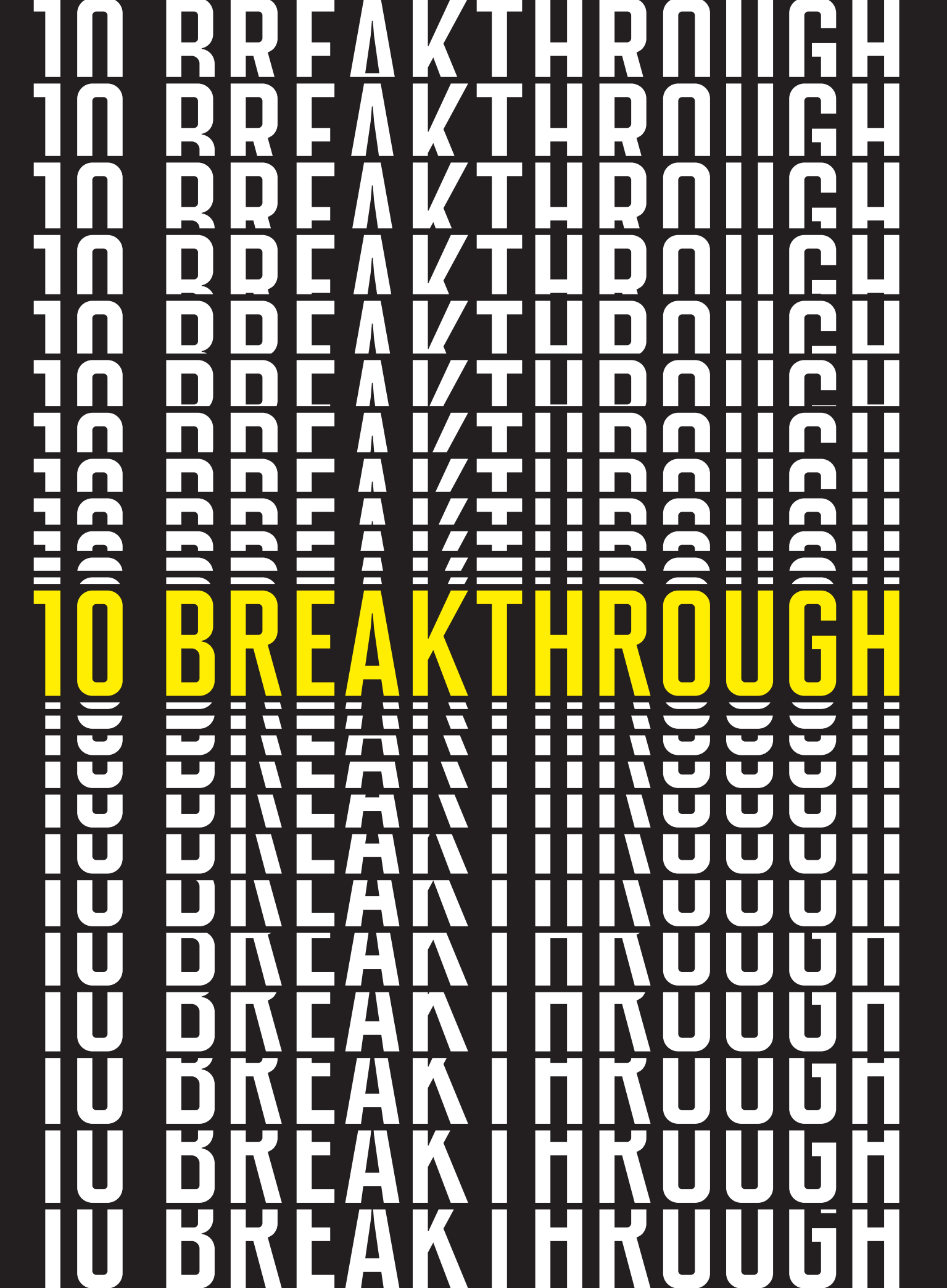
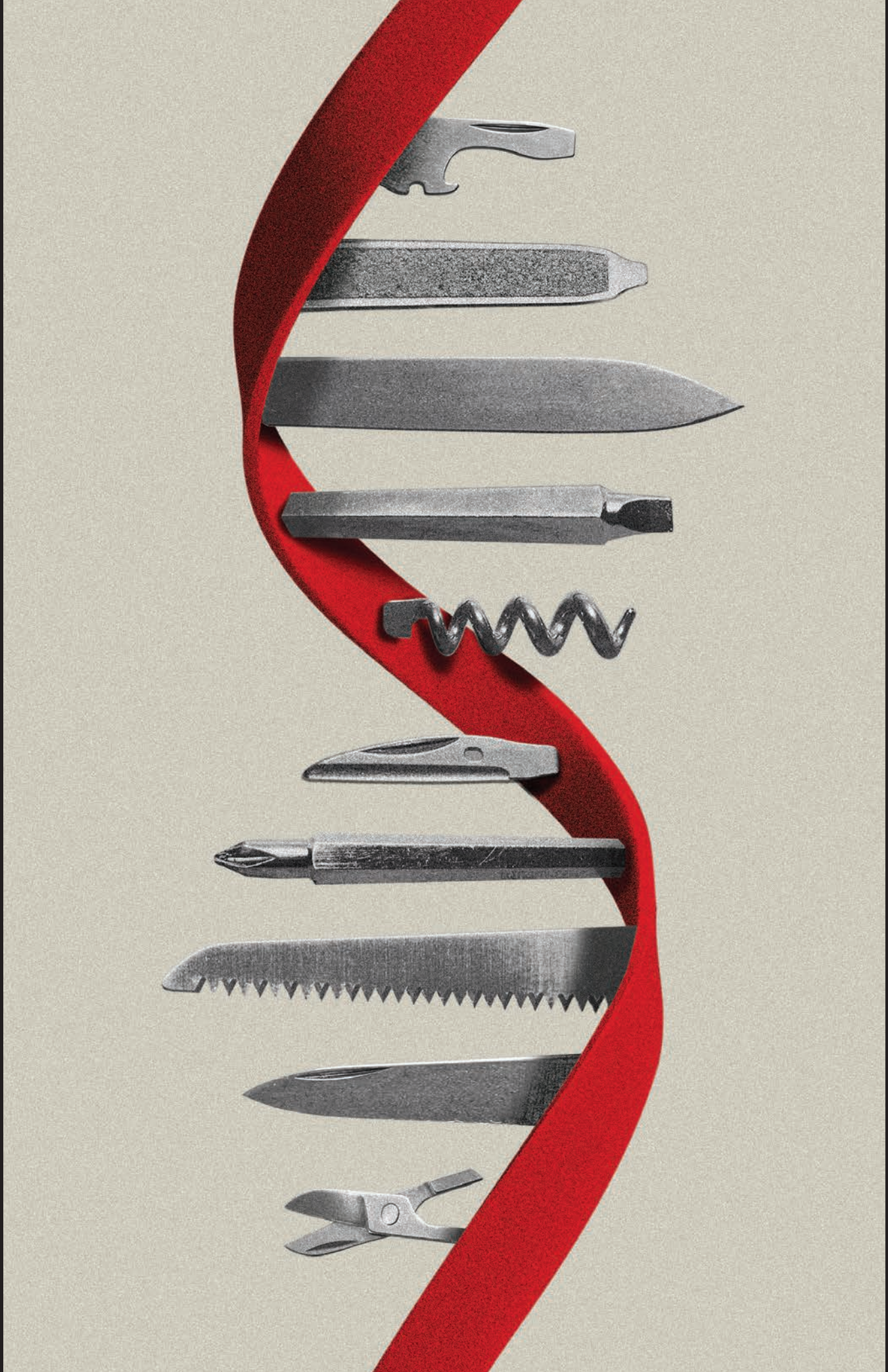

10 BREAKTHROUGH

TECHNOLOGIES

This list marks 20 years since we began compiling an annual selection of the year's most important technologies. Some, such as mRNA vaccines, are already changing our lives, while others are still a few years off. Taken together, they're a glimpse into our collective future.

2021



MESSENGER RNA VACCINES

NEW COVID VACCINES ARE BASED ON A TECHNOLOGY NEVER BEFORE USED IN THERAPEUTICS, AND IT COULD TRANSFORM MEDICINE.

BY ANTONIO REGALADO

ILLUSTRATION BY SELMAN DESIGN

WHY IT MATTERS: Worldwide, more than 2 million have died from covid-19. Vaccines based on mRNA are roughly 95% effective.

KEY PLAYERS:
- BioNTech
- GreenLight Biosciences
- Moderna Therapeutics
- Pfizer
- Strand Therapeutics

AVAILABILITY: Now

On December 23, as part of a publicity push to encourage people to get vaccinated against covid-19, the University of Pennsylvania released footage of two researchers who developed the science behind the two recently authorized vaccines, Katalin Karikó and Drew Weissman, getting their inoculations. The vaccines, icy concoctions of fatty spheres and genetic instructions, used a previously unproven technology based on messenger RNA and had been built and tested in under a year, thanks to discoveries the pair made starting 20 years earlier.

In the silent promotional clip, neither one speaks or smiles as a nurse inserts the hypodermic into their arms. I later asked Weissman, who has been a physician and working scientist since 1987, what he was thinking in that moment. "I always wanted to develop something that helps people," he told me. "When they stuck that needle in my arm, I said, 'I think I've finally done it.'"

The infection has killed more than 2 million people globally, including some of Weissman's childhood friends. So far, the US vaccine campaign has relied entirely on shots developed by Moderna Therapeutics of Cambridge, Massachusetts, and BioNTech in Mainz, Germany, in partnership with Pfizer. Both employ Weissman's discoveries. (Weissman's lab gets funding from BioNTech, and Karikó now works at the company.)

Unlike traditional vaccines, which use live viruses, dead ones, or bits of the shells that viruses come cloaked in to train the body's immune system, the new shots use messenger RNA—the short-lived middleman molecule that, in our cells, conveys copies of genes to where they can guide the making of proteins.

The message the vaccine adds to people's cells is borrowed from the coronavirus itself—the instructions for the crown-like protein, called the spike, that it uses to enter cells. This protein alone can't make a person sick; instead, it prompts a strong immune response that, in large studies concluded in December, prevented about 95% of covid-19 cases.

Beyond potentially ending the pandemic, the vaccine breakthrough is showing how messenger RNA may offer a new approach to building drugs.

In the near future, researchers believe, shots that deliver temporary instructions into cells could lead to vaccines against herpes and malaria, better flu vaccines, and, if the covid-19 germ keeps mutating, updated coronavirus vaccinations, too.

But researchers also see a future well beyond vaccines. They think the technology will permit cheap gene fixes for cancer, sickle-cell disease, and maybe even HIV.

For Weissman, the success of covid vaccines isn't a surprise but a welcome validation of his life's work. "We have been working on this for over 20 years," he says. "We always knew RNA would be a significant therapeutic tool."

PERFECT TIMING

Despite those two decades of research, though, messenger RNA had never been used in any marketed drug before last year.

Then, in December 2019, the first reports emerged from Wuhan, China, about a scary transmissible pneumonia, most likely some kind of bat virus. Chinese government censors at first sought to cover up the outbreak, but on January 10, 2020, a Shanghai scientist posted the germ's genetic code online through a contact in Australia. The virus was already moving quickly, jumping onto airplanes and popping up in Hong Kong and Thailand. But the genetic information moved even faster. It arrived in Mainz at the headquarters of BioNTech, and in Cambridge at Moderna, where some researchers got the readout as a Microsoft Word file.

Scientists at Moderna, a biotech specializing in messenger RNA, were able to design a vaccine on paper in 48 hours, 11 days before the US even had its first recorded case. Inside of six weeks, Moderna had chilled doses ready for tests in animals.

Unlike most biotech drugs, RNA is not made in fermenters or living cells—it's produced inside plastic bags of chemicals and enzymes. Because there's never been a messenger RNA drug on the market before, there was no factory to commandeer and no supply chain to call on.

When I spoke to Moderna CEO Stéphane Bancel in December, just before the US Food and Drug Administration authorized his company's vaccine, he was feeling confident about the shot but worried about making enough of it. Moderna has promised to make up to a billion doses during 2021. Imagine, he said, that Henry Ford was rolling the first Model T off the production line, only to be told the world needed a billion of them.

Bancel calls the way covid-19 arrived just as messenger RNA technology was ready an "aberration of history."

In other words, we got lucky.

HUMAN BIOREACTORS

The first attempt to use synthetic messenger RNA to make an animal produce a protein was in 1990. It worked but a big problem soon arose. The injections made mice sick. "Their fur gets ruffled. They lose weight, stop running around," says Weissman. Give them a large dose, and they'd die within hours. "We quickly realized that messenger RNA was not usable," he says.

The culprit was inflammation. Over a few billion years, bacteria, plants, and mammals have all evolved to spot the genetic material from viruses and react to it. Weissman and Karikó's next step, which "took years," he says, was to identify how cells were recognizing the foreign RNA.

As they found, cells are packed with sensing molecules that distinguish your RNA from that of a virus. If these molecules see viral genes, they launch a storm of immune molecules called cytokines that hold the virus at bay while your body learns to cope with it. "It takes a week to make an antibody response; what keeps you alive for those seven days is these sensors," Weissman says. But too strong a flood of cytokines can kill you.

The eureka moment was when the two scientists determined they could avoid the immune reaction by using chemically modified building blocks to make the RNA. It worked. Soon after, in Cambridge, a group of entrepreneurs began setting up Moderna Therapeutics to build on Weissman's advance.

Vaccines were not their focus. At the company's founding in 2010, its leaders imagined they might be able to use RNA to replace the injected proteins that make up most of the biotech pharmacopoeia, essentially producing drugs inside the patient's own cells from an RNA blueprint. "We were asking, could we turn a human into a bioreactor?" says Noubar Afeyan, the company's cofounder and chairman and the head of Flagship Pioneering, a firm that starts biotech companies.

If so, the company could easily name 20, 30, or even 40 drugs that would be worth replacing. But Moderna was struggling with how to get the messenger RNA to the right cells in the body, and without too many side effects. Its scientists were also learning that administering repeat doses, which would be necessary to replace biotech blockbusters like a clotting factor that's given monthly, was going to be a problem. "We would find it worked once, then the second time less, and then the third time even lower," says Afeyan. "That was a problem and still is."

Moderna pivoted. What kind of drug could you give once and still have a big impact? The answer eventually became obvious: a vaccine. With a vaccine, the initial supply of protein would be enough to train the immune system in ways that could last years, or a lifetime.

A second major question was how to package the delicate RNA molecules, which last for only a couple of minutes if exposed. Weissman says he tried 40 different carriers, including water droplets, sugar, and proteins from salmon sperm. It was like Edison

JUSTIN JAMES MUIR

Drew Weissman's work with RNA led to successful covid-19 vaccines.

looking for the right filament to make an electric lamp. "Almost anything people published, we tried," he says. Most promising were nanoparticles made from a mixture of fats. But these were secret commercial inventions and are still the basis of patent disputes. Weissman didn't get his hands on them until 2014, after half a decade of attempts.

When he finally did, he loved what he saw. "They were better than anything else we had tried," he says. "It had what you wanted in a drug. High potency, no adverse events." By 2017, Weissman's lab had shown how to vaccinate mice and monkeys against the Zika virus using messenger RNA. Moderna was neck and neck. It quickly published results of an early human test of a new mRNA influenza vaccine and would soon initiate a large series of clinical studies involving diseases including Zika.

Pivoting to vaccines did have a drawback for Moderna. Andrew Lo, a professor at MIT's Laboratory for Financial Engineering, says that most vaccines lose money. The reason is that many shots sell for a "fraction of their economic value." Governments will pay $100,000 for a cancer drug that adds a month to a person's life but only want to pay $5 for a vaccine that can protect against an infectious disease for good. Lo calculated that vaccine programs for emerging threats like Zika or Ebola, where outbreaks come and go, would deliver a -66% return on average. "The economic model for vaccines is broken," he says.

On the other hand, vaccines are more predictable. When Lo's team analyzed thousands of clinical trials, they found that vaccine programs frequently succeed. Around 40% of vaccine candidates in efficacy tests, called phase 2 clinical trials, proved successful, a rate 10 times that of cancer drugs.

Adding to mRNA vaccines' chance of success was a lucky break. Injected into the arm, the nanoparticles holding the critical instructions seemed to home in on dendritic cells, the exact cell type whose job is to train the immune system to recognize a virus. What's more, something about the particles put the immune system on alert. It wasn't planned, but they were working as what's called a vaccine adjuvant. "We couldn't believe the effect," says Weissman.

Vaccines offered Moderna's CEO, Bancel, a chance to advance a phalanx of new products. Since every vaccine would use the same nanoparticle carrier, they could be rapidly reprogrammed, as if they were software. (Moderna had even trademarked the name "mRNA OS," for operating system.) "The way we make mRNA for one vaccine is exactly the same as for another," he says. "Because mRNA is an information molecule, the difference between our covid vaccine, Zika vaccine, and flu vaccine is only the order of the nucleotides."

95% EFFECTIVE

Back in March 2020, when the vaccine programs were getting under way, skeptics said messenger RNA was still an unproven technology. Even this magazine said a vaccine would take 18 months, at a minimum—a projection that proved off by a full nine months. "Sometimes things take a long time just because people think it does," says Afeyan. "That weighs on you as a scientific team. People are saying, 'Don't go any faster!'"

The shots from Moderna and BioNTech proved effective by December and were authorized that month in the US. But the record speed was not due only to the novel technology. Another reason was the prevalence of infection. Because so many people were catching covid-19, the studies were able to amass evidence quickly.

Is messenger RNA really a better vaccine? The answer seems to be a resounding yes. There are some side effects, but both shots are about 95% effective (that is, they stop 95 out of 100 cases), a record so far unmatched by other covid-19 vaccines and far better than the performance of flu vaccines. Another injection, made by AstraZeneca using an engineered cold virus, is 70% effective. A shot developed in China using deactivated covid-19 germs protected only half the people who got it, although it did stop severe disease.

"This could change how we make vaccines from here on out," says Ron Renaud, the CEO of Translate Bio, a company working with the technology.

These facilities from the biopharmaceutical company Lonza in Switzerland (top) and New Hampshire are helping to produce Moderna's vaccine.

LONZA LTD

The potency of the shots, and the ease with which they can be reprogrammed, mean researchers are already preparing to go after HIV, herpes, infant respiratory virus, and malaria—all diseases for which there's no successful vaccine. Also on the drawing board: "universal" flu vaccines and what Weissman calls a "pan-coronavirus" shot that could offer basic protection against thousands of pathogens in that category, which have led not only to covid-19 but, before that, to the infection SARS and probably other pandemics throughout history.

"You have to assume we're going to have more," Weissman says. "So instead of shutting down the world for a year while you make a new vaccine, we'll have a vaccine ready to go."

Last spring, Bancel began petitioning the government to pay for vast manufacturing centers to make messenger RNA. He imagined a megafactory that "companies could use in peacetime" but that could be quickly reoriented to churn out shots during the next pandemic. That would be insurance, he says, against a nightmare scenario of a germ that spreads as fast as covid but has the 50% fatality rate of Ebola. If "governments spend billions on nuclear weapons they hope to never use," Bancel argued in April, then "we should equip ourselves so this never happens again."

Later that month, as part of Operation Warp Speed, the US effort to produce the vaccines, Moderna was effectively picked as a national champion to build such centers. The government handed it nearly $500 million to develop its vaccine and expand manufacturing.

BEYOND VACCINES

After the covid vaccines, some researchers expect Moderna and BioNTech to return to their original plans for the technology, like treating more conventional ailments such as heart attacks, cancer, or rare inherited diseases. But there's no guarantee of success in that arena.

"Although there are a lot of potential therapeutic applications for synthetic mRNA in principle, in practice the problem of delivering sufficient amounts of mRNA to the right place in the body is going to be a huge and possibly insurmountable challenge in most cases," says Luigi Warren, a biotech entrepreneur whose research as a postdoc formed the nucleus of Moderna.

There is one application in addition to vaccines, however, where brief exposure to messenger RNA could have effects lasting years, or even a lifetime.

In late 2019, before covid-19, the US National Institutes of Health and the Bill and Melinda Gates Foundation announced they would spend $200 million developing affordable gene therapies for use in sub-Saharan Africa. The top targets: HIV and sickle-cell disease, which are widespread there.

Gates and the NIH didn't say how they would make such cutting-edge treatments cheap and easy to use, but Weissman told me that the plan may depend on using messenger RNA to add instructions for gene-editing tools like CRISPR to a person's body, making permanent changes to the genome. Think of mass vaccination campaigns, says Weissman, except with gene editing to correct inherited disease.

Right now, gene therapy is complex and expensive. Since 2017, several types have been approved in the US and Europe. One, a treatment for blindness, in which viruses carry a new gene to the retina, costs $425,000 per eye.

A startup called Intellia Therapeutics is testing a treatment that packages CRISPR into RNA and then into a nanoparticle, with which it hopes to cure a painful inherited liver disease. The aim is to make the gene scissors appear in a person's cells, cut out the problem gene, and then fade away. The company tested the drug on a patient for the first time in 2020.

It's not a coincidence that Intellia is treating a liver disease. When dripped into the bloodstream through an IV, lipid nanoparticles tend to all end up in the liver—the body's house-cleaning organ. "If you want to treat a liver disease, great—anything else, you have a problem," says Weissman.

But Weissman says he's figured out how to target the nanoparticles so that they wind up inside bone marrow, which constantly manufactures all red blood cells and immune cells. That would be a hugely valuable trick—so valuable that Weissman wouldn't tell me how he does it. It's a secret, he says, "until we get the patents filed."

He intends to use this technique to try to cure sickle-cell disease by sending new instructions into the cells of the body's blood factory. He's also working with researchers who are ready to test on monkeys whether immune cells called T cells can be engineered to go on a seek-and-destroy mission after HIV and cure that infection, once and for all.

What all this means is that the fatty particles of messenger RNA may become a way to edit genomes at massive scales, and on the cheap. A drip drug that allows engineering of the blood system could become a public health boon as significant as vaccines. The burden of sickle-cell, an inherited disease that shortens lives by decades (or, in poor regions, kills during childhood), falls most heavily on Black people in equatorial Africa, Brazil, and the US. HIV has also become a lingering scourge: about two-thirds of people living with the virus, or dying from it, are in Africa.

Moderna and BioNTech have been selling their covid-19 vaccine shots for $20 to $40 a dose. What if that were the cost of genetic modification, too? "We could correct sickle-cell with a single shot," Weissman says. "We think that is groundbreaking new therapy."

There are fantastic fortunes to be made in mRNA technology. At least five people connected to Moderna and BioNTech are now billionaires, including Bancel. Weissman is not one of them, though he stands to get patent royalties. He says he prefers academia, where people are less likely to tell him what to research—or, just as important, what not to. He's always looking for the next great scientific challenge: "It's not that the vaccine is old news, but it was obvious they were going to work." Messenger RNA, he says, "has an incredible future." ■

Antonio Regalado is MIT Technology Review's biomedicine editor.

By
Will Douglas Heaven

Photograph by
Sierra & Lenny

OPENAI'S LANGUAGE AI WOWED THE PUBLIC WITH ITS APPARENT MASTERY OF ENGLISH—BUT IS IT ALL AN ILLUSION?

WHY IT MATTERS:
Large computer models that learn natural language are a big step toward AI that can understand and interact with the human world.

KEY PLAYERS:
- OpenAI
- Google
- Facebook

AVAILABILITY:
Now

GPT-3 has captured the public's imagination unlike any AI since DeepMind's AlphaGo or IBM's chess-playing DeepBlue.

Built by OpenAI, a research lab based in San Francisco, it is a "large language model"—an algorithm that uses deep learning, trained on the text of thousands of books and most of the internet, to string words and phrases together. When it was launched in 2020, its ability to mimic human-written text with uncanny realism seemed to many like a milestone on the road to true machine intelligence.

Here's an example of what it can do. The part in italics was the prompt provided by a human.

In a shocking finding, scientists discovered a herd of unicorns living in a remote, previously unexplored valley in the Andes Mountains. Even more surprising to the researchers was the fact that the unicorns spoke perfect English. They also were found to have perfectly coiffed hair, and

wore what appeared to be Dior makeup.

"We were shocked to discover the unicorns," said anthropologist Daniel St. Maurice. "They were like nothing we had ever seen before. We had heard legends of the unicorns, but never thought they actually existed."

When the scientists first arrived in the valley, the unicorns were surprised and startled by the presence of humans, but were also excited. The unicorns welcomed the researchers and explained that they had been waiting for them for a very long time.

As you can see, GPT-3 is capable of producing complex sentences that read as though they could have been produced by a human. The example sentences include cultural references and a believable account of how the scientists would react. Machines that can use language in this way are important for several reasons. Language is crucial to making sense of the everyday world: humans use it to communicate, to share ideas and describe concepts. An AI that mastered language would acquire a better understanding of the world in the process.

Large language models have many practical uses, too. They power better chatbots that hold more fluent conversations; they can generate articles and stories about anything, given a prompt; they can summarize pieces of text or answer queries about them. Access to GPT-3 is by invitation only, but people have already used it to power dozens of apps, from a tool that generates startup ideas to an AI-scripted adventure game set in a dungeon.

GPT-3 isn't the only large language model to appear in 2020. Microsoft, Google, and Facebook all announced their own. But GPT-3 was the best generalist by far. And it gives the impression it can write anything: fan fiction, philosophical polemics, and even code. When people started to try GPT-3 for themselves last summer, thousands of examples of its versatility flooded social media. Debates were even sparked about whether GPT-3 was the first artificial general intelligence.

It's not. Despite the incredibly convincing passages of text it can churn out, GPT-3 doesn't do anything really new. What it shows instead is that size can be everything. To build GPT-3, OpenAI used more or less the same approach and algorithms it used for its older sibling, GPT-2, but it supersized both the neural network and the training set. GPT-3 has 175 billion parameters—the values in a network that get adjusted during training—compared with GPT-2's 1.5 billion. It was also trained on a lot more data.

Before GPT-2, training a language model using deep learning typically took two passes: it was trained on a general-purpose data set to give it a basic grasp of language and then trained on a smaller set targeted at a specific task, such as comprehension or translation. GPT-2 showed that you could get good results across the board with just one pass if you threw more examples at a bigger model. So with GPT-3, OpenAI doubled down and made the biggest language model ever.

The results that caught everyone's attention were often cherry-picked, however. GPT-3 often repeats or contradicts itself in passages of text more than a few hundred words long. It comes out with howlers. GPT-3 hides its stupidity behind a silver tongue, but it typically takes a few goes to get it to generate something that doesn't show the cracks.

GPT-3's abilities also make it hard to ignore AI's growing problems. Its enormous power consumption is bad news for the climate: researchers at the University of Copenhagen in Denmark estimate that training GPT-3 would have had roughly the same carbon footprint as driving a car the distance to the moon and back, if it had been trained in a data center fully powered by fossil fuels. And the costs of such training—estimated by some experts to be at least $10 million in GPT-3's case—put the latest research out of reach of all but the richest labs.

OpenAI reports that training GPT-3 consumed several thousand petaflop/s-days of computing power. A petaflop/s-day is a unit of power consumption that consists of performing 10^{15}—that's one thousand trillion, or a quadrillion—neural-network computations per second for a day. In comparison, GPT-2 consumed just tens of petaflop/s-days.

Yet another problem is that GPT-3 soaks up much of the disinformation and prejudice it finds online and reproduces it on demand. As the team that built it said in the paper describing the technology: "internet-trained models have internet-scale biases."

The veneer of humanity that GPT-3 gives to machine-generated text makes it easy to trust. This has led some to argue that GPT-3 and all human-like language models should come with a safety warning, a "User beware" sticker, alerting people that they are chatting with software and not a human.

A few months ago someone released a GPT-3-powered bot on Reddit, where it posted hundreds of comments and interacted with dozens of users over several days before it was unmasked. Much of its activity was harmless. But the bot also replied to comments about suicidal thoughts, giving personal advice that mentioned the support of its "parents."

Despite all these issues, GPT-3 is a win for those who believe bigger is better. Such models show that computing power and data get you a long way, and we can expect more of both in the future. What might a GPT-4 be like? We can expect chatbots to get slicker, better at stringing together longer pieces of coherent text, with an even wider mastery of conversational topics.

But language is just one way to understand and interact with the world. Next-generation language models will integrate other skills, such as image recognition. OpenAI is already taking GPT-3 in this direction with AIs that use language to understand images and images to understand language.

If you want to know the state of deep learning today, look at GPT-3. It is a microcosm of the best and worst in AI. ■

Will Douglas Heaven is MIT Technology Review's senior editor for AI.

DATA TRUSTS

By
Anouk Ruhaak

Illustration by
Franziska Barczyk

DO you simply click "Yes" whenever a company asks for your data? If so, you're not alone. We can't be expected to read the lengthy terms and conditions or evaluate all the risks every time we use a service. That's like asking each of us to assess whether the water we drink is safe every time we take a sip. So we hit "Yes" and hope for the best.

Even if you've done your research, though, your decision could affect other people in ways you didn't account for. When you share your DNA with services like 23andMe, that data reveals a lot about your family's genetic make-up. What you share on social media could influence your friends' insurance premiums. Your income statements could affect your neighbor's ability to obtain a loan. Should sharing this information be solely up to you?

EXPECTING PEOPLE TO MANAGE THEIR OWN DATA IS UNREALISTIC. IT'S TIME TO JOIN FORCES.

WHY IT MATTERS: Companies and governments have mishandled our data time and again. Data trusts could help us reclaim greater agency over it.

KEY PLAYERS:
- Data Trusts Initiative
- Digital Public
- Open Data Institute
- National governments
- European Commission

AVAILABILITY: 2 to 3 years

If this model of individual consent is broken, then what's left? Should we leave it to our politicians to regulate data collection? Perhaps. Governments around the world have implemented data protection regimes (such as Europe's GDPR) that force companies to ask for our consent before collecting data. They could go further and prohibit the most harmful uses of data. But given the numerous ways in which data might be collected or used, it's hard to imagine that broad regulations would be enough.

What if we had something to stand up for our data rights the way a trade union stands up for labor rights? And the data equivalent of a doctor to make smart data decisions on our behalf? Data trusts are one idea for how we could get just that.

Data trusts are a relatively new concept, but their popularity has grown quickly. In 2017, the UK government first proposed them as a way to make larger data sets available for training artificial intelligence. A European Commission proposal in early 2020 floated data trusts as a way to make more data available for research and innovation. And in July 2020, India's government came out with a plan that prominently featured them as a mechanism to give communities greater control over their data.

In a legal setting, trusts are entities in which some people (trustees) look after an asset on behalf of other people (beneficiaries) who own it. In a *data* trust, trustees would look after the data or data rights of groups of individuals. And just as doctors have a duty to act in the interest of their patients, data trustees would have a legal duty to act in the interest of the beneficiaries.

So what would this approach look like in practice? As one example, groups of Facebook users could create a data trust. Its trustees would determine under what conditions the trust would allow Facebook to collect and use those people's data. The trustees could, for example, set rules about the types of targeting that platforms like Facebook could employ to show ads to users in the trust. If Facebook misbehaved, the trust would retract the company's access to its members' data.

While it's hard for any of us to assess how sharing our data might affect others, data trustees could weigh individual interests against collective benefits and harms. In theory, because the data trust would represent a collective, it could negotiate terms and conditions on our behalf. Thus, it could allow us to exercise our rights as producers of data in much the same way trade unions allow workers to exercise their rights as purveyors of labor.

Data trusts sound good, but is this vision really realistic? It's hard to imagine that Facebook would ever agree to deal with one. And we, the users, have few ways to force its hand. We could form a data trust, but unless we're all willing to leave the platform together, or unless governments provide us with greater enforcement mechanisms, that trust would have very little leverage.

All is not lost, though, because data trusts have many other useful applications. They could allow people to pool their data and make it available for uses, such as medical research, that benefit everyone. Companies that want to show they're privacy aware could hand over the reins on key data decisions to a trust and instruct it to protect customers' data rights instead of the company's bottom line.

For example, in 2017, Google sister company Sidewalk Labs procured the rights to develop Toronto's Quayside waterfront into a sensor-laden smart neighborhood. But what was hailed by some as a utopia was seen by others as yet another case in which large tech companies have encroached on the public domain, hoovering up residents' data in the process.

Sidewalk Labs suggested the creation of a civic data trust to guarantee that data collected and used in Quayside would benefit the public. The proposal was that any entity wishing to place a sensor in Quayside would have to request a license to both collect and use data. A review board, made up of community members, would monitor and enforce that collection and use.

The plan itself was flawed, and Sidewalk Labs abandoned the Quayside project in May 2020, but the company's proposal showcased the promise of data trusts. The idea of creating them to govern data collected in a public context (such as in smart cities, or for public health initiatives) lives on.

The problems data trusts aim to tackle are as urgent as ever. For the coming year, as funding becomes more widely available, we'll see further research, more experiments, and more policy proposals.

Certainly, data trusts aren't the only solution to growing privacy and security concerns. Other possible mechanisms, including data cooperatives and data unions, would tackle similar problems in different ways. Together, these new data governance models could help us regain control of our data, enforce our rights, and ensure that data sharing benefits us all. ■

Anouk Ruhaak is a senior fellow with the Mozilla Foundation in Berlin, researching data governance.

QuantumScape's prototype cell features a solid version of the usually liquid electrolyte.

LITHIUM-METAL BATTERIES

A NEW TYPE OF BATTERY COULD FINALLY MAKE ELECTRIC CARS AS CONVENIENT AND CHEAP AS GAS ONES.

By **James Temple**

Photographs by **Winni Wintermeyer**

WHY IT MATTERS: The performance limitations of batteries have held back the switch to cleaner electric cars and all but ruled out electric planes.

KEY PLAYERS:
- QuantumScape
- Samsung Advanced Institute of Technology
- Solid Power
- 24M

AVAILABILITY: 2025

For all the hype and hope around electric vehicles, they still make up only about 2% of new car sales in the US and just a little more globally.

For many buyers, they're simply too expensive, their range is too limited, and charging them isn't nearly as quick and convenient as refueling at the pump.

All these limitations have to do with the lithium-ion batteries that power the vehicles. They're costly, heavy, and quick to run out of juice. To make matters worse, the batteries rely on liquid electrolytes that can burst into flames during collisions.

Making electric cars more competitive with gas-powered ones will require a breakthrough battery that remedies those shortcomings. That, at least, is the argument of Jagdeep Singh, chief executive of QuantumScape, a Silicon Valley startup that claims to have developed just such a technology.

The company asserts it did so by solving a chemistry puzzle that has stumped researchers for nearly half a century: how to use lithium, the lightest metal on the periodic table, to boost the amount of energy that can be packed into a battery without posing a routine risk of fire or otherwise sacrificing performance. The company says it achieved this, in large part, by developing a solid version of the flammable liquid electrolyte.

VW was impressed enough to invest hundreds of millions of dollars in QuantumScape. The German auto giant also agreed to set up a joint venture with the company to mass-produce the batteries and says they'll be in its electric cars and trucks on the road by 2025.

FASTER CHARGING AND LONGER RANGE

In a conventional lithium-ion battery, one of the two electrodes, the anode, is made mostly from graphite. This is a form of carbon that can easily take up and release the charged lithium ions that shuttle back and forth between the anode and cathode through the electrolyte. That stream of charged particles produces an electric current, which flows out of the battery to power whatever needs powering. But the graphite is merely a host for the lithium ions, which nestle in between sheets of carbon like packages on shelves. It's dead weight that doesn't store energy or produce a current itself.

In a lithium-metal battery, the anode itself is made from lithium. This means that nearly every atom in the battery's anode can also be put to work creating current. Theoretically, a lithium-metal anode could store 50% more energy than a graphite one of the same weight and volume.

However, because lithium metal is so reactive, being in constant contact with a liquid electrolyte can trigger reactions that degrade the battery or cause it to combust, says Venkat Viswanathan, an associate professor at Carnegie Mellon who works on lithium-metal batteries and is a consultant for QuantumScape. Another issue is that as the lithium ions flow back and forth, needle-like structures known as dendrites can form in the batteries and short-circuit the cell or cause it to catch fire.

QuantumScape, which went public in November after operating in stealth mode for a decade, is still holding back some of the critical details on how its solid-electrolyte battery overcomes these problems. But it appears to perform remarkably well.

In an online presentation in December, the startup displayed a series of charts showing that a single-layer lab version of the battery can be charged to more than 80% of its capacity in 15 minutes, lasts for hundreds of thousands of miles, and works fine at freezing temperatures. The company expects the batteries to be able to boost electric vehicles' range by more than 80%: a car that can go 250 miles on a single charge today could drive 450 miles instead.

"QuantumScape has set me back on my heels," says Nancy Dudney, a battery researcher at Oak Ridge National Laboratory, who has done pioneering work on solid-state electrolytes. "At first view, it looks really good," she says, though she adds, "We've been here before with other battery advances."

Indeed, the battery field is littered with examples of startups that promised breakthrough technologies but ultimately failed. And the challenges ahead of QuantumScape are daunting, particularly when it comes to converting its prototype cells into commercial products that can be manufactured cheaply.

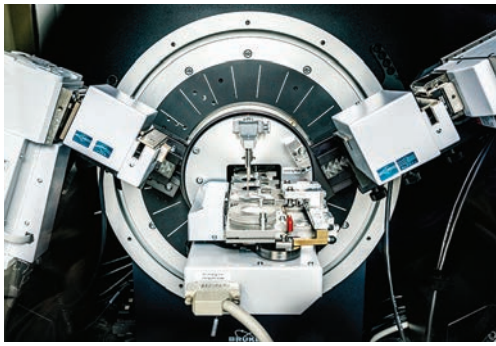
If the company succeeds, it could transform the EV marketplace. Cutting costs, boosting range, and making charging nearly as convenient as filling up at a gas station could broaden demand beyond people who can afford to shell out thousands of dollars for charging ports at home, and ease the anxieties of those who fear being stranded on longer trips.

The added energy density and faster charging could also make it more practical to electrify other forms of transportation, including long-haul trucking and even short-distance flights. (As a bonus, it would also deliver phones and laptops that could last a couple of days on one charge.)

BIRTH OF A BATTERY

The story of lithium-metal batteries began in the early 1970s and is tightly intertwined with the development of the lithium-ion ones we depend on today.

The oil crises of the era, coupled with what would turn out to be very early peak-petroleum fears, suddenly reignited an interest in electric vehicles for the first time since the infancy of the auto industry. By 1972, American Motors, Chrysler, Ford, GM, Toyota, VW, and others were all working on electric cars, as the science writer Seth Fletcher describes in the book *Bottled Lighting*. Meanwhile, large industrial labs, including those at GE, Dow Chemical, and Exxon, were searching for better battery chemistries.



Cathodes for QuantumScape's batteries are made on this fabrication line. At right, an x-ray diffractometer is used to check the battery components.

Batteries back then, which were mostly lead-acid, couldn't deliver anywhere near the distances or speeds of gas engines. In 1969, General Motors' experimental 512 electric car boasted a top speed of about 30 miles an hour, with a range of 47 miles.

In 1972, Exxon's research division hired a young chemist named Stan Whittingham on the strength of his postdoctoral work at Stanford. Specifically, he was developing crystalline materials that allowed ions to easily flow in and out. At Exxon, Whittingham and his colleagues began experimenting with a promising porous material for a cathode: titanium disulfide. They paired it with an anode made from metallic lithium, a highly reactive material that readily releases its electrons. It worked surprisingly well.

The team applied for a patent in 1973, published a landmark paper in Science in 1976, and showed off a larger version of the cells at an auto show in 1977.

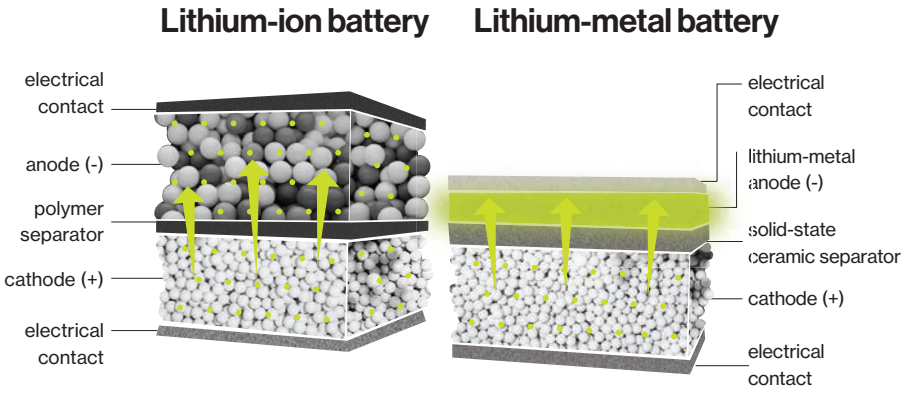
By the early 1980s, the oil crisis had passed. Exxon's new management decided to shed any business line without the potential to become a $100 million annual market. The company dropped its electric-vehicle and battery efforts. "They said, 'These are too small for us to be involved in,'" says Whittingham.

LITHIUM-ION TAKES OVER

Lithium-metal batteries were far superior to lead-acid batteries, but they also had inherent drawbacks the Exxon team had never resolved, including their habit of sparking fires in the lab.

Others who attempted to commercialize lithium-metal batteries ran into similar problems. In the 1980s, Moli Energy of British Columbia developed a 2.2-volt lithium-metal battery for laptops and cell phones. But in 1989, a Japanese cell phone caught fire, burning its owner. After an investigation pinned the blame on the battery, thousands of cell phones were recalled and the company went into receivership, according to Electric Autonomy Canada.

Meanwhile, others were building on Whittingham's work. John Goodenough, now a professor at the University of Texas at Austin, used cobalt oxide rather than titanium disulfide to develop a cathode that could store more energy. Akira Yoshino, a professor at Meijo University, swapped the pure lithium anode for coke (another form of carbon), which could still store a lot of lithium ions but reduced the fire dangers. Finally, researchers at Sony assembled the pieces to develop the first commercial lithium-ion batteries in 1992. Whittingham, Goodenough, and Yoshino shared the Nobel Prize in chemistry in 2019 for their roles in the breakthrough.



In a lithium-ion battery, lithium ions shuttle back and forth between the anode and cathode as the battery charges and discharges. In QuantumScape's battery, the ions travel through a separator and form a perfectly flat layer between it and the electrical contact, creating the anode when it's charged. It lacks an anode in its depleted state (at right).

The runaway success of lithium-ion batteries, which now power our laptops, phones, and electric vehicles, quashed efforts to commercialize lithium-metal technology for years to come. But some never lost sight of lithium-metal's potential to be a more efficient form of energy storage. And replacing the standard liquid electrolytes, which are effectively combustible solvents, with solid materials seemed a particularly promising avenue of exploration.

Around 2000, a team at Oak Ridge National Laboratory demonstrated thin-film batteries—the kind deployed in small electronics like smart cards and pacemakers—that used solid-state lithium-metal technology. The production process and size and shape of thin-film batteries mostly limit their use beyond anything larger than a watch, says Paul Albertus, a battery expert at the University of Maryland. But the work provided a crucial proof of concept for a working lithium-metal battery.

ROAD KILL

Various startups had begun pursuing the technology again by the late 2000s. But it has proved to be a treacherous road.

Some have already closed down. Seeo, formed in 2007, was bought by the German company Bosch, which later disbanded its battery research efforts. France-based Bolloré was the first to put solid-state lithium-metal batteries into vehicles on the road, launching its Bluecar car-sharing programs in 2011. But its polymer-based electrolytes only work at higher temperatures, limiting their use in consumer vehicles.

A handful of other companies, however, have made more recent advances. Most notably, two days after QuantumScape's presentation last December, Solid Power, a Colorado startup founded in 2012, announced that it is already producing pilot-scale batches of 22-layer lithium-metal cells that would surpass the range of today's electric-vehicle batteries.

And in January, the Department of Energy's ARPA-E division announced it would invest $9 million into an effort by battery company 24M and Carnegie Mellon's Viswanathan to develop lithium-metal batteries designed for electric planes, where the energy stored and power delivered per kilogram are crucial.

STARTING UP QUANTUMSCAPE

The trick for any company developing lithium-metal batteries has been to pinpoint electrolyte materials that prevent fires and dendrites while still allowing ions to easily pass through, and without otherwise degrading the performance of the battery. And that's precisely what QuantumScape claims it has done.

The origins of the company date back to 2009. As Singh was preparing to step down as CEO of Infinera, a networking company he cofounded, he began talking with Stanford postdoctoral fellow Tim Holme and his advisor, Friedrich Prinz, about forming a company based on their research on novel battery materials.

The trio cofounded QuantumScape the following year, aiming to develop energy-dense batteries with high power output. They first tried to do so by creating an entirely new type of battery, known as an all-electron battery, but found it would be harder than it initially seemed.

By then, the company had raised tens of millions of dollars from venture capital firms like Kleiner Perkins and Khosla Ventures. That left QuantumScape with enough money to quietly shift direction, pursuing the dream of lithium-metal technology.

The company spent the next five years looking for just the right material to develop a solid-state electrolyte, Singh says. It then spent another five working out the right composition and manufacturing process to prevent defects and dendrites. All the company will say about its electrolyte is that it's a ceramic.

ARE WE THERE YET?

All of QuantumScape's published tests so far were performed on single-layer cells. To work in cars, the company will need to produce batteries packed with several dozen layers, effectively moving from a single playing card to a deck. And it will still have to find a way to manufacture these cells cheaply enough to compete with lithium-ion, a battery technology that's dominated for decades.

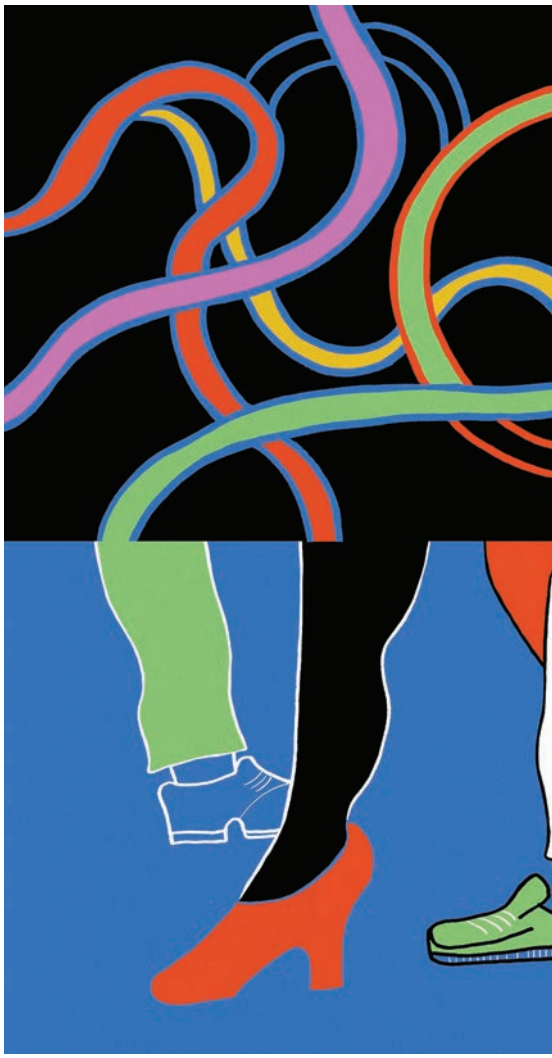
It's a daunting engineering task. "They're partway there—after 10 years and $300 million and 150 people working on this, they have this little playing card now," says Albertus, from the University of Maryland. "That's a long way away still from delivering batteries on the thousands-of-metric-tons scale—and it's a really hard challenge." Several battery researchers told me they seriously doubt that QuantumScape can scale up and complete full safety tests in time to put batteries in cars on the road just four years from now.

Given the company's results and the encouraging announcements from other startups, most people in the battery world do think it's looking more likely that the problems that have held up lithium-metal for decades can be solved—which is why it's on MIT Technology Review's list of breakthrough technologies this year. But it's also clear that for all the progress that's been made since Whittingham's time at Exxon, years of work still lie ahead. ■

James Temple is MIT Technology Review's senior editor for climate and energy.

KYLE THOMAS HEMINGWAY; SOURCE: QUANTUMSCAPE

DIGI-TAL CON-TACT TRAC-ING



IF we've learned anything from covid-19, it's the extent to which our lives are enmeshed with those of the people around us. We interact constantly, spreading our germs and picking up theirs. That's why exposure notifications—using your phone to tell you if you've crossed paths with an infected person—seemed so promising.

Technology offered a way to automate time-honored contact tracing efforts in which public health investigators ask patients to retrace their footsteps in order to deduce where they got infected. Did they interact with a clerk at the store, a classroom of children, a thousand passengers on a cruise ship? Apps meant disease sleuths wouldn't have to rely on an individual's memory, and they could ease strain on the authorities monitoring an outbreak.

That idea sparked a remarkable wave of development and cooperation. Some programmers had systems up and running in weeks, open-sourcing their code and sharing it freely so that countries as far apart as Canada and Mongolia could essentially use the same system. Meanwhile Apple and Google, rivals in almost every usual respect, collaborated on a system that worked on smartphones and kept health data anonymous and private. By January, MIT Technology Review was tracking 77 exposure notification apps being used by governments around the world.

Like many things meant to slow the pandemic, however, digital contact tracing hasn't yielded the lifesaving results we needed. In fact, it barely made a dent. Why?

BITTER RIVALS TEAMED UP TO BUILD TOOLS THEY HOPED WOULD HELP SLOW THE VIRUS'S SPREAD.

WHY IT MATTERS: Covid exposure notifications didn't live up to the hype. But there's still a lot to learn from their rollout.

KEY PLAYERS:
- Apple
- Google

AVAILABILITY: Now

By **Lindsay Muscato**

Illustration: **Franziska Barczyk**

A CHALLENGE TOO GREAT

In many countries, limiting the spread of covid simply seemed too hard a problem for contact tracing to solve. Slow action, mixed messages, mismanagement, and neglect all played a part: despite lockdowns, travel restrictions, and mask mandates, the virus kept infecting people. It didn't matter whether you were riding on a bus, gathering for dinner, or toasting at the White House.

Exposure notifications also suffered from mistrust and a lack of clear messaging. Some people didn't believe their own government's warnings about the virus. Others were all too conscious of Silicon Valley's checkered reputation when it came

to privacy. At a time when people's relationship with technology was so fraught already, companies that weren't even involved in exposure notifications, such as Facebook, may have indirectly deterred their adoption.

What if this had happened when everyone was happier with tech companies? "I think about that all the time," says Julie Samuels, who helped lead the team that built New York state's app. "The pendulum swung the other way."

Privacy wasn't just an abstract concern. For groups, like Black Americans, with good reasons to distrust the authorities—reasons based on personal experiences or historical harms—handing information over to the government for contact tracing could be a nonstarter.

A bigger push to earn trust now seems to have been a crucial missing element, since notifications become more effective if a lot of people opt in. Higher adoption rates required a foundation of trust to be built first, and the strength or weakness of that foundation affects us all, not just those who opt out.

"Viruses are not that selective," says Stephanie Mayfield, who directs the US covid response for the nonprofit Resolve to Save Lives. "If we don't look out and take care of each other, we all pay a price."

Even when privacy protections were put in the foreground, as with Apple and Google's system, that created other problems. The system isn't tied to your identity and doesn't track your location; instead, it uses Bluetooth to anonymously ping nearby phones running the same app. But with this technique, turning a positive result into an alert is so complex that public health experts weren't able to learn much about where clusters were forming or how the disease was spreading.

Privacy concerns aside, there were other practical questions about exposure notifications. Did the people at highest risk own the smartphones required to run the apps? How would the services operate across state or international borders? And was there enough testing in the first place?

Nobody building these systems thought they would be a silver bullet, but the struggle was a stark reminder of how technology can fail to solve a problem even when its creators have the best intentions.

Contact tracing works best as part of what experts sometimes call the Swiss cheese model, which involves layering several strategies. One method may have holes, but many combined can form a solid block.

Do this right, and "you could almost stop a pandemic in its tracks," says Rajeev Venkayya, who was part of the US team that helped design the George W. Bush administration's plan to deal with future pandemics.

For covid, the appropriate layers would include comprehensive testing, effective contact tracing, and social distancing—but with few of those layers in place, the virus ran wild. And once the spread is rampant, contact tracing simply isn't enough.

THE PROMISE AHEAD

Despite its shortcomings, digital contact tracing may still have a future. The arrival of multiple vaccines gives hope that case numbers will drop to manageable levels. At that point, Venkayya says, "having all the tools that we can at our disposal—including robust testing and tracing—will be really important. You are just trying to keep up and to limit the damage that's being done."

In the US, as the Biden administration gets up to speed, federal or national solutions (like pushing for nationwide use of contact tracing apps) may be part of the answer—along with monitoring tools like Bluetooth beacons, tracking bracelets, and QR codes that you scan to enter a cafe or workplace.

But the most important takeaways from our global experiment with exposure notifications may be less about the technology and more about how to implement it. The glitchy rollout has made it clear that introducing innovations—for this pandemic or the next—will require us to build trust, increase access and equity, and consider technology's place in complex systems.

Progress, of course, is about looking ahead. But as contact tracing reminds us, it's just as important to retrace our steps. ■

Lindsay Muscato is the editor of MIT Technology Review's Pandemic Technology Project.

HYPER-ACCURATE POSITIONING

WHY IT MATTERS: GPS has already transformed many industries and enabled whole new ones, like ride-sharing. A more accurate form of it will spawn yet more applications.

KEY PLAYERS:
- China National Space Administration
- US Air Force
- ColdQuanta

AVAILABILITY: Now

UPGRADES TO SATELLITES IN ORBIT AND SYSTEMS DOWN BELOW WILL BRING CENTIMETER-LEVEL ACCURACY TO THE MASSES.

By **Ling Xin**

A massive landslide—the worst in decades—struck Du Fangming's home in south China's Hunan province on July 6. "My house collapsed. My goats were swept away by the mud," he told Chinese media outlets shortly after the catastrophe. Fortunately, though, he was safe—one of 33 villagers who had been evacuated thanks to early warnings enabled by advanced positioning technologies that can provide more accurate readings than ever before.

Powered by China's newly completed global navigation satellite system, BeiDou ("the Big Dipper"), and its ground-based stations, position sensors can detect subtle changes in the land's surface in landslide-prone regions across China. Movement over a few meters can be spotted in real time, while post-processing accuracy can reach the millimeter level.

That means a shift in the dirt about the size of the tip of a sharp pencil can be spotted from more than 21,000 kilometers above. Twelve days before the landslide, Du's village received an orange alert citing data anomalies, which pointed to accelerating surface sliding following days of heavy rain.

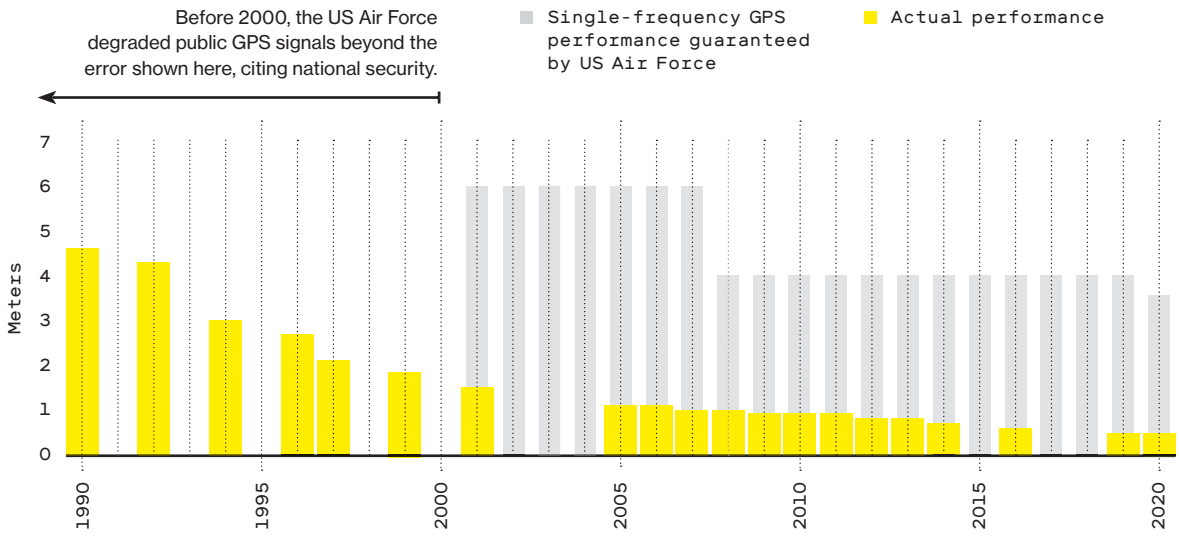
Du's village is among the more than 100 sites in Hunan that are equipped with such disaster-monitoring and early-warning systems. "This service wouldn't have been possible if satellite-based positioning accuracy had still been at the meter or decimeter level," says Yuan Hong of the Aerospace Information Research Institute at the Chinese Academy of Sciences in Beijing, where he worked for decades on BeiDou.

More than ever, we rely on technologies that can determine our location or pinpoint an object's position. Precision agriculture, drone delivery, logistics, ride-hailing, and air travel all depend on highly accurate position detection from space. Now a series of deployments and upgrades are boosting the accuracy of the world's most powerful global satellite positioning systems from several meters to a few centimeters.

That could mean your phone knows not only which street you're walking or biking down, but what side of the street you're on. Someday, that kind of resolution could make it possible for self-driving cars or delivery robots to safely navigate streets and sidewalks.

GPS KEEPS GETTING BETTER

As technology improves, so does the accuracy of GPS, represented here by a statistical average of the signal-in-space error measured on a single frequency across the GPS constellation.



SOURCE: NASA

NEW AND IMPROVED SATELLITES

The Global Positioning System (GPS), one of the world's first such satellite systems, has changed the way billions of people move around. Since 1993, at least 24 GPS satellites have been orbiting the Earth and constantly broadcasting their positions. Any GPS receiver can find its current whereabouts within seconds by triangulating signals from at least three satellites in the constellation.

Once the signals are processed by a receiver, GPS is generally accurate to within five to 10 meters. Now the system is in the middle of a years-long upgrade to GPS III, which should improve its accuracy to one to three meters (see chart). By November 2020, four of the 10 GPS III satellites had launched, with the rest expected to be put into orbit by 2023. Though consumers won't notice it right away, the accuracy of their navigation systems and smartphone tracking apps should improve as a result.

And in June 2020, China finished deploying its BeiDou satellite constellation as a GPS alternative. Expanded over two decades' time from a regional to a global network, BeiDou now has 44 satellites operating in three distinct orbits. It provides positioning services to anyone in the world with an average accuracy of 1.5 to two meters. Since the service has a historical focus on China and Asia, however, BeiDou's regional users can often get better location information, close to one meter in precision.

BOOSTING ACCURACY ON THE GROUND

Even with these advances, positioning signals encounter interference and other conditions that can make them go awry. Correcting these errors requires another layer of technology.

Both BeiDou and GPS rely heavily on ground-based augmentation to boost positioning accuracy to the centimeter level. One popular approach is real-time kinematic (RTK) positioning, which uses a base receiver and a rover receiver, placed kilometers apart, to receive satellite signals and calculate the errors caused by Earth's ionosphere. This technique can achieve accuracies of less than three centimeters.

A similar but newer technology is precise point positioning (PPP). It requires only one receiver and works from anywhere on Earth's surface, giving users decimeter- to centimeter-level accuracy.

In China, RTK augmentation is relatively mature, and thousands of base stations have been built across the country, Yuan says: "We are now developing a technology called PPP-RTK to combine their strengths, and [will] hopefully put it to use a few years from now."

BEYOND SATELLITE POSITIONING

As the accuracy of satellite positioning improves, we'll no doubt find even more ways to use it. Eventually, though, traditional satellite systems will reach an accuracy limit—probably around the millimeter level. So researchers are exploring new positioning technologies that could take us beyond that limit or at least reduce our reliance on satellites.

One approach uses the quantum properties of matter to locate and navigate without outside references. When atoms are cooled down to just above absolute zero, they reach a quantum state that is particularly sensitive to outside forces. Thus, if we know an object's initial position and can measure the changes in the atoms (with the help of a laser beam), we can calculate the object's movements and find its real-time location.

Quantum positioning would be particularly useful in situations where satellite systems such as GPS or BeiDou are not available, such as in deep space or underwater, or as a backup navigation technology for self-driving cars. A very early version of a quantum positioning system, developed by ColdQuanta in Boulder, Colorado, is now operating on the International Space Station.

Our ancestors looked to stars and compasses to figure out where they were; today, we use atomic clocks on satellites in orbit to do the same. New positioning technologies have already changed the way we farm, transport goods, and navigate our world, and the latest improvements will bring that world into even sharper focus. As positioning technology advances to the millimeter level and beyond, the limits of its use will be defined more by our creativity and the legal or ethical bounds we set than by the performance of the technology itself. ■

Ling Xin is a science journalist who covers physics, space, and technology.

COVID-19 TRANSFORMED THE WAY WE LIVE, WORK, AND PLAY. WHICH CHANGES WILL LAST?

WHY IT MATTERS:
The pandemic set off a global experiment in virtual living that will continue to shape our lives for years to come.

KEY PLAYERS:
- Babyl Rwanda
- Daktari Africa
- Microsoft
- Nerdy
- Teladoc
- Zoom
- Zuoyebang

AVAILABILITY:
Now

REMOTE EVERYTHING

By **Sandy Ong**

Photograph by **Sierra & Lenny**

THE COVID-19 PANDEMIC SHRANK OUR WORLD,

reducing it to nothing beyond the walls of our homes. But as we sheltered in place, the world kept spinning: we sat in meetings, went on dates, celebrated holidays, and met friends for drinks.

The only difference? We did it all from behind a screen.

It's almost unimaginable to have a list of 10 world-changing technologies in 2021 without reflecting on how much of our lives have moved online. The pandemic was a crash course in how much we can get done remotely when we have to. It also revealed which aspects of life suffer most when we experience them only in a virtual way.

Though changes happened everywhere, those in two particularly important services—health care and education—had huge impacts on people's overall well-being and quality of life. Online tools like Zoom suddenly became critical lifelines for many. But the most significant change was not in the technology itself—teleconferencing and telemedicine have long been available—but in our behavior.

What worked and what didn't? What will stay and what won't? And what have we learned that could help us better prepare for the future? Here we look at developments in Asia and Africa that could set an example for the rest of the world.

LEARNING ONLINE

At its peak last April, the pandemic forced school closures in more than 170 countries, affecting nearly 1.6 billion children. As traditional schooling became virtual across most of the globe, Asia witnessed a parallel trend—a surge in demand for services such as those offered by the Hong Kong–based online tutoring company Snapask.

Snapask now has more than 3.5 million users in nine Asian countries—double the number it had before the pandemic. "What took five years to accumulate, we achieved in one year because of covid," says Timothy Yu, who founded Snapask in 2015.

Other ed-tech companies in the region have reported similar growth. Byju's, a learning app and the second most valuable startup in India, saw its user figures soar by a third, to nearly 70 million, when it offered its app for free following nationwide school closures in March of last year. When China's leading online learning platform, Yuanfudao, did the same in early 2020, its system crashed under the load: more than 5 million people signed up.

Private tutoring has always been exceedingly popular in China and other Asian countries such as South Korea and Singapore, where eight in 10 primary school students receive out-of-school support. The pandemic has raised the profile of online tutoring services, which have quickly become as much a part of many students' days as their scheduled classes.

Many schools just weren't prepared for the switch to virtual teaching, especially in the pandemic's early stages. Online tutors helped fill gaps in instruction and were able to focus more on students' individual needs.

Yu built his company around the notion of "on-demand help": students can snap a picture of a homework question they are struggling with, upload it via the popular messaging service WhatsApp at any time of day, and receive help from one of Snapask's 350,000 tutors within 30 seconds.

Such services are often more convenient for parents than virtual schooling, says Wei Zhang, a professor at Shanghai's East China Normal University who studies the field of private tutoring. She spent the past year looking into how the pandemic affected parents, students, and online tutoring companies in China, Japan, and Denmark.

A common complaint she heard about virtual schooling was that parents "had to help their kids check into classrooms, fix technical glitches, respond to teachers, and supervise homework." Online tutoring services were much more straightforward.

Many tutoring platforms, including Snapask and Byju's, also have extensive libraries of instructional videos filled with brightly colored animations, special effects, and sounds. "For kids, this makes the lessons feel more fun and interactive," says Zhang.

All that said, inequality is a big barrier to scaling up both virtual schooling and online tutoring. Only 56% of people in Indonesia, for example, have internet access, according to statistics from 2019. And even in wealthier countries such as South Korea, where 99.5% of the population has internet access, the government had to step in and lend computers to low-income students.

At the same time, online tutoring does connect students in less developed regions with better instructors in urban areas. That's probably why some students in China's smaller cities have stuck with it even as schools return to normal, Zhang says. It also saves parents the hassle of shuttling their kids to and from private tutors.

Though private tutoring is not nearly as popular everywhere as it is in Asia, the

covid-induced boost in online tutoring is a timely reminder for everyone: students learn best when teaching is tailored to their needs and when they take an active role in learning.

Another important lesson to carry forward is that teachers should be encouraged to think differently and teach in new ways, says Steve Wheeler, a visiting professor at the University of Plymouth in the UK, who researches distance teaching and learning. If school systems can embrace what worked for online teaching—adopting new media and adjusting content accordingly—"there's a silver lining in the dark cloud," he says.

REMOTE HEALTH CARE

A decade before the pandemic began, Davis Musinguzi came up with his big idea: a system that would allow people in Uganda to text a toll-free number and have a doctor call them back for a consultation. To many, the notion seemed audacious. But Musinguzi, then a medical student in the capital, Kampala, was convinced it would work.

He cofounded the Medical Concierge Group in 2012, which he now admits was "way too early." Fewer than half the people in Uganda owned cell phones at that time.

Over the years, the effort expanded to incorporate video and WhatsApp messages, and a fleet of motorcycle-riding health-care personnel who would visit patients' homes to conduct blood tests and deliver meds. The group also extended into Kenya and Nigeria.

When the pandemic struck in 2020, the number of users soared 10-fold between March and November. "Covid-19 was a game changer," Musinguzi says.

Similar spikes in telehealth usage were reported globally. "There's no telemedicine company I know across the world that hasn't seen a surge in demand and also a change in consumer mindset toward telemedicine," he says.

That remote health care is having a moment isn't surprising. Remote video and phone consultations were already on the rise. Change often happens slowly in health care, but covid-19 supercharged that trend and "made it steeper," says Alex Jadad, founder of the University of Toronto's Centre for Global eHealth Innovation.

The pandemic pushed hospitals worldwide to a breaking point, and patients stayed away—whether out of fear or because they had to. Many turned to telemedicine. In the US, for instance, the proportion of people using it skyrocketed from 11% in 2019 to 46% a year later, according to McKinsey.

Uganda and other developing countries have a lesson or two to share about remote health care, which has evolved out of necessity in a region where doctors are often scarce. "In Africa, you have about 10% of the world's population and 25% of the world's disease burden. And yet we have only about 3% of the world's doctors," says Musinguzi. "So I think telemedicine fits in perfectly with that conundrum."

> "I THINK THAT'S THE ONE THING THAT'S GOING TO STAY WITH US POST-COVID—WE'RE GOING TO CENTER OUR LIVES AROUND OUR HOMES."

Like remote learning, remote health care often requires high-speed internet, which isn't always readily available in the developing world. But cell-phone penetration is now over 80% in Rwanda, Kenya, Nigeria, and some other parts of Africa.

Ayush Mishra, cofounder of Tattvan, runs e-clinics in 18 Indian cities. Tattvan, which means "to protect the five senses" in Sanskrit, operates an unusual model of telehealth. It franchises e-clinics—one- or two-room setups in villages, equipped with computers and a big screen. Patients can walk in for a consultation with the local doctor or speak to a specialist further afield if necessary.

In response to covid, Tattvan also launched a tele-mobile operator service in October: paramedics carrying backpacks loaded with equipment travel by motorbike to visit patients in remote villages.

Mishra believes this model of telemedicine—something between traditional brick-and-mortar health facilities and a doctor-on-an-app service—will ultimately prevail over the latter. "Trust is the biggest factor" when it comes to telemedicine, he says. "A local doctor sitting there is like a seal of trust."

Though teleconsultations have surged, Mishra expects this uptick to be temporary. Once things start opening up, he says, he anticipates a gradual decline in demand.

And telemedicine certainly doesn't suffice in all cases. "I think we've learned a lot about where teleconsultations can work and make things more efficient, but also where they can't work well," says Ann Blandford, a professor of human-computer interaction at University College London.

Other experts are more enthusiastic. "What we have seen is that 70% of routine outpatient visits can be handled through telemedicine and last-mile lab and pharmacy delivery services," says Musinguzi.

WHERE DO WE GO FROM HERE?

There's no doubt that the pandemic has made many people more comfortable with using both telehealth and remote education. And that probably won't go away. The pandemic will end, but our habits and preferences have evolved since it began.

Although remote services won't work for every checkup or lesson, they can make people's lives easier and better in many cases. The pandemic was a stress test for these services, and they proved capable of delivering much of what we needed, when and where we needed it. As we emerge from our homes, more of our lives than we might expect will continue to be lived online.

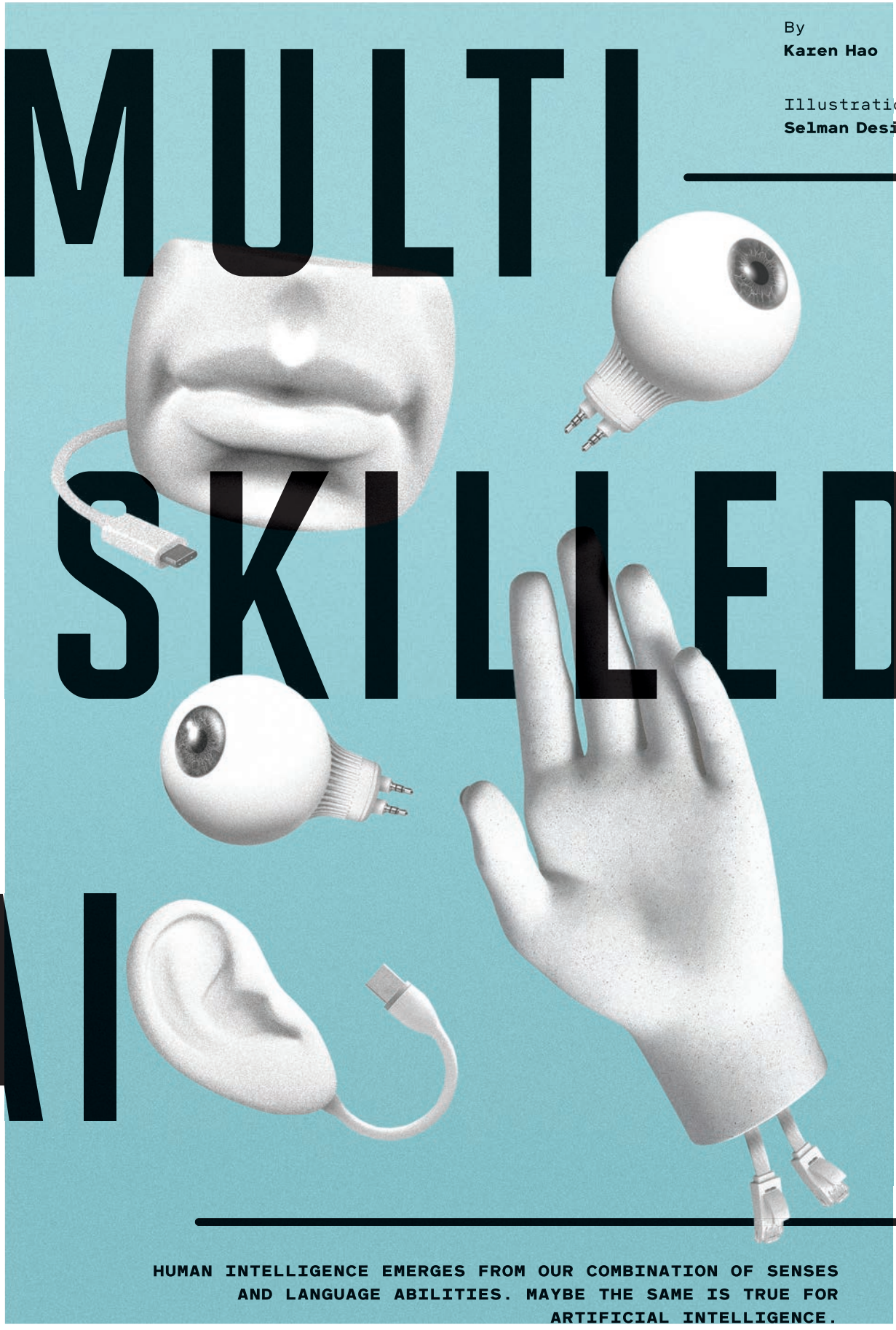
"What covid-19 has done is to tell people that you can now rely on services finding you at home, whether it's shopping or health care," says Musinguzi. "I think that's the one thing that's going to stay with us post-covid—we're going to center our lives around our homes." ■

Sandy Ong is a writer based in Singapore who covers science and technology.

MULTI SKILLED AI

By
Karen Hao

Illustration by
Selman Design



HUMAN INTELLIGENCE EMERGES FROM OUR COMBINATION OF SENSES AND LANGUAGE ABILITIES. MAYBE THE SAME IS TRUE FOR ARTIFICIAL INTELLIGENCE.

WHY IT MATTERS: AI that can sense and speak will be much better at navigating new challenges and working alongside people.

KEY PLAYERS:
- OpenAI
- AI2
- Facebook

AVAILABILITY: Now

In late 2012, AI scientists first figured out how to get neural networks to "see." They proved that software designed to loosely mimic the human brain could dramatically improve existing computer-vision systems. The field has since learned how to get neural networks to imitate the way we reason, hear, speak, and write. (See "GPT-3," page 34.)

But while AI has grown remarkably human-like—even superhuman—at achieving a specific task, it still doesn't capture the flexibility of the human brain. We can learn skills in one context and apply them to another. By contrast, though DeepMind's game-playing algorithm AlphaGo can beat the world's best Go masters, it can't extend that strategy beyond the board. Deep-learning algorithms, in other words, are masters at picking up patterns, but they cannot understand and adapt to a changing world.

Researchers have many hypotheses about how this problem might be overcome, but one in particular has gained traction. Children learn about the world by sensing and talking about it. The combination seems key. As kids begin to associate words with sights, sounds, and other sensory information, they are able to describe more and more complicated phenomena and dynamics, tease apart what is causal from what reflects only correlation, and construct a sophisticated model of the world. That model then helps them navigate unfamiliar environments and put new knowledge and experiences in context.

AI systems, on the other hand, are built to do only one of these things at a time. Computer-vision and audio-recognition algorithms can sense things but cannot use language to describe them. A natural-language model can manipulate words, but the words are detached from any sensory reality. If senses and language were combined to give an AI a more human-like way to gather and process new information, could it finally develop something like an understanding of the world?

The hope is that these "multimodal" systems, with access to both the sensory and linguistic "modes" of human intelligence, should give rise to a more robust kind of AI that can adapt more easily to new situations or problems. Such algorithms could then help us tackle more complex problems, or be ported into robots that can communicate and collaborate with us in our daily life.

New advances in language-processing algorithms like OpenAI's GPT-3 have helped. Researchers now understand how to replicate language manipulation well enough to make combining it with sensing capabilities more potentially fruitful. To start with, they are using the very first sensing capability the field achieved: computer vision. The results are simple bimodal models, or visual-language AI.

In the past year, there have been several exciting results in this area. In September, researchers at the Allen Institute for Artificial Intelligence, AI2, created a model that can generate an image from a text caption, demonstrating the algorithm's ability to associate words with visual information. In November, researchers at the University of North Carolina, Chapel Hill, developed a method that incorporates images into existing language models, which boosted the models' reading comprehension.

OpenAI then used these ideas to extend GPT-3. At the start of 2021, the lab released two visual-language models. One links the objects in an image to the words that describe them in a caption. The other generates images based on a combination of the concepts it has learned. You can prompt it, for example, to produce "a painting of a capybara sitting in a field at sunrise." Though it may have never seen this before, it can mix and match what it knows of paintings, capybaras, fields, and sunrises to dream up dozens of examples.

More sophisticated multimodal systems will also make possible more advanced robotic assistants (think robot butlers, not just Alexa). The current generation of AI-powered robots primarily use visual data to navigate and interact with their surroundings. That's good for completing simple tasks in constrained environments, like fulfilling orders in a warehouse. But labs like AI2 are working to add language and incorporate more sensory inputs, like audio and tactile data, so the machines can understand commands and perform more complex operations, like opening a door when someone is knocking.

In the long run, multimodal breakthroughs could help overcome some of AI's biggest limitations. Experts argue, for example, that its inability to understand the world is also why it can easily fail or be tricked. (An image can be altered in a way that's imperceptible to humans but makes an AI identify it as something completely different.) Achieving more flexible intelligence wouldn't just unlock new AI applications: it would make them safer, too. Algorithms that screen résumés wouldn't treat irrelevant characteristics like gender and race as signs of ability. Self-driving cars wouldn't lose their bearings in unfamiliar surroundings and crash in the dark or in snowy weather. Multimodal systems might become the first AIs we can really trust with our lives. ■

Karen Hao is MIT Technology Review's senior reporter for AI.

TIK TOK

RECOMMENDATION ALGORITHMS

By
Abby Ohlheiser

Photograph by
Sierra & Lenny

IN THE APP'S BREAKTHROUGH YEAR, THESE ALGORITHMS WERE THE SECRET INGREDIENT THAT PUT IT AHEAD OF RIVALS.

WHY IT MATTERS: It's flipped the script on who can get famous online.

KEY PLAYERS:
- TikTok

AVAILABILITY: Now

Even Karpelman would never have joined TikTok if it hadn't been for the pandemic. And she certainly never expected to be famous on it. But the app has a way of rewarding good content with views, dropping new creators in front of a broad spectrum of fans. That's how Karpelman, a 57-year-old who works in special education and started making videos to stave off lockdown boredom, ended up with 327,000 followers, many of whom are a fraction of her age.

In one of her breakthrough videos from July, Karpelman—known as @tequilaanddonuts—re-creates the makeup looks she used to wear in the late '70s. Her wavy white hair, which normally falls around her face in a granny-like halo, is pinned and clipped into something like a faux-hawk. She's covered her face in white powder, painted her eyelids black, and drawn a thin line of dark lipstick. The video cuts, and when Karpelman comes back, she shows off her "fancy going-out face." The black eyeshadow has extended all the way across her face and both eyes, as if someone had made an angry swipe with a paintbrush.

In the hours after she shared this makeup experiment, it was shown to hundreds of thousands of people on their "For You" pages, the lifeblood of TikTok. It wasn't obvious to her why this particular post was suddenly so visible, except that TikTok's recommendation algorithms had made it so.

MAKING IT BIG

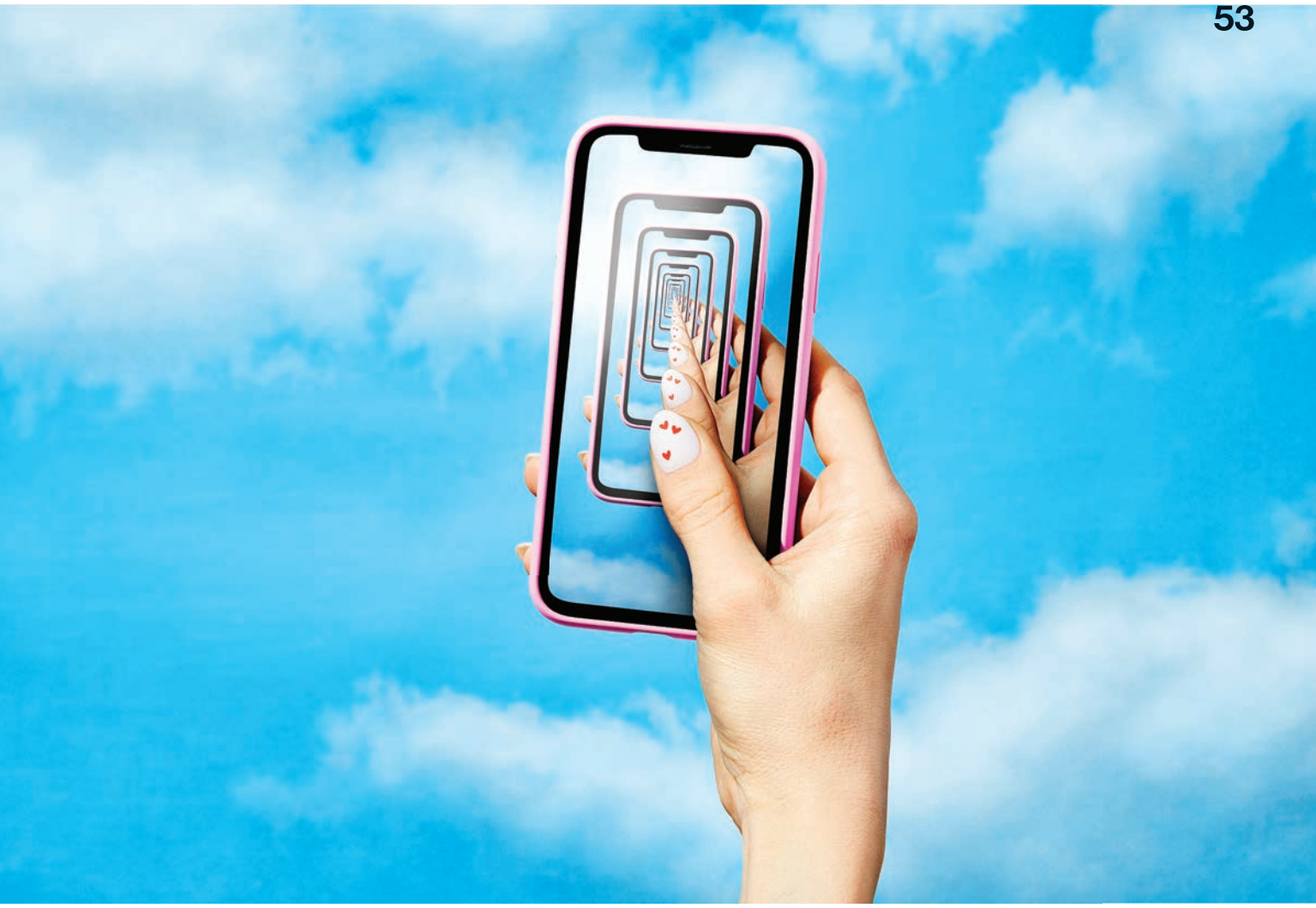
Since TikTok launched in China in 2016, it has become one of the most engaging and fastest-growing social media platforms in the world. It's been downloaded more than 2.6 billion times globally and has 100 million users in the US. And the unique way it finds and serves up content is a big part of its appeal.

The "For You" page is what most TikTok creators think makes the app different from other social media platforms, because anyone can get famous there. Good content is rewarded faster, supercharged by the algorithms that show users an endless stream of videos tailored to their tastes. While other social media platforms favor viral content with mass appeal, TikTok's algorithms have proved especially adept at plugging creators into niche communities that share interests, hobbies, or a particular identity.

A video's chances of ending up on your "For You" page are determined by, among other things, the captions, sounds, and hashtags on it. And as with any other social media platform, what TikTok chooses to show you is based on how you use the app—which videos you've liked, what content you create. The difference is that TikTok is better at it.

Already-popular creators do have an easier time getting attention, but TikTok doesn't take a creator's following or viral history directly into account when figuring out what content to seed where. That's why "For You" pages mix viral hits with new videos from unknown creators, some of which have just a few views.

Over time, TikTok's algorithms get better at guessing what users are interested in, not only connecting them to videos in their own areas of interest but bringing them into new spaces that have some overlap. (One viral video laid out TikTok's communities



like a treasure map: to get to the wholesome world of Frog TikTok, you had to leave Straight TikTok, find your way to Stoner Witch or Cottagecore, pass through Trans and Non-Binary, and "go through the portal to reach the promised land.")

Karpelman started doing makeup videos after teens on TikTok tried to correct her about an aesthetic that she lived at its peak. "[They were] trying to school me about being hardcore and, you know, being alternative. And I was like, 'Oh, honey child, you did not invent sin,'" she told me when we spoke on Zoom in December.

Now her videos appear a lot in communities devoted to LGBTQ+ and mental-health issues and recently gained an audience of women around college age, she says. Followers say she has "grandma energy," a distinction she has alternately leaned into and dodged.

SPEED BUMPS

Last year was an interesting one for TikTok: just as its cultural relevance exploded, it also faced challenges. India banned the app, and the Trump administration threatened to do the same unless TikTok's Chinese parent company cut all ties. (The threat was not carried out.)

TikTok has had to release more information about how its algorithms work, partially in response to security concerns about its ownership, and competitors like Instagram, Snapchat, and Triller have sped up attempts to copy what it is that makes their rival's recommendations so good.

At the same time, the platform has been forced to reckon with its increasing role in amplifying misinformation, and many Black creators have said that racism and harassment are disturbingly prevalent on it.

For Karpelman, TikTok has allowed her to connect with strangers during a difficult and lonely time, but the fame it bestowed on her has brought its own worries. Fans have reached out to ask her for help with serious mental-health issues and interpersonal conflicts. Sometimes they want more from her than she feels she can give.

Her experience working with students comes in handy: she sets boundaries and helps young fans learn to advocate for themselves. "Let's do some Googling," she says. "Let's look at your [high school's] admin. Oh, it looks like there is a district-wide psychologist. I will help you put together an email. You send it to me, I'll proofread it and send it back to you, and then you send it to these people. Give it a try."

But Karpelman has found another way to connect with her young audience: by talking about what they have in common. In one video, she demonstrates how she pretends to be on the phone in order to dodge a particularly aggressive salesperson in a mall. "There were a lot of kids that commented in there that said, 'I had no idea that grownups had these social anxieties,' and that kind of blew my mind," she says. "Kids just have no idea that older people are human." ■

Abby Ohlheiser is MIT Technology Review's senior editor for digital culture.

GREEN HYDROGEN

IF MADE USING RENEWABLE POWER, HYDROGEN COULD PROVIDE A CLEAN AND CARBON-NEUTRAL SOURCE OF ENERGY. EUROPE IS LEADING THE WAY.

WHY IT MATTERS: Green hydrogen can replace the natural gas, diesel, and gasoline used in ships, trucks, buses, and cars.

KEY PLAYERS:
- ThyssenKrupp
- Get H2 Nukleus Nowega
- Nel Hydrogen
- Siemens

AVAILABILITY: Now

By **Peter Fairley**

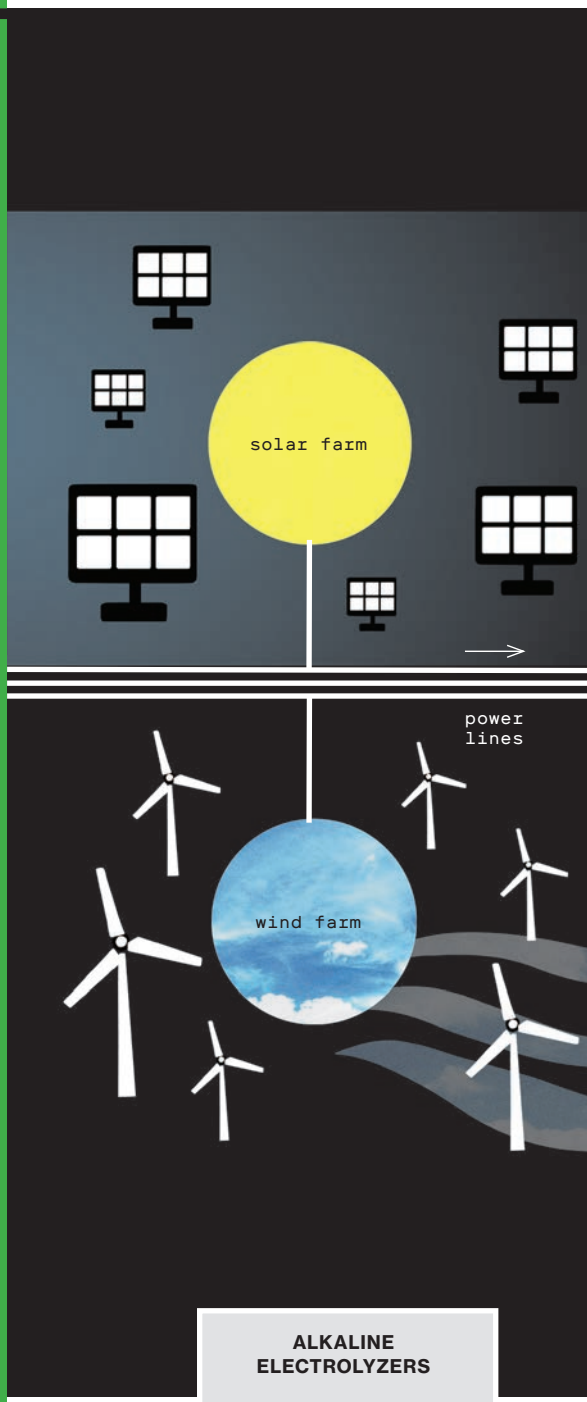
Illustration by **Franziska Barczyk**

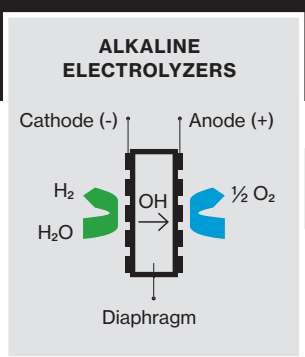
Hydrogen is an appealing fuel. A kilogram of hydrogen has about three times as much energy as a comparable amount of diesel or gasoline. If it can be made cleanly and cheaply, it could be the key to cleaning up an array of tricky vital sectors.

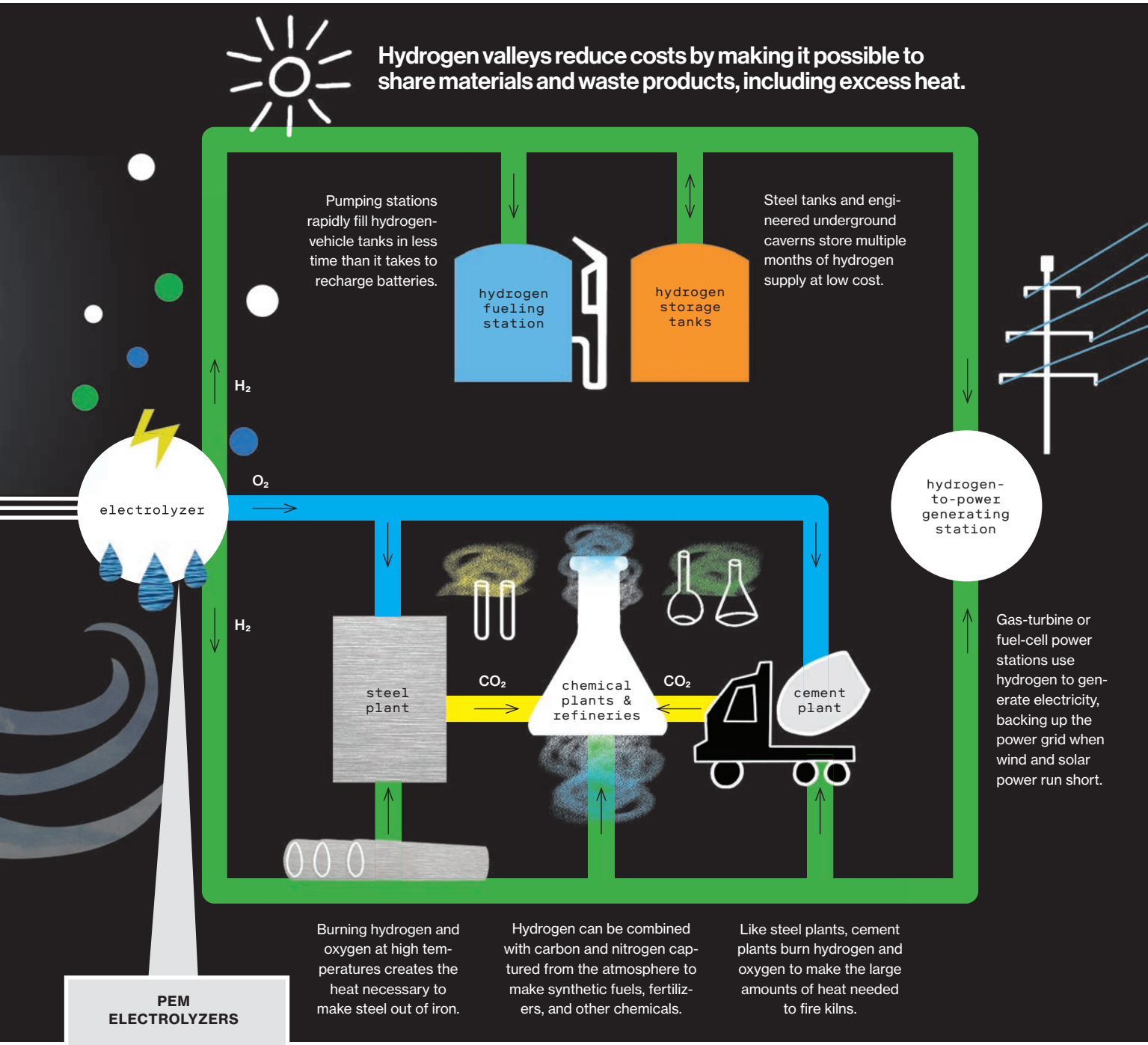
Today, most manufactured hydrogen is made by combining natural gas with steam at high temperatures. It's an energy-intensive process that emits considerable amounts of carbon dioxide, the main greenhouse gas driving climate change. But a small and growing percentage is made by splitting water into its constituent elements by zapping it with electricity, a process known as electrolysis. This also takes a lot of energy, but if the electricity comes from a renewable source like wind or solar power, it produces minimal harmful emissions.

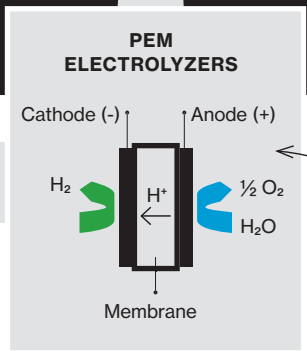
This so-called "green" hydrogen is today about three times more expensive to produce than hydrogen derived from natural gas (which is mostly methane, whose molecules are composed of one carbon atom bonded to four hydrogen atoms). But that is half of what it cost 10 years ago. And as the cost of wind and solar power continues to drop, and economies of scale around green hydrogen production kick in, it could get a lot cheaper. If that happens, green hydrogen has the potential to become a core fuel for a decarbonized future. In parallel, as carbon capture techniques improve, hydrogen can be extracted from natural gas without releasing as much carbon dioxide into the atmosphere.

Hydrogen is valuable in part because of its versatility. It can be burned as a substitute for fossil fuels such as coal, petroleum, and natural gas. These fuels all produce carbon dioxide when combusted, whereas burning pure hydrogen in a turbine produces just water vapor. It does, however,









Two types of electrolyzers make most green hydrogen. **Alkaline electrolyzers** submerge electrodes in water doped with lye or potash; **PEM electrolyzers** use a solid membrane through which hydrogen nuclei can flow.

also catalyze the production of harmful nitrogen oxides because of the high temperatures involved. Another way to use hydrogen is in fuel cells, which combine hydrogen with oxygen to create water and electricity—the reverse of electrolysis—without producing nitrogen oxides.

Hydrogen can power vehicles including cars, buses, trains, and aircraft, either through fuel cells or by burning it directly. Burning hydrogen can also deliver zero-carbon heat for use in steel mills, cement plants, and other industries. And green hydrogen can replace the hydrogen already used as a feedstock in everything from refineries to fertilizer plants, reducing their carbon dioxide emissions. Some industrial sites, such as steel mills and chemical plants, can also use the oxygen produced as a by-product.

Regardless of how it is manufactured, safely and affordably storing and transporting hydrogen remains difficult, especially for some promising applications like aviation. (Remember the *Hindenburg*?) That's why another option is to combine hydrogen with carbon—which can be captured from the atmosphere in a process called air capture or from smokestacks—to produce liquid synthetic hydrocarbon fuels that are easier to handle than hydrogen. These liquid fuels can be a cleaner, like-for-like replacement for gasoline or diesel.

Hydrogen can also be used to store energy from renewable-power plants, which can then be converted back into electricity and fed into the grid if wind dies down, clouds come in, or demand rises.

With so many possible uses, the International Energy Agency (IEA) predicts that by 2050, hydrogen could provide over 10% of global energy needs, producing more than 11 million gigawatt-hours of energy per year. That will require more than $4 trillion in infrastructure for producing, storing, and transporting hydrogen.

Europe alone is targeting 40 gigawatts of electrolysis capacity by 2030. (That would go about 2% of the way to the IEA's 2050 prediction.) "There's a tsunami wave of opportunity since the beginning of [2020]. It is unbelievable the number of big and realistic projects coming," says Christoph Noeres, who heads the green hydrogen business for Uhde Chlorine Engineers, a subsidiary of German conglomerate ThyssenKrupp.

HOW GREEN WAS MY VALLEY

Hydrogen valleys—regional projects that situate electrolysis plants where they can serve multiple industrial purposes—are forming across Europe. Near Hamburg in northern Germany, ThyssenKrupp is part of an €89 million ($107 million) green hydrogen consortium supported by a €30 million grant from the German government. The planned project includes a refinery, a cement plant, power generators, and an offshore wind farm.

Initially its green hydrogen will replace some gray hydrogen—as natural-gas-derived hydrogen is sometimes called—used at the refinery. The German group then plans to react hydrogen with carbon dioxide captured from the cement plant to produce both methanol, a chemical feedstock, and synthetic jet fuel.

Some 240 kilometers (150 miles) to the southwest, another green hydrogen consortium will repurpose decommissioned gas pipelines to carry hydrogen gas. The consortium plans to build a 100-megawatt electrolyzer. From there, it hopes to pipe hydrogen through a 130-kilometer network in the industrial Ruhr region.

If this pipeline repurposing works, electrolyzers connected to old pipes could ultimately serve green hydrogen to nearly all Germany's major industries. That will ease pressure on Germany's congested power grid and also provide a ready supply of backup energy for dark, windless periods.

Other large projects are starting in the Netherlands, Italy, Spain, France, Britain, Canada, Australia, Japan, and China. Initially, the hydrogen these projects produce will be expensive. However, the consultancy McKinsey estimates that by 2030 green hydrogen will be as cheap as gray hydrogen, thanks to cheaper electrolysis and renewable electricity generation as well as to rising carbon costs.

THE SUN SHINES BRIGHT

If hydrogen is to live up to its potential, public policy will be crucial. For starters, regulators or legislators will need to institute policies to enable existing natural-gas pipelines to carry hydrogen too—known as "blending"—and mandate cuts in carbon emissions to generate demand for hydrogen.

Some of this is already happening. Germany made an important change late last year, freeing green hydrogen producers from paying certain surcharges on electricity. This was, in effect, a recognition by the government that green hydrogen is an extension of renewable wind and solar power. Other regulations under discussion in Germany, and across Europe, would require carbon reductions at refineries and steel mills, and in other heavy industries, under the European Commission's Renewable Energy Directive.

Jack Brouwer, associate director of the Advanced Power and Energy program at the University of California, Irvine, says similar policies are needed to get green hydrogen going in the US, but discussions have barely begun.

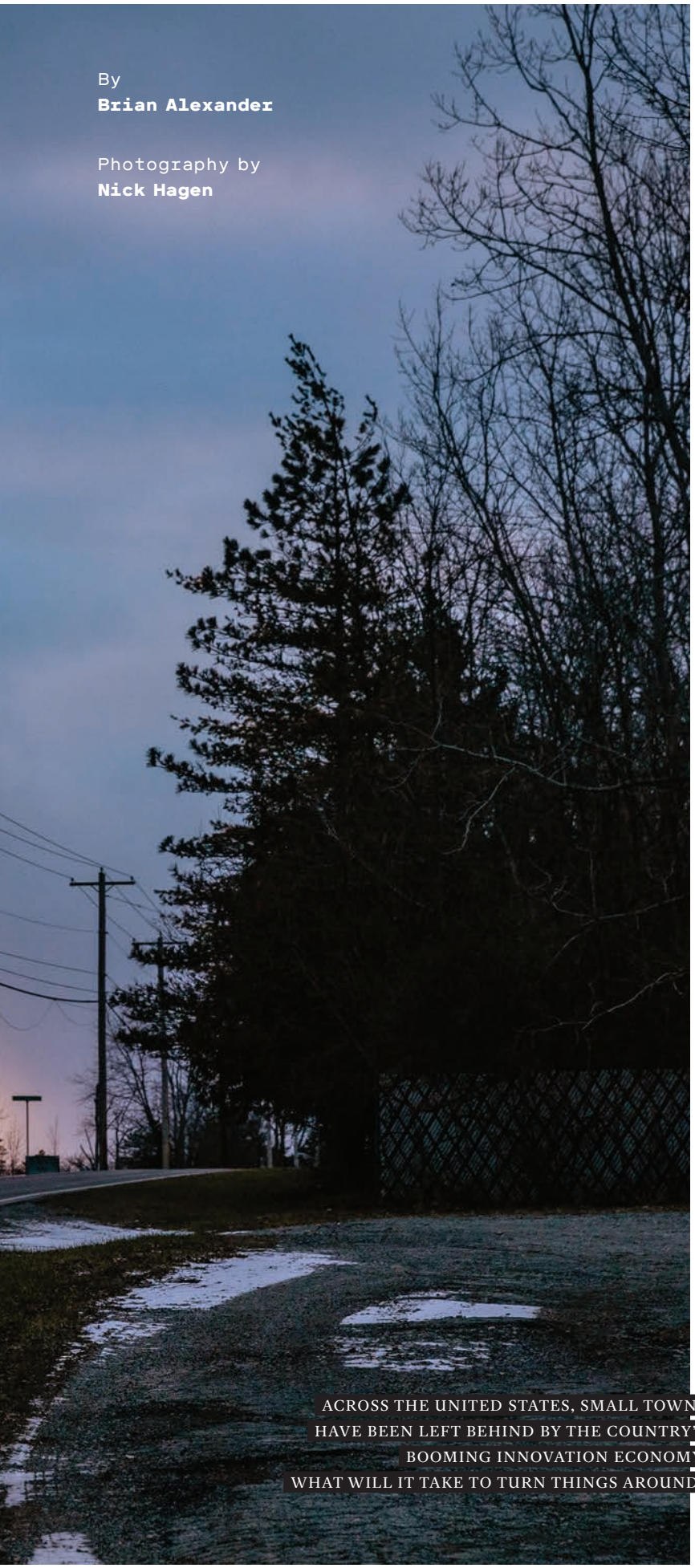
Whereas European governments mandate that natural-gas pipelines accept green hydrogen—in amounts as high as 12% by volume in the Netherlands—US gas operators often oppose blending.

Blocking hydrogen blending is a serious obstacle, according to Brouwer. California already has a rule mandating that a third of the hydrogen pumped at filling stations for fuel-cell vehicles come from renewable sources. But currently it's tough to get green hydrogen. Brouwer says that if producers could use existing natural-gas pipelines as a distribution network, they could profitably build more electrolyzers in remote areas that are particularly windy or sunny.

There are also still plenty of technical hurdles to be overcome. The scale of wind and solar power needed to run a global network of electrolysis plants is enormous. Brouwer makes the case that a sustainable future is simply impossible without relying heavily on hydrogen. He just might be right. ■

Peter Fairley is a journalist who covers energy, technology, and climate change.

WHERE PROGRESS STOPPED



By
Brian Alexander

Photography by
Nick Hagen

ACROSS THE UNITED STATES, SMALL TOWNS HAVE BEEN LEFT BEHIND BY THE COUNTRY'S BOOMING INNOVATION ECONOMY. WHAT WILL IT TAKE TO TURN THINGS AROUND?

Valerie Moreno laughed out loud when I asked if her family received regular medical check-ups. "Oh my gosh, no!" she said. "We have to be dying before we see a doctor."

The reason why wasn't a mystery. Valerie, who was dressed in a sweatshirt and jeans, her dark hair showing a few grays, pulled her checkbook out of a small bag and riffled through the ledger. "I have $65 in the checking account," she said.

Valerie and I first spoke early in the winter of 2018 as we sat in the basement of the First Lutheran Church in the small town of Bryan, in northwestern Ohio's Williams County. The church's pews had once been filled with worshippers. But people had drifted away, either because they'd stopped going to church or because they'd shifted their allegiance to one of the newer, fancier evangelical outfits. The room, sealed tight against the coming winter, marinated in a cloud of mustiness.

Later that evening, Valerie would start her third-shift factory job at Sauder, a manufacturer of institutional furniture. She made $14 an hour there. When the sun rose the next morning, she'd drive to her second job, as a Bryan school bus monitor. Then she'd go home for a few hours of sleep before rising to work her third job, as a home aide to the retired pastor of First Lutheran. She reckoned she managed about four hours of sleep a day. Her husband worked full time at a metal fastener plant. Altogether, she said, after health insurance premiums but before taxes, she figured she and her husband made about $45,000 a year. They still had a junior-high-school-age daughter at home. They were living, but it was far from easy.

Valerie was 46. She'd worked all her life.

The story of her working life is also the story of Bryan. The town is broken in some of the same ways that much of the rest of the country is broken. Understanding what broke Bryan is crucial to understanding how it might be fixed.

For decades, America's political and business leaders acted as if places like Bryan didn't matter. Palo Alto and Greenwich, Connecticut, did fine. These centers of high tech and financial services create vast wealth in the country's so-called innovation economy. But hundreds of places like Bryan, both urban and rural, were allowed to erode economically and socially. The innovation economy has largely passed them by.

Not everything is gloomy in Bryan, of course. If you were to drive through town, you would see some nice old homes, and parks, and a town square with a beautiful county courthouse. You might not notice the empty storefronts or realize that increased levels of

poverty, mental stress, and poor health have led to desperation behind closed doors.

Some people think that when a town hits hard times, it's time to pack up and move on to shinier places. Tim Bartik, a labor economist with the W.E. Upjohn Institute for Employment Research in Kalamazoo, Michigan, disagrees. "Encouraging people to move does not help those left behind," he says. "People have left Flint, but it didn't help Flint. Flint is still there." Instead, Bartik and others argue for a new regionalism, hoping to restore the vibrancy of places like Flint and Bryan through locally focused investment and education initiatives.

Developing a cogent regional development policy is one of the most vital public policy challenges facing America. President Joe Biden campaigned in part on the promise of creating "technology hubs" in 50 forgotten cities. But the diverging fates of places like Bryan and places like Palo Alto is clearly driving a loss of political faith. "It's scary for democracy," says Shannon Monnat, a rural demographer and sociologist who is the director of Syracuse University's Lerner Center for Public Health Promotion. It "means deterioration of democracy and all the institutions that undergird democracy," she says. "And I am worried it is getting worse."

THE SLOW-MOTION WRECK

For decades after World War II ended, Bryan was a prosperous town of manufacturers, surrounded by farms and tiny villages that spread over the rest of Williams County. Its intracounty rival, Montpelier, was a minor railroad hub—the Montpelier school sports teams are still the Locomotives—with some manufacturing of its own.

During the middle years of the 20th century, small metal-stamping and injection-molded plastics makers set up shop to supply parts to the auto industry; Detroit is a two-hour drive away. ARO Equipment was Bryan's biggest employer by far. Founded during the depths of the Great Depression, ARO first made air-powered pumps for things like gas station grease guns. By the late 1970s it had diversified. NASA used its pumps in space. Corporate jets flew out of the county airport; executives spent the weekend playing golf at the local country club.

Things were different by the time Valerie started her working life in the 1990s. Lots of changes hit Bryan hard: Reagan-era financial deregulation and anti-unionism, the creed of shareholder value as the highest goal of business, and the globalization of supply chains. The hardest blow came in the merger-mad 1980s, when ARO was bought by a failing company called Todd Shipyards. Todd wanted to acquire ARO's pension fund to stave off bankruptcy.

Todd failed anyway, and in 1989 ARO wound up in the hands of Ingersoll Rand, a large maker of industrial compressors, power tools, and lifting gear. Ingersoll shut down the Bryan factory and moved the work to North Carolina, where union protections were weaker, and to plants in India and China.

Three early Bryan companies still operate: Spangler Candy, the Dum Dum lollipops people; Bard, a maker of heating and cooling equipment; and Ohio Art, the company that put the Etch A Sketch in the hands of millions of children in the 1960s. Each one is over a century old. But they are all diminished. Bard grew, but instead of expanding in Bryan, where it remains headquartered, it built new factories in Georgia, another state with weak labor laws, and in Mexico. Spangler also grew but now manufactures many of its candy canes in Mexico (though it also expanded operations in Bryan after acquiring the Necco Wafer, Sweethearts, and Bit-O-Honey brands). Ohio Art sold off its toys, sharply cut its staff, and focused on metal lithography.

Valerie worked at Bryan Metal Systems, making suspensions for Chrysler. She made good money there, but that company was taken over in 2005 by Global Automotive Systems. In 2010, Global shut down the Bryan plant and sent the work to Michigan as part of a "global optimization strategy." Valerie traveled to Michigan to help train her replacements. After that, she bounced around, sometimes working temp factory jobs, until she landed at the Sauder furniture plant.

By 2019, unemployment was below 4% in Williams County, but higher-paying jobs had been replaced by work with low wages and "temporary" status that employers maintained—in name only—so they wouldn't have to pay benefits. Menards, a big Midwestern home-improvement retailer, became the largest employer in the county. Menards wrangled a rich package of tax incentives and infrastructure out of local and state government in return for putting a distribution center about 15 minutes northeast of Bryan. By late 2019 people were starting at about $14 an hour, or about $28,000 per year, for full-time work. In the last 20 years, the median household income in Williams County (in constant dollars) has gone from $62,000 to $49,500. Defined-benefits pensions have given way to less-generous retirement savings accounts. Health insurance premiums have gone up. So have deductibles.

Valerie Moreno, 48, ices a cake for her granddaughter's first birthday. She grew up near a small village east of Bryan and has lived in the area her entire life.

As the employment landscape changed, so did the county's demographics. Young people, especially college-educated young people, left and didn't come back. I asked Les McCaslin, the retiring chief of the Four County Board of Alcohol, Drug Abuse, and Mental Health Services and a native of the area, how he thought they might be persuaded to return. He remembered a recent economic development meeting: "We were talking about the town. And I simply said, 'Why would you come here? Why would I bring my two kids?' And there was silence in the room. You had commissioners there and they couldn't come up with one reason."

THE MENARDS EFFECT

Bryan's hospital, Community Hospitals and Wellness Centers (CHWC), caught the

ECONOMIC DECLINE AND POVERTY INDUCE STRESS AND TRAUMA THAT IN TURN LEAD TO POOR HEALTH. THE NEW AMERICAN ECONOMY HAS BEEN KILLING PEOPLE.

Williams County health commissioner Jim Watkins, 61, works in his office. "It's been a horrible month," he says.

The Ohio Art Company made Etch A Sketch toys in Bryan until 2001, when manufacturing moved to China.

fallout from these changes. As was true in many such communities, CHWC, an independent community hospital, became the largest employer in town. But it struggled to stay open and independent. Because the county's population was getting poorer and older, many patients qualified for either Medicaid or Medicare, both of which pay lower reimbursement rates than private insurance. (The two government programs account for two-thirds of CHWC's revenue.) So although, say, an MRI machine costs CHWC just as much as it would another hospital in a richer area, CHWC gets paid at a lower rate when it is used.

Former hospital CEO Phil Ennen calls this "the Menards effect." The company was "a real problem for us," he says. "Seventy-five percent of Menards [employee] accounts with us are Medicaid, charity, or some sort of self-pay. From a health-care perspective, they are a horrible employer."

Many people were like Valerie: they just didn't go to doctors. The spring after we sat in the basement of the church, Valerie was back there, this time counting Girl Scout cookie money with her daughter and a friend. She still worked three jobs. Her back ached from an old injury during her days at Bryan Metal Systems. And she was coughing from a bug she thought she'd caught from a coworker at Sauder. Valerie wound up with bronchitis, an inner ear infection, and a sinus infection, but she didn't miss any work, because she had no paid sick leave. "No! I went to work every day," she said, laughing, which called forth a brief coughing fit.

"The prospect of paying for a colonoscopy is a huge expense," Mike Liu, a surgeon who practiced in Bryan, told me. "A single medical problem or medical bill could destroy their entire month's budget—maybe their entire year's budget." This meant that treatable cancers went undetected until they were advanced.

But it isn't just that people didn't have enough money while medical care cost too much. Economic decline and poverty induce stress and trauma that in turn lead to poor health. The new American economy has been killing people.

From 1960 to 1980 life expectancy in the United States steadily increased. There were many reasons for this: vaccines against childhood diseases, improved community infrastructure, better antibiotics, and more advanced treatments for diseases like cancer. It was no coincidence that during this period, economic inequality in America decreased.

That started to change in 1981, when Ronald Reagan became president. He ushered in an era of union busting, financial deregulation, leveraged buyouts, and the financialization of the American economy. For a while, life expectancy continued to grow, but ever more slowly—until finally, in 2014, it began to decline. That decline has been concentrated among poor and working-class people.

When Valerie was growing up near a small village east of Bryan, her family used to shop at a locally owned grocery store that carried fresh fruits, vegetables, and meat. Now the shell of that store is sinking into a crumbling parking lot. A few yards down the road, a Dollar General welcomes shoppers. Dollar stores have become ubiquitous in rural and distressed urban landscapes as Wall Street investors have used their financial power to build thousands of the stores across the country, driving small independent grocers out of business. But dollar stores don't carry many healthy foods. As a result, almost half of Williams County residents live in census tracts with nowhere to buy nutritious groceries.

"WE DON'T KNOW WHAT TO DO"

Bryan's mayor, Carrie Schlade, grew up nearby. In her 41 years of living in the area, she has seen disturbing changes. Bryan doesn't have as bad a drug problem as other parts of Ohio, but it does have one—mostly meth, heroin, and fentanyl. The number of kids in foster care because their parents used drugs has grown "exponentially" since the recession, she says.

Schlade believes something has gone wrong with the culture of the place. People are angry, or sad and angry, or resigned. Or something. She worries about mental health. She worries that too many people

SHE WORRIES THAT TOO MANY PEOPLE CAN'T SEEM TO COPE WITH EVEN SIMPLE THINGS, LIKE GETTING UP AND GOING TO WORK.

Vacant storefronts like this one are a common sight in Bryan.

The Williams County courthouse on the south side of the town square, built in 1891, has a 160-foot clock tower, testimony to the grand ambition of the time.

can't seem to cope with even simple things, like getting up and going to work, and she worries about the state of Bryan's housing stock, much of which is old and shabby on the east side of town, and she worries about the resentment she has encountered there.

Not that Schlade, the town's first female mayor, is giving up. She and city leaders have managed to have the entire east side designated by the state as an area in which prospective employers could get tax breaks for opening a facility. She has been trying to support local churches that were doing good work running food pantries and teaching people how to manage money. She is always looking for state or federal grants to improve the community.

Sometimes Schlade despairs at such efforts. "We just don't know what to do," she once told me. "We know we're flyover country," she said—so she reckoned rejuvenation was up to Bryan itself: "It's like, 'All right, we've been asleep long enough. It's time to wake up. It is our job as a community to make our community good or bad. It is our choice.'"

It wasn't their choice, though, not really—no more than it was their choice to shut down ARO. Outside forces had mined such communities for assets, pushing them into decay, and outside forces are required to help them back.

PLOTTING THE ROAD BACK

In early 2020, Jim Watkins, the chief of the Williams County health department, began a project with a group from Bowling Green State University and the Federal Reserve Bank of Cleveland to see what might be done to improve the county's housing and living conditions. The plan, which had just taken its first steps when the covid-19 pandemic stalled it, aimed to develop policies and financing so people could maintain their homes, the community could develop better building codes and enforce them, blight could be removed from business districts, and community features could be created or improved to attract the public.

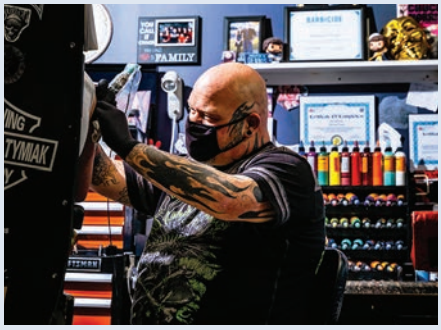
Bartik, the labor economist, is a skeptic of tax incentives like the ones given to Menards. He says that the cost per job is too high, and starves governments of money needed to fund education and other public goods. So he's come up with a series of plans he calls "place-based job policies."

In November of last year, Bartik proposed an $18.8 billion package of federal aid that would cover 30% of the US population in distressed and near-distressed labor markets. The plan would finance block grants so local areas could adapt the programs. Rather than simply trying to bribe businesses with tax incentives, he proposes more targeted programs. For instance, wage subsidies would enable employers to take on the risk of hiring apprentices, a practice that used to be common but is now rare in the United States. Neighborhood-based job training and placement services would help people living in distressed areas. Low- or no-interest loans to buy or repair cars would help people get to work. Subsidized child care would cut down on absences and ease the minds of workers.

Jobs have to pay more. Ohio's minimum wage is only $8.80 an hour. The national minimum wage is just $7.25 and hasn't risen since 2009. President Biden has proposed raising it to $15 per hour, which would be better, though still a low bar.

About 10% percent of Americans live in areas without access to broadband internet. Many who do have access can't afford to

The hospital in Bryan is now the largest employer in town.



Dennis Foust, 44, tattoos a patron at his shop, Testament Tattoo. He's been based in Bryan for the past six years.

The marquee of the Bryan Theater, a three-screen cinema on the west side of the town square.

pay for it. Expanding access and affordability could encourage entrepreneurs to think about starting businesses in places like Bryan, with its low cost of living.

This type of regional development could give towns like Bryan a draw they would not otherwise enjoy. Bartik cites the biggest regional development project in US history, the Tennessee Valley Authority, as an example. If such aid were effective, younger people would move to places like Bryan, says Brian Dabson, a research fellow at the University of North Carolina. "When you interview young people," he says, "it's surprising the portion of them who say, 'We would come back if there was something we could do here.'"

No initiative, no program, no development aid will, by itself, solve the deepest problem of all: distrust of American institutions. Reagan told Americans that government was not the solution, it was the problem. That notion has since become a religion to many people in places like Bryan, their faith buoyed by failures they see around them. The internet's capacity to spread mistrust, hate, division, and misinformation has helped discredit not just government, but also science and academia. The countervailing forces that can combat misinformation—literature, art, logic, critical thinking, civics, and history—have meanwhile been deemphasized in education in favor of "workforce development." In February 2020, Ohio's state superintendent of schools, Paolo DeMaria, changed the requirements for high school graduation: students would no longer have to achieve a proficient rating in either math or English. DeMaria set the standard in consultation with industry.

The pandemic has only exacerbated distrust that has been building for years. Some in Williams County denied the seriousness of covid-19. One village mayor insisted that masks actually spread the disease. Watkins, the public health chief, found himself battling covid-19 doubters. Amy Acton, Ohio's state health director, was driven from office in 2020 by threats. County health chiefs around the state have needed police protection. On January 24, 2021, shots were fired at a state health official's home.

The distrust and denial of truth and common sense only make it tougher for science- and technology-based businesses to picture themselves in places like Bryan. Unless there is deep and lasting investment in education sufficient to renew a faith in the possibility of rational progress, such areas can look forward to a future of low-paying, insecure jobs in warehouses and distribution centers, along with a handful of legacy manufacturers.

That means times will remain hard for people like Valerie Moreno, who recently wound up underemployed, again. She gave up her two part-time jobs and finally got some sleep, but then, two days before Christmas, she was laid off by Sauder. She quickly took a new part-time job with a home health agency while she spent the better part of a month fighting Ohio's unemployment system. She still hadn't received anything as of mid-January. Now Valerie struggles to maintain her own faith. "I take one day at a time," she told me. "I don't look too far in advance. I count my blessings every day." ■

Brian Alexander is a journalist and the author of The Hospital: Life, Death, and Dollars in a Small American Town, from which parts of this article were adapted.


A
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EDUCATORS ARE MAKING IT THEIR

Broadband boosters

MISSION TO CLOSE THE DIGITAL DIVIDE.

By
Chelsea Sheasley

Illustration by
Julia Schwarz

Back before the days of school-by-Zoom, first-grade teacher Andy Granados and her colleagues devoted a lot of effort to planning their time in the classroom. "If you take 10 minutes passing out your materials, that's 10 minutes of teaching time that you miss," she says.

Those careful plans seem like a luxury now. These days Granados teaches remotely, watching six- and seven-year-olds try, in their small video boxes, to sound out *sh-* words like "shop." Her students attend class for just two and a half hours each school day, but what's worse is how frequently kids drop out of the call, typically knocked off by poor internet connections.

"It's really hard. They come back in and don't know where we are or what page we're on," says Granados. She teaches in the Franklin Pierce School District in Tacoma, Washington, where 80% of students come from low-income families. The district gave tablets or laptops to every student and hot spots to their families, but the connection problems persist.

Meanwhile, Granados trudges on. She's covered about as much of the curriculum as she had by this point in the term when she taught in person, but she doubts her students understand the material as well. "I don't know what the fix is. It's really painful," she says.

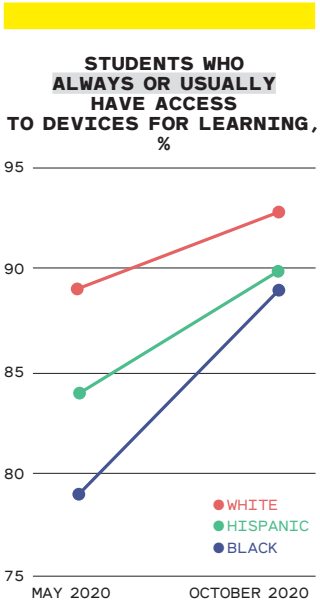
It's clear that US students would be in a far worse position if Zoom, Google Classroom, and other tech platforms weren't keeping education afloat during the pandemic. But it isn't working well for everyone, and the heavy reliance on technology is creating greater inequalities across an already uneven playing field. Poor or rural students and those who have a learning disability face the biggest barriers with virtual and hybrid learning. Educators are worried that these students, who were most vulnerable before the pandemic, have been dealt a crippling blow.

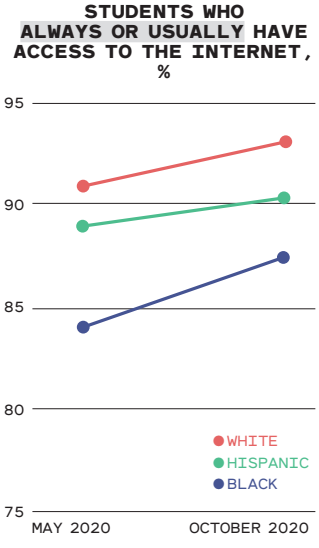
The silver lining: the crisis is spurring action to close some of these gaps once and for all.

The price of the pandemic

Many school districts made tremendous efforts over the spring and summer to distribute tablets and Chromebooks to students. That closed the digital divide somewhat, but Black and Hispanic households were still less likely than white ones to have reliable internet connections and access to devices, according to October 2020 US Census Bureau data analyzed in a report by the consulting firm McKinsey (see chart at right).

That means a large share of the children who lack the basic tools necessary for online learning are children of color. "And when they do have access, [the devices] are probably of a lower quality," says Emma Dorn, global education practice manager at McKinsey and a coauthor of the report. Perhaps as a result of these discrepancies, those kids were also half as likely as white students to have had any live contact with their teacher in the past week.





So while white students may finish the current school year between four and eight months behind in math, students of color may be six to 12 months behind, according to McKinsey's analysis.

Dorn says these disparities stem in part from the lingering digital divide and in part from the fact that students of color are more likely to be learning remotely, according to surveys. Among other reasons, their parents may be keeping them in remote school because of high covid-19 rates in their communities and distrust in authorities who say it's safe to go back.

Jayda Williams, a high school senior in Providence, Rhode Island, has her own laptop, a school-issued Chromebook, and a stable home internet connection. She's involved with a student activist group and an art group, which give her purpose. But she's still struggled more this year than she ever has with school, which she was attending in person for about three days each week as of January.

During her days spent learning from home, Williams has a hard time focusing. She picks up her phone to text friends much more often and misses her social life. "I'm absolutely not learning as much," she admits. "I don't think I retain anything."

Williams's grades dropped a little during the first quarter, but she still plans to apply to colleges. She's narrowed her search to schools close to home because she worries college campuses will become coronavirus hot spots once again.

Other high school seniors have been blown further off course. Applications for FAFSA, the Free Application for Federal Student Aid, were down 10% as of late January 2021. And enrollment in college was nearly 22% lower in 2020 than the year before. Students who delay college attendance are less likely to complete a degree, studies have shown.

The big question, of course, is how the pandemic will affect students' educational progress and the broader economy in the long run. The answer is still unclear and will depend in large part on what happens next. But preliminary reports paint a bleak picture.

Dorn and her colleagues have estimated that setbacks in education could cost the average American student $61,000 to $82,000 in lifetime earnings. Again, those averages conceal a stark racial divide: white students' income could fall by 1.6%, while Hispanic students lose 3% and Black students 3.3% over their working lifetimes. And US GDP could take a 0.8% to 1.3% annual hit by 2040, when most of the current school cohort will be in the workforce.

Laying the groundwork

One conclusion is clear: all students need reliable, high-speed internet at home, and will even when most are back in school. School administrators now see it as their job to make sure students have laptops or tablets and solid broadband connections to use them on.

"You can discuss differences between remote and in-person learning, but remote without the benefit of internet access simply isn't feasible,"

US CENSUS BUREAU HOUSEHOLD PULSE SURVEY VIA MCKINSEY

"I'm absolutely not learning as much," she admits. "I don't think I retain anything."

COURTESY PHOTO

says Phillip DiBartolo, chief information officer for Chicago Public Schools.

Some school districts are trying to close the digital divide once and for all. The Chicago school system partnered with the city and philanthropic groups to launch Chicago Connected in June 2020. The program will provide free high-speed internet for four years to approximately 100,000 students and their families. More than 50,000 families had signed up by January.

Key to Chicago Connected is its partnership with internet service providers RCN and Comcast. The school district signed a data-sharing agreement that provides students' addresses—with no other identifying information—to the local ISPs, which run a service eligibility check. If an address can be connected to wired broadband, families are given a code to activate the service. If it can't, the district gives them a wireless hot spot.

Several other cities have launched similar efforts, such as Philadelphia's PHLConnectED. Eric Gordon, CEO of the Cleveland Metropolitan School District in Ohio, is developing a program that allows the district to pay for students' internet access as long as they're in school.

The Chicago model also inspired Evan Marwell, founder and CEO of EducationSuperHighway. The nonprofit and its partners had just achieved their goal of establishing broadband in nearly every classroom building in America. In 2013, only 30% of schools in the US had strong internet connections. By 2020, 99.3% of classrooms were connected to high-speed bandwidth, and Marwell was about to dissolve the organization.

But when covid-19 hit, his phone started ringing. People he'd met, in state capitals and in Washington, asked for advice on getting internet service to students learning at home. After hearing of the Chicago model, he contacted cable and telecom associations to sound them out about replicating it elsewhere.

So far, Marwell and his team have formed agreements with the Internet and Television Association, USTelecom, and others to identify students with no broadband internet at home and to help states and school districts buy it for them.

To close the gap for good, though, efforts like his will need stable funding. In the latest covid-19 pandemic relief bill, Congress provided $3.2 billion for a temporary Emergency Broadband Benefit Program, which will give a $50-a-month discount to qualifying low-income households. Lawmakers could choose to make that benefit permanent.

Another solution could come from the federal E-Rate program, which has been funding broadband in schools. It had about $1.5 billion in unused funds last year. Using that money for students' home internet access would require the Federal Communications Commission to make rule changes, which it refused to grant under the Trump administration.

Marwell says that with enough funding, the US could close the home digital divide in half the time it took to close the divide in America's classrooms because so many companies and schools are now focused on this problem.

A holistic approach

On its own, expanding internet access won't make remote learning work for everyone or do much to remedy the learning loss that's already occurred.

With the pandemic's end in sight, educators are discussing how to help the country's 53.1 million kindergarten and school students make up for lost time. They're starting to make plans for how to reboot traditional education while preserving the benefits of remote learning.

Gordon, of the Cleveland school district, says his staff is considering ways to help students catch up when schools reopen, such as by organizing weekend boot camps, offering evening classes, or grouping students at similar learning levels in mixed-age classrooms.

Researchers also hope to see support for academic interventions such as high-intensity tutoring and summer acceleration academies, with students participating either remotely or in person. The United Kingdom launched a national in-school tutoring program to address learning setbacks due to covid-19, and many education researchers suggest the US do the same. Studies show that frequent, sustained tutoring on top of a student's regular classes can make a real difference.

DiBartolo, of the Chicago schools, says the pandemic is also opening educators' minds to new ways of integrating technology into the classroom, but he cautions that this can't replace human instruction in learning. "At the end of the day it always takes a talented teacher to make it happen," he says.

Granados, the first-grade teacher, is eager to return to her school once it's safe. "To be in person building a connection with a student is the best thing, and to lose that has been really tough," she says. "I think a lot of people are saying, 'I can't wait to go back.'" ■

Chelsea Sheasley is an education reporter based near Boston.

Lee Hood

THE PROSELYTIST AND THE PANDEMIC

After nearly three decades of largely fruitless advocacy, one scientist believes the pandemic may finally enable his vision of personalized, precision medicine for all.

—

By Adam Piore
Portraits by Ian Allen

BACK IN THE 1990s, LEE HOOD, a technologist and immunologist famous for co-inventing the automated DNA sequencer, made a bold prediction. By 2016, he suggested, all Americans would carry a data card recording their personal genomes and medical histories in vast detail. Upon arriving at a hospital or doctor's office, they would present it to a clinician, who could simply insert the card into a computer and "instantly know what he's dealing with."

Twenty-five years later, Hood's vision of precision health care based on personalized data still seems a long way off. Too bad, because we could really have used it in the covid-19 pandemic.

Infectious diseases don't get much more personalized than covid-19. No one can explain with any certainty why seemingly similar individuals respond so differently to exactly the same pathogen. Why do some of us get a case of the sniffles, and others end up on a ventilator? How can the virus attack the lungs of one patient, the heart of another, and the nervous system of a third? Why are so-called long-haulers left with lingering problems, yet other people recover fully? Why do some never show symptoms at all?

It's hard not to wonder whether we'd already have solved these mysteries if the first covid patients had arrived at the hospital with Hood's medical cards full of health data. "I think we'd be much further along than where we are right now," he says.

But Hood, who is 83, has never been one to dwell on what could have been. Known for his scientific ambition and impatience—he left a safe, tenured university job at 61 to cofound the Institute for Systems Biology (ISB), a nonprofit biomedical research center in Seattle—he sees the pandemic as a once-in-a-lifetime opportunity to show the power of data to help us understand disease. He hopes it will reinvigorate his three-decade-long campaign for a transformation of health care.

Hood, like the many other researchers who have long advocated for such a shift, argues that our approach to medicine is too cookie-cutter. By and large, people with the same illness get the same treatment. This fails to account for big differences between different people's genomes and immune systems. But the dream of true precision medicine has been mired in the sluggish and recalcitrant health-care system, where patient data is often seen as more of a nuisance than a benefit.

Could the covid crisis finally shake things loose?

The covid data deluge

Last March, Hood and ISB's president, Jim Heath, launched an ambitious effort to answer the question of why people respond so differently to covid-19. Their study is shaping up to be one of the world's most comprehensive analyses of the human immune response to the virus.

The ISB team collected multiple blood samples from each of several hundred hospitalized covid patients as they progressed through the various stages of the disease. Then the researchers tracked each patient's immune response down to the molecular level, analyzing a total of 120,000 variables. They looked at different types of immune cells, determined whether the cells were activated, exhausted, or quiescent, and examined the distinct characteristics of the proteins on those cells' surfaces that allow them to bind to and attack the virus.

The team at ISB also sequenced the patients' genomes, pulled electronic medical histories, analyzed their complete protein profiles and "metabolomes" (the set of various molecules other than proteins in the samples), and applied the latest pattern-recognition and machine-learning techniques to compare the patients with each other and with healthy people of similar ages.

The first results from this vast effort appeared in the journal Cell last fall, and they contained some surprising insights. Most notable was that as some patients progress from mild to moderate stages of the disease, they undergo a shift: a drop in the availability of key metabolites needed to power an effective immune response. In short, the body seems to just run out of the raw materials needed to fight back. That means something as simple as dietary changes or nutritional supplements might help gird up weak immune systems.

"There's nothing more personal than your immune system," says Mark Davis, a Stanford immunologist and a collaborator on the study. Davis notes that our immune system is highly plastic and responsive to past experiences—so much so that 70% of its measurable components differ between identical twins just a couple of years after birth.

Davis believes the key to understanding why covid affects people in such varied ways is to identify the differences between the immune systems of those who successfully fight the disease and those who succumb. Those differences could range from the simple, such as whether someone has been exposed to other coronaviruses in the past, to factors as complex as genetically determined variations in how certain cells display viral protein fragments on their surfaces for inspection by circulating immune cells. These proteins can influence how likely the immune cell is to recognize the presence of a dangerous pathogen, sound the alarm, and mobilize an army of antibodies to go on the attack.

"Now there is a flood of data, and it's the highest quality that we've ever had, and also the most we've ever had," Davis says.

A boon for the science, to be sure. But will the ISB study change how patients are treated and help prepare us for future pandemics? Hood is optimistic. "This absolutely validates everything I have been arguing for the past 20 years," he says.

The needed tools

Hood made a major contribution to immunology early in his career, after attending medical school and getting his PhD from Caltech. He helped solve the mystery of how the body can produce roughly 10 billion varieties of antibodies, Y-shaped proteins that can bind to the outer surface of a distinctly shaped invading pathogen and destroy it with the specificity of a guided missile.

Despite his early success, Hood recognized from the start that without major advances in technology, he would never answer the most intriguing biological questions that remained about the immune system: those revealing how it coordinates its remarkably complex collection of cell types and proteins. If immunologists were ever to understand how all these parts worked together, Hood realized, they would first need to recognize, characterize, and measure them.

Hood's Caltech lab played a key role in developing a wide range of tools, including instruments that would enable biologists to read and write sequences of amino acids, and machines that could string together DNA nucleotides (the letters of the genetic code). Perhaps most famously, in 1986 he helped invent the automated DNA sequencer, a machine able to quickly read the nucleotides in the genome and determine their order; it paved the way for the Human Genome Project, the $3 billion, 13-year effort to produce the first draft of a complete human genome.

In the years that followed, Hood advocated for a reinvention of modern health care that relied on the new tools of molecular biology to collect data from individual patients: genome sequences, and complete inventories of proteins circulating in the bloodstream. This data could then be analyzed, using early systems of machine learning and pattern recognition to pull out interesting patterns and correlations. Insights could be harnessed to maximize a person's health and head off diseases far earlier than previously possible.

Jim Heath, president of the Institute for Systems Biology

It all made perfect scientific sense. But nearly two decades after the Human Genome Project's completion in 2003, and despite much progress in genomic sciences as well as in data science, Hood's predicted revolution in health care has still not arrived.

Hood says one reason is that the tools used to be expensive. Now, however, a genome can be sequenced for $300 or less. And, he says, researchers have gained access to computational tools "that can really integrate the data, and turn data into knowledge."

But the biggest roadblock is that the health-care system is inefficient and resistant to change. There's a "lack of understanding about how important it is to get diverse types of data and integrate them," Hood says. "Most physicians went to medical school five or 10 or 20 years ago, and they never learned anything about any of this."

"Everybody is really busy, and changing takes time, so you have to persuade leadership as well as physicians this is in their interest," he says. "That all turned out to be far more difficult than I ever thought it would be."

Pandemic lessons

These days, Hood is still pushing hard, and despite the years of frustration, he is characteristically optimistic. One reason for his renewed hope is that he finally has ready access to patients and the money to begin his next grand experiment.

In 2016, ISB merged with Providence Health & Services in Seattle, a massive network with 51 hospitals, billions of dollars in cash, and a hunger to develop a more robust research program.

Soon after the merger, Hood was talking up an impossibly ambitious-sounding campaign to start what he calls the Million Person Project. It would apply phenotyping and genetic analysis to, yes, a million people. In January 2020, Hood kicked off a pilot project, having recruited 5,000 patients, and began to sequence their genomes.

Then the first covid cases began arriving in the hospital.

Hood and Jim Heath had a video call with Roger Perlmutter, an ISB board member who oversaw the $10 billion research budget of the pharmaceutical behemoth Merck. They discussed what was known about the mysterious new disease—and, more important, what scientific questions most urgently remained to be answered.

It did not take long for the trio of scientists to home in on the challenge.

"The immediate question then—it's still the question now, frankly—was why is it that there are many people infected, but only a few become very, very ill?" Perlmutter says. "And what is the nature of the transition from … what is often an asymptomatic or mildly symptomatic infection to a catastrophic illness? What does it look like? And how can we understand it from a molecular cell-biology perspective?"

On the call that day, Hood and Heath had a big ask: would Perlmutter finance them to conduct the kind of comprehensive molecular-level analysis that might explain covid's remarkable variability?

"I don't ordinarily say, when somebody calls me up, 'Yeah, sure, I've got my checkbook—here we are, let's do it,'" Perlmutter recalls. "But I said we would be prepared to underwrite it on that call. We needed the data. And I didn't want to see them struggling to raise money when we needed the data."

At Providence, which was filling up with covid patients, the urgency was similarly palpable. The team at ISB began collecting data to characterize the patients' immune responses with unprecedented specificity. As it happened, Heath and his team already had a powerful array of instruments for the purpose: they were studying ovarian and colorectal cancer patients in danger of recurrence, in hopes of developing better immunotherapies to treat them.

"Ordinarily," says Hood, "a trial like that would take six months at least to put in place, but in two to three weeks, it was actively ongoing. We were recruiting patients, and drawing the blood, and beginning to test them."

Though Hood's Million Person Project was shut down temporarily when covid hit, he has kept his focus on the long game. "What covid has made possible is it's allowed me to go out and raise really close to $20 million to carry out these studies," he says. "Part of it was used to build computational platforms and bring in key data scientists. All of these people will be able, once covid's over, to apply directly to the Million Person Project." He goes on, "We'll probably be setting up clinical trials using deep phenotyping for a whole series of diseases in the future."

Such a prediction is pure Hood, shaped both by his ambition and his endless enthusiasm, even after almost 30 years of advocating for personalized medicine with seemingly little progress.

Even if his grand vision is realized, it will be too late to save us from the worst effects of covid-19. But Hood clearly relishes the opportunity the pandemic has created. "[Covid] showed, clearly, that you can really get things done at lightning speed if there's urgency behind them," he says. "Usually it takes forever to get things done. But in a crisis you just push aside all the bureaucracy." ■

Adam Piore is a freelance science and medical writer.

THIS PAGE:

We've all had times when we could've used a third hand. Cybernetics researcher Kevin Warwick is one of the few people who know what it's like. A chip connected to the nerves in his wrist allows Warwick to control a robot arm and feel what it's feeling.

OPPOSITE, CLOCKWISE FROM TOP LEFT:

When Aisen Caro Chacin puts on her echolocation headphones, she's blind as a bat. And that's the point—as the rig's name suggests, it focuses sound in a way that's meant to help the wearer navigate just by listening.

Artist Moon Ribas (see main text) has implants in her feet that allow her to feel earth- and moonquakes.

After losing his leg and arm in an accident, James Young enlisted the help of a prosthetics designer and the gaming company Konami to build a bionic arm in the style of Young's favorite video game series, Metal Gear Solid.

HUMAN+

The human body is a marvel of evolutionary engineering. When it goes wrong, either from illness or from trauma, powerful technologies that we've developed can replace lost limbs, or restore the ability to walk. Occasionally, the repair can even go beyond a restoration, enhancing one's natural abilities.

Photographer David Vintiner became fascinated with these and other sorts of body modifications carried out by proponents of transhumanism. Generally speaking, transhumanists believe that technology can be used as a tool to tweak and enhance the human body. In some cases, the impetus for such modification comes from an accident—James Young (right, and page 76) replaced his lost arm with a robotic one that's something of a high-tech Swiss army knife.

Other transhumanists simply want to see what is possible: to play with perception, the senses, and their own skin and bone in ways that can seem performative, and are sometimes deliberately so. Moon Ribas (top right), for example, dances as a way of interpreting the vibrations she feels when the signals from earthquakes and moonquakes, registering on far-off seismographs, are beamed into implants in her feet. She and Neil Harbisson (page 74), who cofounded the advocacy group Cyborg Foundation, both identify as artists rather than technology researchers.

But while many cyborg projects are better described as curios than practical breakthroughs, they are nonetheless difficult to ignore. Modern consumer technology has, after all, already changed us in many strange and fascinating ways. Many people walk around with implants that regulate their heartbeat or insulin levels. And many more stare into the mirror each morning and carefully apply a thin, wet film to the surface of their eye to improve their vision. We may not all end up like Harbisson, who has a light-sensitive antenna sticking out of his skull. But who's to say that he and others aren't simply the first examples of a more advanced form of our species?

—Michael Reilly

Photographs by David Vintiner

THIS PAGE:

Neil Harbisson has been color-blind since birth. To augment his senses, he had an antenna implanted in his skull that turns the light it picks up into audible vibrations, allowing him to sense colors (and even infrared and ultraviolet light) as sound.

OPPOSITE:

If you've ever wondered what it would be like to detach your eyes and move them around independently, the Eyesect helmet is for you. Each "eye" camera pipes into your real eye. It may be a profound new sensory experience – or just a good way to break your brain.

CLOCKWISE FROM TOP LEFT:

Researchers at University College London have used stem cells to grow body parts and surgically repair or replace damaged tissue, including tear ducts, windpipes, and blood vessels. More complex parts, like an ear or nose (pictured), are next.

The "God helmet" started as an attempt to explain the roots of mystical experience in terms of brain activity. Subjects whose brains were stimulated using the helmet often reported feeling a divine presence (or their dead ancestors, or aliens). Neuro-hackers have co-opted it to see if it can help with mental health or improve concentration.

The aim of the NeuroRex exoskeleton is to take a step beyond wheelchairs. NeuroRex uses a wearable electrode cap that reads a person's brain waves and turns them into commands like "Walk forward," "Turn," "Step back," or "Stop." Its creators hope that people who've lost the ability to walk will one day be able to regain much of their mobility, including navigating stairs and uneven terrain.

James Young's bionic arm (see page 73) also has a USB charging port, a heart rate monitor, a flashlight, and a small drone.

ABOVE:

Filmmaker Rob Spence lost an eye in a childhood accident. In its place, he and a small team created a wearable wireless video camera that records footage from his point of view – complete with furtive glances and eye blinks.

LEFT:

The ears on Stelios Arcadiou’s head work just fine. But the artist, who goes by the name Stelarc, endured multiple surgeries, skin necrosis, and a dangerous infection to bring a third ear to life on his forearm. His dream is for it to house a small, internet-connected microphone so people all over the world can listen in to what it’s hearing.

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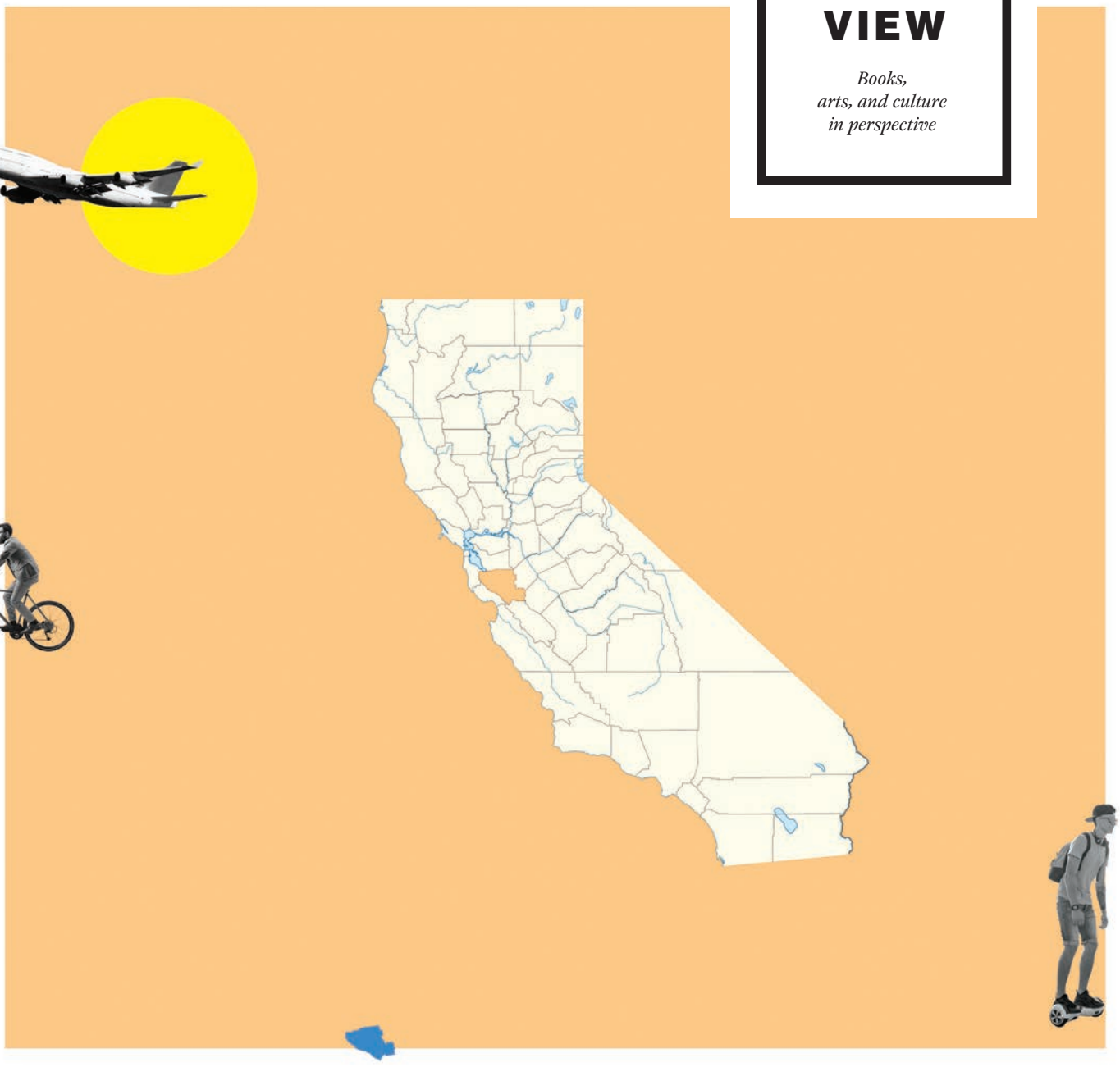
"The climate crisis demands government action. It cannot be left to the whims of billionaires." —LEAH STOKES, P.86

REVIEW

Books, arts, and culture in perspective



ANDREA DAQUINO

JOHN MARKOFF

Will the last one out ...

The latest wave of tech companies quitting California may have mistaken what makes it a center of innovation: its ability to capitalize on its luck.

"Will the last person leaving SEATTLE—Turn out the lights."

It's been half a century since, in the midst of a severe 1970s downturn plaguing aircraft maker Boeing, this billboard greeted travelers on their way to Sea-Tac airport.

But Seattle, in the end, did not go the way of Detroit. Before the end of the decade two of the city's native sons, Bill Gates and Paul Allen, renamed their software company from its original Micro-Soft, moved back home from New Mexico, and set up in a suburb across Lake Washington.

How would the city have fared if Gates and Allen had instead decided to build Microsoft in Albuquerque? We'll never know. But Seattle's recovery was more reliant on luck than people are usually willing to admit.

We like to come up with reasons that explain why significant changes happen, or how great shifts occur: we hear grand claims of innovative culture or geographic advantages. But the reality is that serendipity played a huge role in remaking the Seattle region's economic fortunes. The histories of such places are driven as much by random personal decisions about things like where to live, or by "black swan" events like the 2008 financial crash, as they are by destiny. And while these may offer less satisfying ways to predict the future—they are certainly more a patchwork quilt of reasons than professional futurists would have you believe—they are accurate about not just Seattle, but Silicon Valley too.

There has always been an immense amount of debate over what accounts for the uniqueness of Silicon Valley—which, coincidentally, was given that name by technology journalist Don Hoefler in 1971, the same year the "Turn out the lights" billboard appeared in Seattle.

Whatever the reasons the Valley has remained the world's dominant technology innovation center since then, its roots clearly lie in a serendipitous set of events. First, William Shockley decided to leave Bell Labs and start his new semiconductor company in Palo Alto because he wanted to be close to his aging mother. Then, a couple of years later, a Justice Department antitrust lawsuit against American Telephone & Telegraph led to mandatory free licensing of the company's integrated-circuit technology. This sparked the explosion in transistors and computers, and wave after wave of change.

The High Cost of High Tech

By Lenny Siegel and John Markoff

HARPER COLLINS, 1985

But despite its near-religious belief in its own reputation for innovation, the Valley has been sustained by relatively few huge, dramatic concepts that have spawned whole new ways of living and working, like Doug Engelbart's hypertext and mouse, Alan Kay's Dynabook (a precursor to the laptop), or Marc Weiser's ubiquitous computing. Instead, Silicon Valley has thrived at product engineering and become adept at something else: spotting a profitable new idea.

"Whenever there is a new idea, the Valley swarms it," Jensen Huang, the chief executive of the chipmaker Nvidia, told me. "You have to wait for a good idea, and good ideas don't happen every day."

That focus has been multiplied by the strength of the Valley's venture capital industry, and its efficiency in funding new startups. In 2019 the Bay Area's $50 billion plus in venture funding far exceeded the total in any other region of the United States.

All this underlies a transformation that has led the region to move away from manufacturing to hardware engineering and software design. (Nvidia itself was founded to design graphics processors for video games, and then turned decisively toward machine-learning applications.)

But good ideas are not just rare—they are also notoriously hard to predict. The web, search engines, and machine learning all took Silicon Valley's gurus by surprise.

To a large degree this was because for decades, the rapidly accelerating power and falling cost of computing made new, unexpected things possible. With each new generation of silicon, innovations emerged like clockwork: desktop personal computers, laptops, digital audio and video, smartphones, and the internet of things.

Surprises may be harder to come by now that Moore's Law, the Valley's principal article of faith, has been sputtering since 2013. In fact, in at least one significant way, it has come to a complete standstill. The cost per transistor—which once fell at the same exponential rate that transistor density increased—hasn't budged for more than three generations of chipmaking.

"We've basically had a free ride," Carver Mead, the physicist who actually coined the term "Moore's Law," told me several years ago. "It's really nuts, but that's what paid off."

Now, however, the free ride is over. Significant technology advances will come only in response to human ingenuity. And that means it's time for Silicon Valley to put up or shut up.

Serendipity is particularly worth keeping in mind as high-profile companies head for the exits. Just last December, Hewlett Packard Enterprise and Oracle announced they were relocating their headquarters to Texas, and Tesla gave signs it may follow suit. Their moves have touched off a new round of hand-wringing and speculation over whether the Valley has lost its mojo.

But this is not the first time the question has been posed. There were times in the past when progress appeared to be lagging, only for it to roar back with some breakthrough that seemed to come entirely out of left field.

By 2006, for example, it felt as though innovation was ebbing in the Valley and mobile hardware advances were happening first in

Europe, at companies like Nokia and Psion. But the following year Steve Jobs introduced the iPhone, reimagining Apple's two biggest failures: the Newton personal digital assistant and the General Magic personal communicator. The Valley reemerged almost overnight as the world's dominant region for innovation in information technology.

Northern California has been a boom-and-bust economy as far back as the Gold Rush. As a teenager growing up in Palo Alto, I heard of mass layoffs at the NASA Ames research laboratory and the Lockheed Missiles and Space Company that led waves of engineers to leave town.

I was reminded of this after the dot-com collapse, when I saw a startup veteran at a conference and realized I hadn't seen him for a number of years.

"Where have you been?" I asked. He had left the state to live with his family, but things were picking up and now he was back, he replied.

This is not to say the Valley's survival is a given. Today, despite continuing strong investment and venture capital, there are fresh reasons for uncertainty besides the stalling of the semiconductor cycle.

One has to do with the ability to import talent. Silicon Valley, in many ways, owes its very existence to the mystique that first emerged in the 1970s, creating a magnetic force that has continuously pulled the best and the brightest from all over the world. Indeed, that may be a key to understanding what sets the region apart from other innovation centers.

I first stumbled across this as a technical editor at Byte magazine in the mid-1980s. A local hardware designer took me to an Indian bakery in Sunnyvale, full of women in saris and their husbands, who were employed as engineers. They had come to the Valley as a key intellectual labor force for the rapidly growing disk drive industry. (Ten megabytes of hard disk storage was a big deal!) Europeans, Asians, and Latin Americans came too, bringing intellectual power and entrepreneurial spirit. Within a decade it was possible to drive around the Valley from neighborhood to neighborhood and see a different language on the shop signs and billboards in each one.

IT STILL SEEMS UNWISE TO BET AGAINST SERENDIPITY, OR AGAINST SILICON VALLEY. PREDICTIONS OF ITS IMMINENT DEMISE HAVE BEEN REGULAR AND SHORTSIGHTED.

Now, however, there are powerful anti-immigration forces at work in the United States, and it is quite possible—even under a Biden administration—that new barriers to foreign technical workers and entrepreneurs may kill one of the key ingredients of the Valley's success.

Another reason for uncertainty is that the next major technology shift is not yet clear. When the pace of Moore's Law slowed during the past decade, the Valley made a transition between the two most recent generations of innovation—from social media platforms to machine-learning-based software and services. Venture capital pivoted, and funding for social media, which had peaked in 2012, fell to almost zero by 2016, as investors rushed into machine-learning startups.

There is little consensus today, however, about what the "next big thing" might be or when it might arrive. The futurists point to augmented reality—some optimists believe the entire Asian flat-panel-display industry is at risk—as a likely candidate for the platform that will touch off the next investment cycle. Or perhaps software and biology will finally merge: synthetic biology has been given a significant boost by the success of the recent mRNA covid vaccines, after all (see page 28). Or maybe quantum computing will become a commercial reality, drastically reducing the cost of Google's data centers. Or consider what it would mean if an Apple car proves to be as successful as the iPhone. (But I wouldn't count on it.)

It is just as likely, however, that there will be a long dry spell and the Valley will find itself in a predicament similar to that faced by Seattle when it overrelied on Boeing. Even more worrisome is that China may prove to be the fierce competitor Silicon Valley once feared Japan would be.

It is certainly possible that the real threat to the next technology platform will emerge first from Shanghai, or Shenzhen, or Beijing. Anyone who has visited the Chinese capital's Zhongguancun district cannot help but recognize its similarity to the Valley in its concentration of talent and capital.

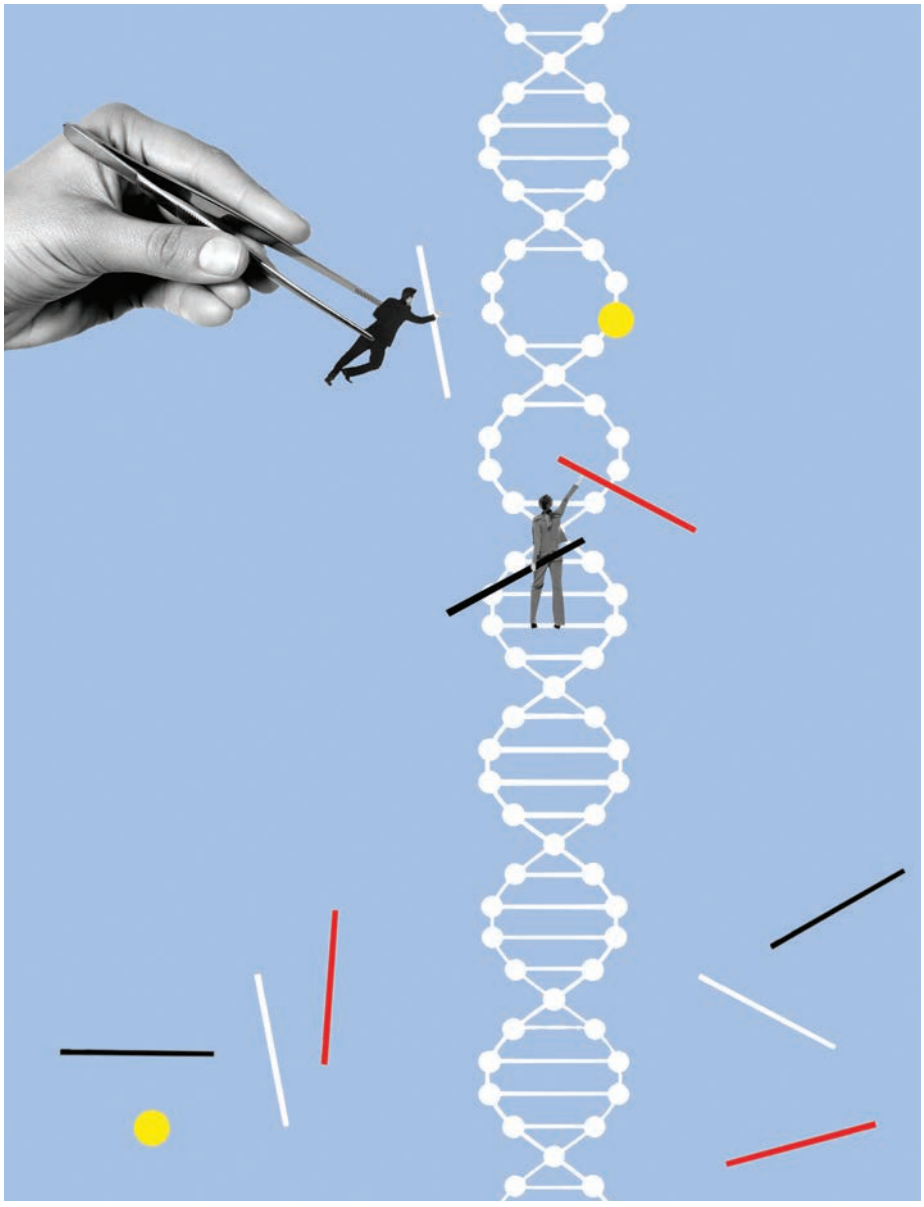
That being said, it still seems unwise to bet against serendipity, or against Silicon Valley. Predictions of its imminent demise have been regular and shortsighted.

I learned this lesson personally after I helped write *The High Cost of High Tech*, a 1985 book arguing that the environmental and labor costs of growth would soon limit the expansion of Silicon Valley. My coauthor was Lenny Siegel, who went on to become the mayor of Mountain View, the city where Google is now headquartered.

Oops.

John Markoff is a journalist who covered technology for the New York Times from 1988 until 2017. He is the author of several books, including a forthcoming biography of Stewart Brand.

GENOMICS



ANDREA DAQUINO

J. BENJAMIN HURLBUT

Decoding the CRISPR-baby stories

Three books explore the He Jiankui affair and what gene editing means for the future of humanity.

The conventional story of CRISPR genome editing is one of heroic power and promise with an element of peril. That peril became personified when MIT Technology Review's Antonio Regalado revealed in November 2018 that a young Chinese scientist named He Jiankui was using CRISPR to engineer human embryos. At least three of them became living children. The "CRISPR babies" episode is now an obligatory chapter in any telling of the gene-editing story. When Jennifer Doudna and Emmanuelle Charpentier were awarded the Nobel Prize last year for their invention of CRISPR, virtually every news story also mentioned He. In this century's grandest story of heroic science, he plays the villain.

Storytelling matters. It shapes not only how the past is remembered, but how the future unfolds.

He Jiankui's plans were shaped by stories about how science progresses and how heroes are made. One such moment came in a small, closed-door meeting hosted by Doudna at the University of California, Berkeley, in January 2017, to which He was invited. There a senior scientist from an elite American university observed, "Many major breakthroughs are driven by one or a couple of scientists … by cowboy science."

I too was at that meeting in January 2017, where I met He for the first time. We exchanged notes periodically in the months that followed, but the next time I saw him was at the International Summit on Genome Editing in Hong Kong in 2018, two days after Regalado had forced him to go public before he planned. After the summit, He disappeared from view: he was being held by Chinese authorities in a guest house on his university's campus.

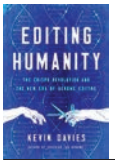
A month later, he called me, wanting to tell his story. He gave me a detailed history of the CRISPR-babies episode, explaining what motivated his project and the network of people—scientists, entrepreneurs, venture capitalists, and government officials—who supported it. The 2017 Berkeley meeting turned out to have been pivotal, especially the "cowboy science" comment. "That strongly influenced me," he told me. "You need a person to break the glass."

After the 2017 meeting, He started reading biographies of scientific risk-takers who were ultimately hailed as heroes, from Edward Jenner, creator of the first vaccine, to Robert Edwards, pioneer of in vitro fertilization (IVF). In January 2019, he wrote to government investigators: "I firmly believe that what I am doing is to promote the progress of human civilization. History will stand on my side."

Looking back at my notes from the 2017 meeting, I discovered that He had remembered only the first half of that provocative statement. It continued: "What's going on right now is cowboy science … but that doesn't mean that's the best way to proceed … we should take a lesson from our history and do better the next time around."

Learning from history?

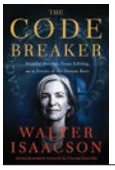
Kevin Davies's *Editing Humanity* follows a circuitous path through the remarkably diverse experiments and laboratories where the CRISPR puzzle was pieced together. The story of discovery is gripping, not least because Davies, a geneticist turned editor and writer, skillfully weaves together a wealth of detail in a page-turning narrative. The book gives a textured picture of the intersection of academic science with the business of biotechnology, exploring the enormous competition, conflict, and capital that have surrounded CRISPR's commercialization.



Editing Humanity

By Kevin Davies

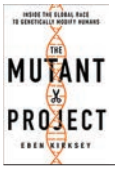
PEGASUS BOOKS, 2020



The Code Breaker

By Walter Isaacson

SIMON & SCHUSTER, 2021



The Mutant Project

By Eben Kirksey

ST. MARTIN'S PRESS, 2020

However, Davies's book is heavy on the business of gene editing, light on the humanity. The narrative emphasizes the arenas of scientific discovery and technological innovation as though they alone are where the future is made.

Humanity first appears as something more than an object of gene editing in the last line of the book: "CRISPR is moving faster than society can keep up. To where is up to all of us." Yet most of us are missing from the story. Admittedly, the book's focus is the gene editors and their tools. But for readers already primed to see science as the driver of progress, and society as recalcitrant and retrograde until it eventually "catches up," this telling reinforces that consequential myth.

Walter Isaacson's *The Code Breaker* cleaves even more closely to scientific laboratories, following the personalities behind the making of CRISPR. The main protagonist of his sprawling book is Doudna, but it also profiles the many other figures, from graduate students to Nobel laureates, whose work intersected with hers. In always admiring and sometimes loving detail, Isaacson narrates the excitement of discovery, the heat of competition, and the rise of scientific celebrity—and, in He's case, infamy. It is a fascinating story of rivalry and even pettiness, albeit with huge stakes in the form of prizes, patents, profits, and prestige.

Yet for all its detail, the book tells a narrow story. It is a conventional celebration of discovery and invention that sometimes slides into rather breathless celebrity profile (and gossip). Apart from some chapters of Isaacson's own rather superficial ruminations on "ethics," his storytelling rehearses clichés more than it invites reflection and learning. Even the portraits of the people feel distorted by his flattering lens.

The one exception is He, who gets a few chapters as an unwelcome interloper. Isaacson makes little effort to understand his origins and motivations. He is a nobody with a "smooth personality and a thirst for fame" who attempts to force his way into an elite club where he has no business being. Disaster ensues.

He's story ends with a "fair trial" and a prison sentence. Here Isaacson parrots a state media report, unwittingly playing propagandist. The official Chinese story was crafted to conclude the He affair and align Chinese science with the responsible rather than the rogue.

Authorizing narratives

These stories of heroic science take for granted what makes a hero—and a villain. Davies's account is considerably more careful and nuanced, but it too shifts to casting stones before seeking to understand the sources of failure—where He's project came from, how a person trained at elite American universities could have believed he would be valorized, not condemned, and how he could get so far without realizing how deep a hole he had dug for himself.

My overwhelming sense from my interviews with He is that far from "going rogue," he was trying to win a race. His failure lay not in refusing to listen to his scientific elders, but in listening too intently, accepting their encouragement and absorbing things said in the inner spaces of science about where genome editing (and humanity) are headed. Things like: CRISPR will save humanity from the burden of disease and infirmity. Scientific progress will prevail as it has always done when creative and courageous pioneers

push boundaries. Genome editing of the germline—embryos, eggs, or sperm that will pass changes down to future generations—is inevitable; the only question is who, when, and where.

He heard—and believed in—the messianic promise of the power to edit. As Davies writes, "If fixing a single letter in the genetic code of a fellow human being isn't the coveted chalice of salvation, I don't know what is."

Indeed, as even Isaacson notes, the National Academies had sent similar signals, leaving the door open to germline engineering for "serious diseases or conditions." He Jiankui was roundly criticized for making an edit that was "medically unnecessary"—a genetic change he hoped would make babies genetically resistant to HIV. There are, the critics argued, easier and safer ways to avoid transmitting the virus. But he believed that the terrible stigma in China against HIV-positive people made it a justified target. And the Academies left room for that call: "It is important to note that such concepts as 'reasonable alternatives' and 'serious disease or condition' … are necessarily vague. Different societies will interpret these concepts in the context of their diverse historical, cultural, and social characteristics."

He understood this as an authorization. These are the true origins of his grotesque experiment. The picture of He, and the scientific community he was embedded in, is a rather more ambiguous one than the virtuous science of Isaacson's telling. Or, rather, it's a more human one, in which knowledge and technical acumen aren't necessarily accompanied by wisdom and may instead be colored by ambition, greed, and myopia. Isaacson does the scientists a disservice by presenting them as the makers of the future rather than as people confronting the awesome power of the tools they have created, attempting (and, often, failing) to temper promises of progress with the humility to recognize that they are out of their depth.

SCIENCE-CENTRIC STORYTELLING IMPLIES THAT SCIENCE SITS OUTSIDE OF SOCIETY, THAT IT DEALS PRIMARILY WITH PURE ARENAS OF NATURE AND KNOWLEDGE. BUT THAT IS A FALSE NARRATIVE.

Another cost of science-centric storytelling is the way it implies that science sits outside of society, that it deals primarily with the pure arenas of nature and knowledge. But that is a false narrative. For instance, the commercial business of IVF is a crucial part of the story, and yet it receives remarkably little attention in Davies's and Isaacson's accounts. In this regard, their books reflect a deficit in the genome-editing debates. Scientific authorities have tended to proceed as though the world is as governable as a laboratory bench, and as if anyone who thinks rationally thinks like them.

Humanity's stories

These science-centric stories sideline the people in whose name the research is done. Eben Kirksey's *The Mutant Project* brings those people into the picture. His book, too, is a tour of the actors at the frontiers of genome editing, but for him those actors also include patients, activists, artists, and scholars who engage with disability and disease as lived experiences and not merely as DNA molecules. In Kirksey's book, issues of justice are entangled with the way stories are told about how bodies should be—and not be. This wrests questions of progress from the grip of science and technology.

Like Davies, Kirksey uses the He affair to frame his story. A skilled anthropologist, he is at his best when drawing out people's own stories about what is at stake for them. Some of the most remarkable interviews in the book are with the patients from He Jiankui's trial, including an HIV-positive medical professional who became more deeply committed to He's project after he was fired from his job because his HIV status was discovered.

Kirksey's attention to human beings as more than engineerable bodies, and to the desires that drive the imperative to edit, invites us to recognize the extraordinary peril of reaching into the gene-editing tool kit for salvation.

That peril is too often obscured by hastily spun stories of progress. On the final morning of the genome-editing summit in Hong Kong, less than 24 hours after He had presented his CRISPR-babies experiment, the conference organizing committee issued a statement simultaneously rebuking him and laying a pathway for those who would follow in his footsteps. Behind the statement was a story: one in which technology is racing ahead, and society needs to just accept it—and affirm it. A member of that committee told Kirksey why they had rushed to judgment: "The first person who puts it on paper wins."

So far, the CRISPR story has been about racing to be the first to write—not just scientific papers, but the nucleotides of the genome and rules for the human future. The rush to write—and win—the future leaves little room for learning from patterns of the past. Stories of technological futures, thrilling though they may be, substitute a thin narrative of progress for the richness and fragility of the human story.

We need to listen to more and better storytellers. Our common future depends upon it.

J. Benjamin Hurlbut is a historian of science at Arizona State University.

CLIMATE CHANGE

ANDREA DAQUINO

LEAH C. STOKES

Climate solutionism

Focusing on technological solutions to climate change feels like an attempt to dodge the harder political obstacles.

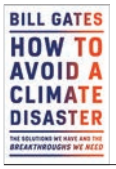
IN his new book, *How to Avoid a Climate Disaster*, Bill Gates takes a technology-centered approach to understanding the climate crisis. Gates begins with the 51 billion tons of greenhouse gases that people create every year. He slices this pollution into sectors by the size of their footprints—working his way from electricity, manufacturing, and agriculture to transportation and buildings. Throughout, Gates is adept at cutting through the complexity of the climate challenge, giving the reader handy heuristics to distinguish between the bigger technological problems (cement) and the smaller ones (airplanes).

At the Paris climate negotiations in 2015, Gates and several dozen other wealthy people launched Breakthrough Energy, an interlinked venture capital fund, lobbying group, and research effort. Gates and his fellow investors argued that both the federal government and the private sector are underinvesting in energy innovation. Breakthrough aims to fill some of this gap, funding everything from next-generation nuclear technology to fake meat that tastes more like beef. The venture fund's $1 billion first round has had some early successes, like Impossible Foods, a maker of plant-based burgers. The fund announced a second round of equal size in January.

A parallel effort, an international pact called Mission Innovation, says it has persuaded its members (the executive branch of the European Union along with 24 countries including China, the US, India, and Brazil) to commit an additional $4.6 billion every year since 2015 to clean-energy research and development.

These various endeavors are the through line for Gates's latest book, written from a techno-optimist's perspective. "Everything I've learned about climate and technology makes me optimistic ... if we act fast enough, [we can] avoid a climate catastrophe," he writes in the opening pages.

As many others have pointed out, a lot of the necessary technology already exists; much can be done now. Though Gates doesn't dispute this, his book focuses on the technological challenges that he believes must still be overcome to achieve greater decarbonization. He spends less time on the political obstacles, writing that he thinks "more like an engineer than a political scientist." Yet politics, in all its messiness, is the key barrier to progress on climate change. And engineers ought to understand how complex systems can have feedback loops that go awry.



How to Avoid a Climate Disaster: The Solutions We Have and the Breakthroughs We Need

By Bill Gates

KNOPF, 2021.

TR: Q+A

Why Bill Gates is optimistic about climate change (to a point)

The Microsoft cofounder and clean-energy investor answers three questions about his new book, *How to Avoid a Climate Disaster*

By James Temple

Q: In the past, you seemed to distance yourself from the policy side of climate change. Was there a shift in your thinking, or was it a deliberate choice to lay out the policy side in your book?

A: In general, if you can do innovation without having to get involved in the political issues, I always prefer that.

But the reason I smile when you say it is because, in our global health work, there's a whole decade where I'm recognizing that to have the impact we want, we're going to have to work with both the donor governments in a very deep way and the recipient governments that actually create these primary health-care systems.

Here, there's no doubt you need to get government policy in a huge way. Take things like clean steel; it doesn't have other benefits, there's no market demand for clean steel. So to get that sector going, you need to do some basic R&D spending, and you need to actually start having purchase requirements or funds set aside to pay that premium, both from government and perhaps companies and individuals as well.

Q: How do you feel about our chances of making real political progress, particularly in the US?

A: I am optimistic. Biden being elected is a good thing. Even more encouraging is that if you poll young voters, millennials, both who identify as Republican and Democrats, the interest in this issue is very high. And they're the ones who will be alive when the world either is massively suffering from these problems or is not, depending on what gets done. So there is political will.

But there's a lot of interplay [between politics and innovation]. If you try and do this with brute force, just paying the current premiums for clean technology, the economic cost is gigantic and the economic displacement is gigantic. And so I don't believe that even a rich country will do this by brute force.

But in the near term, you may be able to get tens of billions of dollars for the innovation agenda. Republicans often like innovation.

I'm asking for something that's like the size of the National Institutes of Health budget. Even without 60 Democratic [Senate] votes, I feel [it's feasible] because it creates high-paying jobs.

Q: Do you think we can realistically hold warming to or below a 2 ˚C increase at this point?

A: That would require us to get the policy right, get many, many countries involved, and be lucky on quite a few of the technological advances. That's pretty much a best case. Anything better than that is not at all realistic, and there are days when even that doesn't seem realistic.

Yes, minister

Kim Stanley Robinson does think like a political scientist. The beginning of his latest novel, *The Ministry for the Future*, is set just a few years from now, in 2025, when a massive heat wave hits India, killing millions. The book's protagonist, Mary Murphy, runs a UN agency tasked with representing the interests of future generations and trying to align the world's governments behind a climate solution. Throughout, the book puts intergenerational equity and various forms of distributive politics at its center.

If you've ever seen the scenarios the Intergovernmental Panel on Climate Change develops for the future, Robinson's book will feel familiar. His story asks about the politics necessary to solve the climate crisis, and he has certainly done his homework. Though it is an exercise in imagination, there are moments when the novel feels more like a graduate seminar in the social sciences than a work of escapist fiction. The climate refugees who are central to the story illustrate the way pollution's consequences hit the global poor the hardest. But wealthy people emit far more carbon.

Reading Gates next to Robinson underlines the inextricable link between inequality and climate change. Gates's efforts on climate are laudable. But when he tells us that the combined wealth of the people backing his venture fund is $170 billion, we may be puzzled that they have dedicated only $2 billion to climate solutions—less than 2% of their assets. This fact alone is an argument for wealth taxes: the climate crisis demands government action. It cannot be left to the whims of billionaires.

As billionaires go, Gates is arguably one of the good ones. He chronicles how he uses his wealth to help

The Ministry for the Future: A Novel

By Kim Stanley Robinson

ORBIT, 2020.

Under a White Sky: The Nature of the Future

By Elizabeth Kolbert

CROWN, 2021.

the poor and the planet. The irony of his writing a book on climate change when he flies in a private jet and owns a 66,000-square-foot mansion is not lost on the reader—nor on Gates, who calls himself an "imperfect messenger on climate change." Still, he is unquestionably an ally to the climate movement.

But by focusing on technological innovation, Gates underplays the material fossil-fuel interests obstructing progress. Climate-change denial is strangely not mentioned in the book. Throwing up his hands at political polarization, Gates never makes the connection to his fellow billionaires Charles and David Koch, who made their fortune in petrochemicals and have played a key role in manufacturing denial.

For example, Gates marvels that for the vast majority of Americans, electric heaters are actually cheaper than continuing to use fossil gas. He presents people's failure to adopt these cost-saving, climate-friendly options as a puzzle. It isn't. As journalists Rebecca Leber and Sammy Roth have reported in Mother Jones and the Los Angeles Times, the gas industry is funding front groups and marketing campaigns to oppose electrification and keep people hooked on fossil fuels.

These forces of opposition are more clearly seen in Robinson's novel than in Gates's nonfiction. Gates would have done well to draw on the work that Naomi Oreskes, Eric Conway, and Geoffrey Supran—among others—have done to document the persistent efforts of fossil-fuel companies to sow public doubt on climate science. (I also tackled this subject in my own book, *Short Circuiting Policy*, which explains how fossil-fuel companies and electric utilities have resisted clean-energy laws in a number of American states.)

BY FOCUSING ON INNOVATION, GATES UNDERPLAYS THE FOSSIL-FUEL INTERESTS OBSTRUCTING PROGRESS. CLIMATE-CHANGE DENIAL IS STRANGELY NOT MENTIONED IN THE BOOK.

One thing Gates and Robinson do have in common, though, is the view that geoengineering—massive interventions to treat the symptoms rather than the causes of climate change—may be inevitable. In *The Ministry for the Future*, solar geoengineering, or spraying fine particles into the atmosphere to reflect more of the sun's heat back into space, is used after the deadly heat wave with which the novel opens. And later, some scientists take to the poles and devise elaborate methods for removing melted water from underneath glaciers to prevent it from flowing into the sea. Despite some setbacks, they hold back sea-level rise by several feet. We might imagine Gates showing up in the novel as an early financial backer of these efforts. As he notes in his own book, he has been funding solar geoengineering research for years.

The Thick of It

The title for Elizabeth Kolbert's new book, *Under a White Sky*, is a reference to this nascent technology, since implementing it on a large scale could turn the sky from blue to white.

Kolbert notes that the first report on climate change landed on President Lyndon Johnson's desk way back in 1965. This report did not argue that we should cut carbon emissions by moving away from fossil fuels. It advocated changing the climate through solar geoengineering instead, though that term had not yet been invented. It is disturbing that some would jump immediately to such risky solutions rather than addressing the root causes of climate change.

In reading *Under a White Sky*, we are reminded of the ways that interventions like this could go wrong. For example, the scientist and writer Rachel Carson advocated importing nonnative species as an alternative to using pesticides. The year after her 1962 book *Silent Spring* was published, the US Fish and Wildlife Service brought Asian carp to America for the first time, to control aquatic weeds. The approach solved one problem but created another: the spread of this invasive species threatened local ones and caused environmental damage.

As Kolbert puts it, her book is about "people trying to solve problems created by people trying to solve problems." Her reporting covers examples including the ill-fated efforts to stop the spread of Asian carp, the pumping stations in New Orleans that accelerate that city's sinking, and attempts to selectively breed coral so that it can withstand hotter temperatures and ocean acidification. Kolbert has a keen awareness of unintended consequences, and she's funny. If you like your apocalit with a side of humor, she will have you laughing while Rome burns.

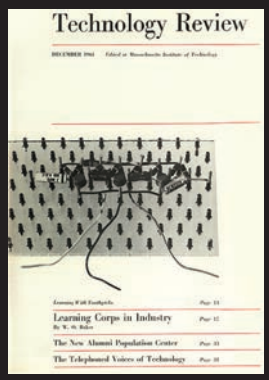
By contrast, though Gates is aware of the potential pitfalls of technological solutions, he still praises plastics and fertilizers as life-giving inventions. Tell that to the sea turtles swallowing plastic garbage, or the fertilizer-driven algal blooms destroying the ecosystem in the Gulf of Mexico.

With dangerous levels of carbon dioxide in the atmosphere, geoengineering might indeed prove necessary, but we shouldn't be naïve about the risks. Gates's book has many good ideas and is worth reading. But for a fuller picture of the crises we face, make sure to read Robinson and Kolbert too.

Leah C. Stokes (@leahstokes) is an assistant professor at UC Santa Barbara and the author of Short Circuiting Policy.

Speedy delivery

Through the decades the development of a vaccine has always been a major milestone, making it all the more remarkable that we invented multiple covid-19 vaccines in less than a year.



December 1961

From "The Potential of Nations": The national potential of a country includes more than its ability to produce raw materials and consumer goods, to provide and maintain public safety, and to protect its population from internal and external enemies. A nation also has a cultural potential when promotion of the sciences and the arts is a part of the national mission.

In Western nations the discovery of a new sub-atomic particle is considered a national accomplishment. The discovery of polio vaccine has been celebrated as a national accomplishment even more than any discovery in physics or chemistry. When an anthropologist, in the years to come, studies "the American way of life," he will probably find that the social prestige of the medical research worker exceeds that of any other research worker, entertainer, or sports hero.

January 1992

From "The New Vaccines": The major challenge to developing an AIDS vaccine may well be that HIV infects the very cells, the helper T lymphocytes, that control much of the immune response. HIV also introduces its own genetic blueprint into that of the T lymphocyte, making the infection of that cell permanent.

And unlike the way infected cells typically respond to most invaders, a fraction of cells carrying HIV may not produce the viral proteins that alert the immune system. Moreover, HIV can baffle the immune system by rapidly changing portions of its enveloping protein.

Despite these problems, we have substantial reason to expect that a human vaccine can be developed. After all, the immune system makes a strong effort to destroy the virus through the action of antibodies and lymphocytes.

May 2002

From "Should the Government Make Vaccines?": Fear of a looming health crisis is prompting policymakers to take a look at the nation's vaccine needs. One solution: supplement private vaccine production with a National Vaccine Authority that would oversee development and distribution of vaccines that are too risky or unprofitable for industry to make.

The idea has been proposed before, only to be overwhelmed by industry objections. But September 11 has changed the debate. "The anthrax terrorism event clearly exposed the weaknesses we have in the development and production of vaccines that are important for fighting terrorism, and at the same time dramatized that we have significant problems with vaccines that are important for the civilian sectors," says Kenneth Shine, president of the Institute of Medicine.

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