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The innovation issue

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Pandemic.
Inequality.
Misinformation.
Unrest.

Technology has let us down.

Here's how to make it work for us again ... and 35 young innovators leading the charge

Two entrepreneurs share a goal: to help people overcome opioid addiction. One, Zack Gray, has an Ivy League education and $2.7 million in venture capital funding. The other, Nikki King, went to the University of Kentucky and has a fraction of that amount, cobbled together from grants, donations, and Medicaid reimbursements.

But Gray's investors will want their money back some day. That means the only people he can help are people who can pay. This is the inexorable logic of venture capital, as Elizabeth MacBride writes (page 50): it funnels money from people who have it (customers) to people who have even more of it (investors). Those who have none of it have no say in one of the main driving forces of American innovation.

The technology we have mirrors the society we have, and specifically the way power in that society is distributed. Those who have power, be it through money, connections, or other kinds of privilege, have much more say in deciding which technologies get built and whom they benefit.

Such a system fails many people. Covid-19 and, more recently, the protests in the US sparked by the police officer who calmly murdered the unarmed, unresisting George Floyd in full view of cameras have made this clearer than ever. The venture-capital-driven tech boom of recent decades has not given the country much of the technology and infrastructure it needs to fight a pandemic. It has worsened economic inequality, political polarization, and the spread of misinformation. It has not reduced racial injustice: even though police brutality against black people has been documented countless times on cell phones and police bodycams in the past few years, the death toll has stayed perfectly steady. Indeed, the US has used technology to make racial oppression more systematic, as Charlton McIlwain writes (page 12).

The pandemic exacerbates these inequities. Not only are people in some of the lowest-paid, most precarious jobs—delivery drivers, supermarket cashiers, warehouse staff—at highest risk of catching covid-19, but as Erika Hayasaki explains (page 64), the crisis is likely to accelerate their replacement with robots and other forms of automation.

None of this is the fault of technology, but of a society that gives markets, and therefore the rich and powerful, too much say over which technologies are built and how they are used. This is not a call for socialism: free markets are essential to innovation. But America's technology prowess owes much to government funding and direction, both of which have declined over the decades, as David Rotman (page 6) and Ilan Gur (page 58) explain. More muscular policy and regulation could also help with the post-covid recovery, writes Nathan Schneider (page 48), by creating incentives and support for local entrepreneurs to build technological solutions for their own communities.

IAN ALLEN

Gideon Lichfield is editor in chief of MIT Technology Review.

It's hard to see much appetite for that kind of policymaking in the current US government. For signs of hope, one might look to Canada (page 42), where the tech hub of Toronto is trying (or so its boosters say, at any rate) to be a sort of gentler, kinder Silicon Valley, driven less by rapacious capitalism and more by a concern for technology's social consequences.

Look, too, at individual scientists, inventors, and entrepreneurs with ambitious, idealistic goals. As we do every year, we've assembled a global and—importantly—diverse group of leading young innovators (page 15). We've also interviewed some of the past years' winners about what they've learned along their journeys (page 60). Their examples, we hope, can serve to inspire funders, policymakers, and other technologists with a reminder of the good technology can do when it is directed at helping everyone—not just the moneyed and powerful.

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THE STATE OF INNOVATION

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The mission of MIT Technology Review is to make technology a greater force for good by bringing about better-informed, more conscious technology decisions through authoritative, influential, and trustworthy journalism.

WHY TECH DIDN'T SAVE US FROM COVID-19

The pandemic reveals that the US is not nearly as innovative as we thought. Here's how to fix that.

By David Rotman

Illustration by Selman Design

Technology has failed the US and much of the rest of the world in its most important role: keeping us alive and healthy. As I write this, more than 380,000 are dead, the global economy is in ruins, and the covid-19 pandemic is still raging. In an age of artificial intelligence, genomic medicine, and self-driving cars, our most effective response to the outbreak has been mass quarantines, a public health technique borrowed from the Middle Ages.

Nowhere was the technology failure more obvious than in testing. Standard tests for diseases like covid-19 use polymerase chain reaction (PCR), a more than 30-year-old chemistry technique routinely used in labs around the world. Yet although scientists identified and sequenced the new coronavirus within weeks of its appearance in late December—an essential step in creating a diagnostic—the US and other countries stumbled in developing PCR tests for general use. Incompetence and a sclerotic bureaucracy at the US Centers for Disease Control meant the agency created a test that didn't work and then insisted for weeks that it was the only one that could be used.

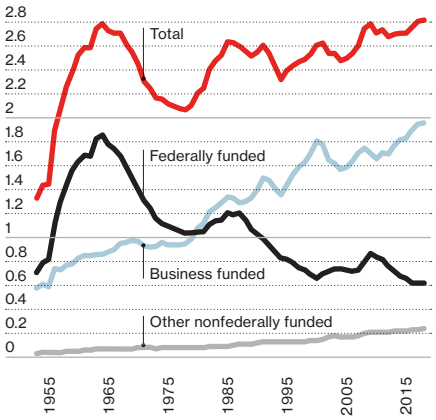
Meanwhile, the six-inch nasopharyngeal swabs needed to reach far up a person's nose to collect samples for PCR testing were in short supply, as were the chemical reagents necessary to process the samples. In the critical early weeks when the coronavirus could still have been contained, many Americans, even those seriously ill, couldn't get tested for the deadly virus. Even four months into the pandemic, the US still isn't equipped to do the massive and frequent screening needed to safely end a general lockdown.

Combined with the lack of testing, a splintered and neglected system of collecting public health data meant epidemiologists and hospitals knew

Where did all the money go?

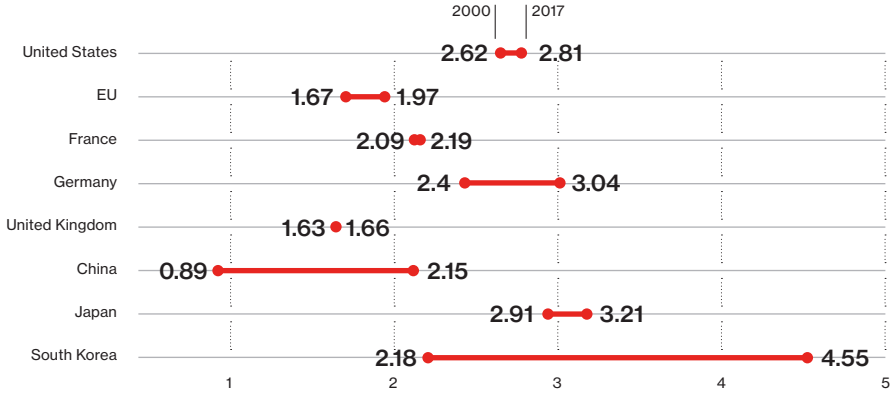
US federal funding for R&D has fallen. That's one cause of sluggish productivity growth. *By Tate Ryan-Mosley*

1 Federal funding has been dropping for decades. (US R&D as % of GDP)



NATIONAL SCIENCE FOUNDATION

2 The US is lagging behind South Korea, Japan, and Germany, and China is catching up. (R&D as % of GDP in 2000 vs. 2017)



NATIONAL SCIENCE FOUNDATION

too little about the spread of the infection. In an age of big data in which companies like Google and Amazon use all sorts of personal information for their advertising and shopping operations, health authorities were making decisions blind.

It wasn't only the lack of testing and data that doomed so many people, of course. There weren't enough ventilators or protective masks, nor factories to make them. "The pandemic has shone a bright light on just how much US manufacturing capabilities have moved offshore," says Erica Fuchs, a manufacturing expert at Carnegie Mellon University.

Why couldn't the US's dominant tech industry and large biomedical sector provide these things? It's tempting to simply blame the Trump administration's inaction. Rebecca Henderson, an economist and management expert at Harvard, points to a long history of the US government's directing industry and innovation during crises. Many companies, she says, were waiting for the administration to mobilize the effort and guide priorities. "I kept thinking, 'Let's focus the US thoughtfulness on testing and we'll get this.' I kept waiting for it to happen," she says. But it never did: "There is simply a vacuum."

But Henderson and other experts who study innovation point to a problem deeper than the lack of government intervention. A once-healthy innovation ecosystem in the US, capable of identifying and creating technologies essential to the country's welfare, has been eroding for decades.

Any country's capacity to invent and then deploy the technologies it needs is shaped by public funding and government policies. In the US, public investment in manufacturing, new materials, and vaccines and diagnostics has not been a priority, and there is almost no system of government direction, financial backing, or technical support for many critically important new technologies. Without it, the country was caught flat-footed.

Instead, as Henderson writes in her book *Reimagining Capitalism*, the US has, over the last half-century, increasingly put its faith in free markets to create innovation. That approach has built a wealthy Silicon Valley and giant tech firms that are the envy of entrepreneurs around the world. But it has meant little investment and support for critical areas such as manufacturing and infrastructure—technologies relevant to the country's most basic needs.

Though written before covid-19 emerged, Henderson's book was published in mid-April, as the pandemic was surging in many parts of the US. In it, she describes the role business can play in tackling big problems like climate change and inequality, but she also documents decades of government failure to support the private sector in doing so. Today, she says, it feels as though she's "living the book."

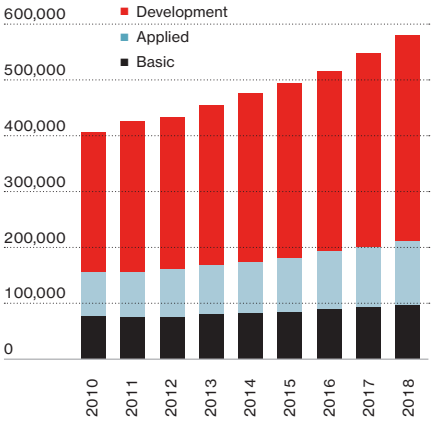
The US's paralysis in the face of covid-19 matters not only because it has already doomed tens of thousands to an early death and crippled the largest economy in the world, but because it reveals a deep and fundamental flaw in how the nation thinks about innovation.

Building stuff we need

Economists like to measure the impact of innovation in terms of productivity growth, particularly "total factor productivity"—the ability to get more output from the same inputs (such as labor and capital). Productivity growth is what makes advanced nations richer and more prosperous over the long run. For the US as well as most other rich countries, this measure of innovation has been dismal for nearly two decades.

There are a lot of different ideas about why the innovation slowdown happened. Perhaps the kinds of inventions that previously transformed the economy—like computers and the internet, or before that the internal-combustion engine—stopped coming along. Or perhaps we just haven't yet learned how to use the newest technologies, like artificial intelligence, to improve productivity in many sectors.

3 Spending on basic research has been nearly flat. ($ million)



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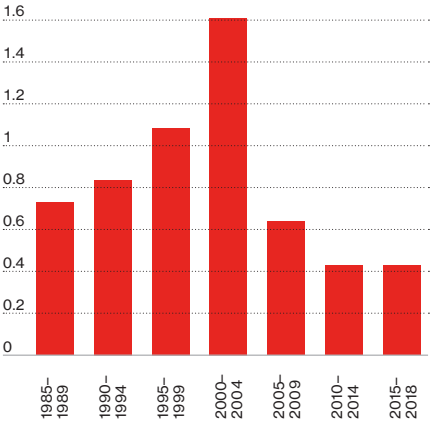
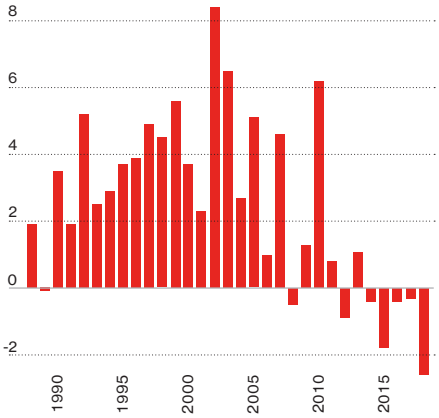
4 Total factor productivity (TFP) is sluggish. (Growth rate, %)



OECD

5 And manufacturing TFP has collapsed. (Growth rate, %)



US BUREAU OF LABOR STATISTICS

But one likely factor is that governments in many countries have significantly cut investments in technology since the 1980s.

Government-funded R&D in the US, says John Van Reenen, an economist at MIT, has dropped from 1.8% of GDP in the mid-1960s, when it was at its peak, to 0.7% now (chart 1). Governments tend to fund high-risk research that companies can't afford, and it's out of such research that radical new technologies often arise.

The problem with letting private investment alone drive innovation is that the money is skewed toward the most lucrative markets. The biggest practical uses of AI have been to optimize things like web search, ad targeting, speech and face recognition, and retail sales. Pharmaceutical research has largely targeted the search for new blockbuster drugs. Vaccines and diagnostic testing, so desperately needed now, are less lucrative. More government money might have boosted those pursuits.

Nor is it enough to invent new technologies: public support is also vital for helping companies adopt them. That's especially true in large, slow-moving sectors of the economy such as health care and manufacturing—precisely where the country's crippled capabilities have been most evident during the pandemic.

In a widely circulated blog post, internet pioneer and Silicon Valley icon Marc Andreessen decried the US's inability to "build" and produce needed supplies like masks, claiming that "we chose not to have the mechanisms, the factories, the systems to make these things." The accusation resonated with many: the US, where manufacturing has deteriorated, seemed unable to churn out things like masks and ventilators, while countries with strong and innovative manufacturing sectors, such as China, Japan, Taiwan, and Germany, have fared far better.

But Andreessen is wrong to portray the unwillingness to build as a deliberate choice. And the country's ability to make stuff isn't something that can be quickly revved up. The decline of US manufacturing has been caused by years of financial market pressures, government indifference, and competition from low-wage economies.

In the US, manufacturing jobs dropped by almost a third between 2000 and 2010 and have barely recovered since. Manufacturing productivity has been particularly poor in recent years (chart 5). What has been lost is not only jobs but also the knowledge embedded in a strong manufacturing base, and with it the ability to create new products and find advanced and flexible ways of making them. Over the years, the country ceded to China and other countries the expertise in competitively making many things, including solar panels and advanced batteries—and, it now turns out, swabs and diagnostic tests too.

No country should aim to make everything, says Fuchs, but "the US needs to develop the capacity to identify the technologies—as well as the physical and human resources—that are critical for national, economic, and health security, and to invest strategically in those technologies and assets."

Regardless of where products are made, Fuchs says, manufacturers need more coordination and flexibility in global supply chains, in part so they aren't tied to a few sources of production. That quickly became evident in the pandemic; for example, US mask makers scrambled to procure the limited supply of melt-blown fiber required to make the N95 masks that protect against the virus.

The problem was made worse because manufacturers keep inventories razor-thin to save money, often relying on timely shipments from a sole provider. "The great lesson from the pandemic," says Suzanne Berger, a political scientist at MIT and an expert on advanced manufacturing, is "how we traded resilience for low-cost and just-in-time production."

Berger says the government should encourage a more flexible manufacturing sector and support domestic production

by investing in workforce training, basic and applied research, and facilities like the advanced manufacturing institutes that were created in the early 2010s to provide companies with access to the latest production technologies. "We need to support manufacturing not only [to make] critical products like masks and respirators but to recognize that the connection between manufacturing and innovation is critical for productivity growth and, out of increases in productivity, for economic growth," she says.

The good news is that the US has had this discussion during previous crises. The playbook exists.

Declaring war on the virus

In June 1940, Vannevar Bush, then the director of the Carnegie Institution for Science in Washington, DC, went to the White House to meet President Franklin D. Roosevelt. The war was under way in Europe, and Roosevelt knew the US would soon be drawn into it. As Simon Johnson and Jonathan Gruber, both economists at MIT, write in their recent book *Jump-Starting America*, the country was woefully unprepared, barely able to make a tank.

Bush presented the president with a plan to gear up the war effort, led by scientists and engineers. That gave rise to the National Defense Research Committee (NDRC); during the war, Bush directed some 30,000 people, including 6,000 scientists, to steer the country's technological development.

The inventions that resulted are well known, from radar to the atomic bomb. But as Johnson and Gruber write, the investment in science and engineering continued well after the war ended. "The major—and now mostly forgotten—lesson of the post-1945 period is that modern private enterprise proves much more effective when government provides strong underlying support for basic and applied science and for the commercialization of the resulting innovations," they write.

A similar push to ramp up government investment in science and technology "is clearly what we need now," says Johnson. It could have immediate payoffs both in technologies crucial to handling the current crisis, such as tests and vaccines, and in new jobs and economic revival. Many of the jobs created will be for scientists, Johnson acknowledges, but many will also go to trained technicians and others whose work is needed to build and maintain an enlarged scientific infrastructure.

This matters especially, he says, because with an administration that is pulling back from globalization and with consumer spending weak, innovation will be one of the few options for driving economic growth. "Scientific investment needs to be a strategic priority again," says Johnson. "We've lost that. It has become a residual. That's got to stop."

Johnson is not alone. In the middle of May, a bipartisan group of congressmen proposed what they called the Endless Frontier Act to expand funding for "the discovery, creation, and commercialization of technology fields of the future." They argued that the US was "inadequately prepared" for covid-19 and that the pandemic "exposed the consequences of a long-term failure" to invest in scientific research. The legislators called for $100 billion over five years to support a "technology directorate" that would fund AI, robotics, automation, advanced manufacturing, and other critical technologies.

Around the same time, a pair of economists, Northwestern's Ben Jones and MIT's Pierre Azoulay, published an article in Science calling for a massive government-led "Pandemic R&D Program" to fund and coordinate work in everything from vaccines to materials science. The potential economic and health benefits are so large, Jones argues, that even huge investments to accelerate vaccine development and other technologies will pay for themselves.

Vannevar Bush's approach during the war tells us it's possible, though the funding needs to be substantial, says Jones. But increased funding is just part of what is required, he says. The initiative will need a central authority like Bush's NDRC to identify a varied portfolio of new technologies to support—a function that is missing from current efforts to tackle covid-19.

The thing to note about all these proposals is that they are aimed at both short- and long-term problems: they are calling for an immediate ramp-up of public investment in technology, but also for a bigger government role in guiding the direction of technologists' work. The key will be to spend at least some of the cash in the gigantic US fiscal stimulus bills not just on juicing the economy but on reviving innovation in neglected sectors like advanced manufacturing and boosting the development of promising areas like AI. "We're going to be spending a great deal of money, so can we use this in a productive way? Without diminishing the enormous suffering that has happened, can we use this as a wake-up call?" asks Harvard's Henderson.

"Historically, it has been done a bunch of times," she says. Besides the World War II effort, examples include Sematech, the 1980s consortium that revived the ailing US semiconductor industry in the face of Japan's increasing dominance, by sharing technological innovations and boosting investment in the sector.

Can we do it again? Henderson says she is "hopeful, though not necessarily optimistic."

The test of the country's innovation system will be whether over the coming months it can invent vaccines, treatments, and tests, and then produce them at the massive scale needed to defeat covid-19. "The problem hasn't gone away," says CMU's Fuchs. "The global pandemic will be a fact of life—the next 15 months, 30 months—and offers an incredible opportunity for us to rethink the resiliency of our supply chains, our domestic manufacturing capacity, and the innovation around it."

It will also take some rethinking of how the US uses AI and other new technologies to address urgent problems. But for that to happen, the government has to take on a leading role in directing innovation to meet the public's most pressing needs. That doesn't sound like the government the US has now.

David Rotman is editor at large of MIT Technology Review

OF COURSE TECHNOLOGY PERPETUATES RACISM. IT WAS DESIGNED THAT WAY.

Black Americans have seen technology used to target them again and again. Stopping it means looking at the problem differently.

By **Charlton McIlwain**

Today the United States crumbles under the weight of two pandemics: coronavirus and police brutality.

Both wreak physical and psychological violence. Both disproportionately kill and debilitate black and brown people. And both are animated by technology that we design, repurpose, and deploy—whether it's contact tracing, facial recognition, or social media.

We often call on technology to help solve problems. But when society defines, frames, and represents people of color as "the problem," those solutions often do more harm than good. We've designed facial recognition technologies that target criminal suspects on the basis of skin color. We've trained automated risk profiling systems that disproportionately identify Latinx people as illegal immigrants. We've devised credit scoring algorithms that disproportionately identify black people as risks and prevent them from buying homes, getting loans, or finding jobs.

Charlton McIlwain is a professor of media, culture, and communication at New York University and author of Black Software: The Internet & Racial Justice, From the AfroNet to Black Lives Matter

So the question we have to confront is whether we will continue to design and deploy tools that serve the interests of racism and white supremacy.

Of course, it's not a new question at all.

Uncivil rights

In 1960, Democratic Party leaders confronted their own problem: How could their presidential candidate, John F. Kennedy, shore up waning support from black people and other racial minorities?

An enterprising political scientist at MIT, Ithiel de Sola Pool, approached them with a solution. He would gather voter data from earlier presidential elections, feed it into a new digital processing machine, develop an algorithm to model voting behavior, predict what policy positions would lead to the most favorable results, and then advise the Kennedy campaign to act accordingly. Pool started a new company, the Simulmatics Corporation, and executed his plan. He succeeded, Kennedy was elected, and the results showcased the power of this new method of predictive modeling.

Racial tension escalated throughout the 1960s. Then came the long, hot summer of 1967. Cities across the nation burned, from Birmingham, Alabama, to Rochester, New York, to Minneapolis, Minnesota, and many more in between. Black Americans protested the oppression and discrimination they faced at the hands of America's criminal justice system. But President Johnson called it "civil disorder," and formed the Kerner Commission to understand the causes of "ghetto riots." The commission called on Simulmatics.

As part of a DARPA project aimed at turning the tide of the Vietnam War, Pool's company had been hard at work preparing a massive propaganda and psychological campaign against the Viet Cong. President Johnson was eager to deploy Simulmatics' behavioral influence technology to quell the nation's domestic threat, not just its foreign enemies. Under the guise of what it called a "media study," Simulmatics built a team for what amounted to a large-scale

COURTESY PHOTO

ILLUSTRATION SOURCE: GETTY IMAGES

When the rioting started, black people were again seen as a threat to law and order, a threat to a system that perpetuates white racial power.

surveillance campaign in the "riot-affected areas" that captured the nation's attention that summer of 1967.

Three-member teams went into areas where riots had taken place. They identified and interviewed strategically important black people. They followed up to identify and interview other black residents, in every venue from barbershops to churches. They asked people what they thought about the news media's coverage of the "riots."

But they collected data on much more, too: how people moved in and around the city during the unrest, who they talked to before and during the protests, and how they prepared for the aftermath. They collected data on toll booth usage, gas station sales, and bus routes. They gained entry to these communities under the pretense of trying to understand how news media supposedly inflamed "riots." But Johnson and the nation's political leaders were trying to solve a problem. They aimed to use the information that Simulmatics collected to trace information flow during protests to identify influencers and decapitate the protests' leadership.

They didn't accomplish this directly. They did not murder people, put people in jail, or secretly "disappear" them. Instead, by the end of the 1960s, this kind of data had helped create what came to be known as "criminal justice information systems." These then proliferated, laying the foundation for racial profiling, predictive policing, and racially targeted surveillance. They left behind a legacy that includes millions of black and brown women and men incarcerated.

Reframing the problem

Blackness and black people. Both persist as our nation's—dare I say even our world's—problem. When contact tracing first cropped up at the beginning of the covid-19 pandemic, it was easy to see it as a necessary but benign health surveillance tool. The coronavirus was the world's problem, and new surveillance technologies like exposure notification, temperature monitoring, and threat mapping began emerging to help address it.

But something both curious and tragic happened. It was discovered that black people, Latinx people, and indigenous populations were disproportionately infected and affected. Suddenly, we—those black and brown people—also became a national problem; we disproportionately threatened to spread the virus.

That was compounded when the tragic murder of George Floyd by a white police officer sent thousands of protesters into the streets. When the looting and rioting started, we were again seen as a threat to law and order, a threat to a system that perpetuates white racial power. It makes you wonder how long it will take for law enforcement to deploy those technologies first designed to fight covid-19 to quell the threat that black people supposedly pose to the nation's safety.

If we don't want our technology to be used to perpetuate racism, then we must make sure that we don't conflate social problems like crime or violence or disease with black and brown people. When we do that, we risk turning those people into the problems that we deploy our technology to solve, the threat we design it to eradicate.

35 Innovators Under 35

In chaotic times it can be reassuring to see so many people working toward a better world. That's true for medical professionals fighting a pandemic and for ordinary citizens fighting for social justice. And it's true for those among us striving to employ technology to address those problems and many others.

The 35 young innovators in these pages aren't all working to fight a pandemic (though some are: see Omar Abudayyeh, page 16, and Andreas Puschnik, page 27), and they're not all looking to remedy social injustices (though some are: see Inioluwa Deborah Raji, page 28, and Mohamed Dhaouafi, page 37). But even those who aren't tackling those specific problems are seeking ways to use technology to help people. They're trying to solve our climate crisis, find a cure for Parkinson's, or make drinking water available to those who are desperate for it.

This contest generates more than 500 nominations each year. The editors then face the task of picking 100 semifinalists to put in front of our 25 judges, who have expertise in artificial intelligence, biotechnology, software, energy, materials, and so on. With the invaluable help of these rankings, the editors pick the final list of 35. —*The editors*

JUDGES

Nora Ayanian
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Burcin Becerik-Gerber
Professor of Civil and Environmental Engineering and Director of the Center for Intelligent Environments, University of Southern California

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Ilan Gur
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Linda J. and Mark C. Smith Professor and Chair, School of Interactive Computing, Georgia Tech

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Jennifer West
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Jackie Ying
A*STAR Senior Fellow, NanoBio Lab

Ben Zhao
Neubauer Professor of Computer Science, University of Chicago

Inventors

Their innovations point toward a future with new types of batteries, solar panels, and microchips.

OMAR ABUDAYYEH

MIT

Age 30 | Country of birth: US

He's working to use CRISPR as a covid-19 test that you could take at home.

CRISPR has been called the discovery of the century for its potential to change biomedical research and treatment of genetic diseases. But it was Omar Abudayyeh who helped turn the gene-editing tool into a diagnostic test, one that might help slow down the covid-19 pandemic.

Seizing on the precise gene-finding mechanism, in 2016 Abudayyeh, along with Jonathan Gootenberg and other colleagues at MIT, forged CRISPR into a tool to spot cancer mutations, bacteria, and mosquito-borne viruses like Zika. Soon, there was a spinout startup company called Sherlock Biosciences, $49 million in funding, and newspaper stories about CRISPR's "new capabilities."

Then came covid-19. Genetic tests to spot the pathogen were in desperately short supply in the US, with the workhorse technology, PCR, floundering. By early May, three months into the outbreak, around 2% of Americans had been tested for covid-19. Some economists say the country needs to test that many people *every day* to reopen with confidence.

That's why, since January, Abudayyeh and his colleagues have been trying to forge CRISPR into an at-home test for the virus. The basic chemistry is simple enough, they think, to create an easy-to-use test that you could give yourself before heading to work, or maybe take at an airport gate before catching a flight.

If they succeed, virus testing could happen anywhere, anytime, and the gene-editing revolution would reach directly into people's homes and lives for the first time.

Here's how it works

The CRISPR revolution began with discoveries, in the early 2000s, that bacteria had evolved a way to chop up marauding phage viruses. CRISPR, whose name is an acronym for this natural biological invention, can spot unique sequences of DNA letters and cleave them with a cutting enzyme, Cas9. The tool, it turned out, was easy to use and worked in many species. Biotech startups began racing to treat genetic disease in humans. Gene-edited human twins were even born in China.

During what he calls the "Cas9 craze," Abudayyeh was drafted into a less visible avenue of research: the effort to discover and characterize novel CRISPR enzymes.

Soon the list was growing, and Abudayyeh and colleagues were demonstrating what the new editors could do. There would be Cpf1, also known as Cas12a, and then Cas12b. But one called Cas13, discovered literally under our noses (it's part of a human oral bacterium called *Leptotrichia shahii*), was special. Instead of cutting DNA, the enzyme could instead target RNA, the genetic messenger molecule inside of cells, which is also the primary genetic material of many viruses, including the coronavirus.

It was a totally new way to edit. What hadn't changed was Abudayyeh's close and ongoing collaboration with fellow gene editor Jonathan Gootenberg. The pair first met as MIT undergrads and then worked together in the busy lab of CRISPR pioneer Feng Zhang (who made our list of 35 innovators in 2013) at the Broad Institute. They've written 28 papers together, and in 2017 they were hired to establish a joint lab at the MIT McGovern Institute, which they christened the "AbuGoot Lab."

"We joke that it's a scientific bromance that just keeps on going," says Abudayyeh, who reckons he's the more practical of the two, while Gootenberg is more mathematical. "Our brains haven't quite merged, but it's close."

And they needed two heads to understand the new RNA editor, Cas13. The enzyme turned out to have a bizarre "collateral effect." Not only did it cut specific RNA strands, but once it got going, it would furiously chop up and degrade any RNA in its path. "The mechanism was insane and very confusing at first," says Abudayyeh. "We think it's part of a cell-suicide mechanism"—a natural self-destruct device in bacteria attacked

Portrait by David Vintiner

by a virus. "When it activates, it shuts down everything in the cell."

The indiscriminate cutting, though, meant Cas13 wasn't a great editor on its own. "It was kind of disappointing, but we came from an engineering background, so we asked what it is good for," says Abudayyeh. Maybe they could blow up RNA in a cancer cell, bringing it to a halt?

The idea that the collateral damage could turn CRISPR into a lab diagnostic was first floated by scientists from the rival laboratory of Jennifer Doudna at the University of California, Berkeley. There a team proposed that indiscriminate cutting could serve as a detection mechanism. In short, if the enzyme found a match in a test tube—a piece of RNA belonging to a virus, say—the collateral cutting could be used to sever special RNA that, when broken, would set off a visible fluorescent signal.

Great idea, but on its own, Cas13 wasn't sensitive enough to create a test. So Abudayyeh and Gootenberg got help from MIT professor Jim Collins, who showed them how to add a preamplification step, or a way to copy and multiply the RNA before testing for a match. By 2017, the group was showing off a complete CRISPR diagnostic system called Sherlock that could locate unique mutations that cause cancer or flag the presence of

"I think our goal right now is to have it ready for the fall. For when the second wave comes."

bacteria, or even the Zika virus. And it was highly accurate. Imagine being able to pick out one person's face from the population of 100 million Earths. That's the equivalent of what Sherlock could do in sorting through RNA.

Sherlock soon had competition from the Berkeley team, which started its own CRISPR diagnostics company, Mammoth Biosciences. One result: a tangle of competing diagnostic patents that is reminiscent of the bruising, costly fight between the two institutions over the original CRISPR inventions. Abudayyeh shrugs: "It's more exciting when you have more than one group working on it. And it's better for CRISPR diagnostics that it's not just one company trying to peddle a technology."

He's right: reaching the market is the hard part. That's because diagnostic testing is a business of giant companies, big machines, and centralized labs. It can take a hundred million dollars to develop a test that sells for $45. "Not for the faint of heart" is how venture capitalist Bruce Booth once described the business. By late 2019, Sherlock, a company Abudayyeh cofounded, was still edging the CRISPR-based tests toward the market.

But then the pandemic exploded out of China and changed everything. When the shortage of tests in the US became clear, the Food and Drug Administration started giving emergency approvals to makers of dozens of tests, allowing them into the market immediately. In May, Sherlock Biosciences won US authorization to perform a version of the CRISPR test that had to be done in a lab, although at press time no one had yet used it on a patient.

A home test

Still, it wasn't easy enough for someone without training to use. Back on MIT's campus, Abudayyeh, Gootenberg, and Zhang set out to simplify the technology. They reasoned that if they could eliminate some of the fluid mixing steps, the test could be used in workplaces, in pharmacies, or even at home. It didn't need repeated heating and cooling, as PCR does. And the readout was easy to understand: just colored bars on a paper strip, like a pregnancy test. "Our vision is really testing that can be done at home," says Abudayyeh. "So how can we push this so it's fewer steps, simple, and cheap?"

Right now, so-called point-of-care diagnostic tests do exist, but they need to be run on machines that cost thousands of dollars. One device, ID NOW, which is sold by Abbott, returns coronavirus results in 15 minutes and is used by the White House to screen visitors meeting with President Donald Trump. But the machine that processes the test costs thousands to buy. Abudayyeh says CRISPR home tests might cost $6 each and only use simple equipment.

By May, the researchers had created a simplified version and launched a website to share the new chemistry, which they showed could spot the coronavirus in swabs from patients. They are working with a design firm to create a prototype of a plastic cartridge to hold and mix the test ingredients. So has Abudayyeh tested himself? He hasn't. "It's tempting to spit in the tube," he says. "But it's also a scary thing to do."

Pretty soon, though, people around the world may be having such "Do I or don't I have it?" moments regularly, or at least that's the hope.

The work is "not final," Abudayyeh says. "Final is a simple device you can spit in. But this is the version of the chemistry that would work for the home. I think our goal right now is to have it ready for the fall. For when the second wave comes."

—Antonio Regalado

ANASTASIA VOLKOVA

Flurosat

Age 28 | Country of birth: Ukraine

Her platform uses remote sensing and other techniques to monitor crop health—helping farmers focus their efforts where they're most needed.

If there's one thing that frustrates Anastasia Volkova, it's inefficiency. So when she realized she could combine remote sensing data with scientific modeling to improve crop yields, reduce the use of agricultural chemicals, and make better use of water, she knew she'd found her life's work. It didn't matter that she was still pursuing her doctorate in aerospace at Sydney University or that she would need to single-handedly raise more than $5 million in startup money: Volkova, the daughter of a self-taught botanist and the goddaughter of a successful farmer, wanted to fix what she thought was wrong with large-scale farming.

Her resulting venture, Flurosat, uses imaging sensors on satellites, planes, and drones to detect when crops are in trouble long before their distress is discernible to the naked eye. Like humans, plants spike a fever when they're sick. They also heat up in response to pests or because they're not getting the nutrition or water they need. Flurosat uses multispectral and thermal cameras to record these changes and AI to calibrate crop models. Comparing a real crop with its digital twin then enables Volkova and her team to make real-time recommendations to agronomists and farm managers about what their yields need to thrive.

This kind of monitoring and support could reduce the overuse of nitrogen, pesticides, and herbicides and optimize irrigation. *—Kathryn Miles*

COURTESY PHOTO

LEILA PIRHAJI

ReviveMed

Age 34 | Country of birth: Iran

She developed an AI-based system that can identify more small molecules in a patient's body, faster than ever before.

Leila Pirhaji built an AI-based tool for measuring tiny molecules in the body called metabolites, and her work could help us better detect and treat diseases. "There are 100,000 metabolites in the body," she says. "They are involved in our metabolism and are downstream from DNA, so they show the effects of both our genes and lifestyle." Such metabolites include everything from blood sugars and cholesterol to obscure molecules that appear in significant numbers only when someone is sick.

The problem is that measuring and identifying metabolites is expensive and time consuming, and fewer than 5% of metabolites in a patient can be identified using common technologies.

So Pirhaji developed a platform that uses machine learning to do it much more quickly. First she built a huge database of all known information about existing metabolites and how they interact with various proteins and other molecules. Then her team collected tissue and blood samples from patients with known diseases, and measured the metabolites.

Her platform was able to analyze the data, understand the complex connections between diseases and metabolites, and use this information to discover new drugs. When she tested it in a mouse with Huntington's disease during her PhD at MIT, her team learned new mechanisms for the disease and found new potential ways of treating it.

As CEO of ReviveMed, Pirhaji is focusing on liver, immune, inflammatory, and other diseases. Using her platform, the startup partners with major pharmaceutical companies to match existing medicines to new treatments and find new targets for future drugs.

—Russ Juskalian

CHRISTINA BOVILLE

Aralez Bio

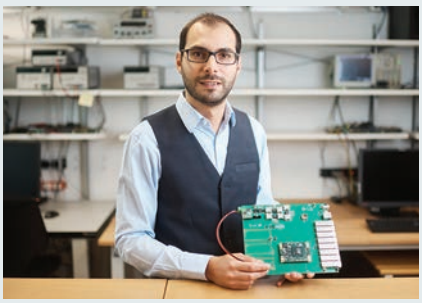
Age 32 | Country of birth: US

She modifies enzymes to enable production of new compounds for industry.

Christina Boville helped design a process that improves on biology's way of controlling chemical reactions. She starts with natural enzymes—proteins that enable chemical reactions in living cells—and engineers them to produce useful chemicals that don't exist in nature. The approach can reduce manufacturing times for compounds used in the pharmaceutical industry from months to days, shrink waste by up to 99%, and cut energy consumption in half.

In 2019, Boville cofounded Aralez Bio with David Romney and Frances Arnold, who won a Nobel Prize in 2018 for a new way of creating enzymes called directed evolution. Boville's process creates chemicals known as non-canonical amino acids (ncAAs), which are used in making 12% of the 200 best-selling medicines, including those for migraines and diabetes, and are also used in agriculture. "Nature was built using 20 amino acids, and now our enzymes can make hundreds more," she says. Drug ingredients "normally take five to 10 steps to make," she adds, "but we can do it in a single step."

Aralez Bio was recently approached by a pharmaceutical company to produce ncAAs that had taken the company nine months to make with conventional methods. Boville's enzymes now makes the same compound overnight. *—Russ Juskalian*



MANUEL LE GALLO

IBM RESEARCH

Age 34 | Country of birth: Canada

He uses novel computer designs to make AI less power hungry.

Training a typical natural-language processor requires so much computing power that it emits as much carbon as the life span of five American cars. Training an image recognition model releases as much energy as a typical home puts out in two weeks—and it's something that leading tech companies do multiple times a day.

Much of the energy use in modern computing comes from the fact that data needs to be constantly transferred back and forth between memory and the processor. Manuel Le Gallo is working with a research team at IBM that's building technology to enable new kinds of computing architecture that aims to be faster and more energy efficient but still highly precise.

Le Gallo's team developed a system that uses memory itself to process data, and his team's early work has shown they can achieve both precision and huge energy savings. The team recently completed a process using just 1% as much energy as when the same process was performed with conventional methods.

As companies from the financial sector to life sciences constantly train their AI models to improve them, their energy needs will balloon. "What will change is we will be able to change models faster and more energy efficiently, which will definitely reduce the carbon footprint and energy spent training those models," Le Gallo says. *—Patrick Howell O'Neill*

COURTESY PHOTOS (PIRHAJI, BOVILLE); SAMUEL TRÜMPY (LE GALLO)

Her goal is to give anyone with an idea the means to efficiently translate it into physical reality.

NADYA PEEK

University of Washington

Age 34 | Country of birth: US

She builds novel modular machines that can do just about anything you can imagine.

Nadya Peek began tinkering with machines out of stubbornness.

As an undergraduate, when she collaborated with artists on their installations, she often ran into limitations with the tools and equipment they were using. Rather than accept her fate, she hacked the machines until they finally did what she wanted. It got her thinking: why couldn't machines be more flexible? What if instead of changing your idea to fit the tools, you could change the tools to fit your idea? Thus began her quest to create application-specific machines that could help anyone do almost anything.

Peek is now an assistant professor at the University of Washington, where she dedicates herself to this vision. She designs modular components—motors, mechanical arms, and material cutters—that can be assembled every which way and programmed with a little bit of code to carry out tasks from the frivolous to the scientific. When she teaches people to use her components, she delights in their creativity: they've made T-shirt-designing machines and cocktail-mixing machines, 3D printers, and chemistry pipetting machines. The machines are often no larger than a desktop and can be broken down and reassembled for new tasks once they've outlived their original use.

Peek tries to make her tools as low-cost and accessible as possible: some use only cardboard for their frames, and the designs are available to download. Her machines have been used by students, hackers, and even architects.

Peek's goal is to give anyone with an idea the means to translate it into physical reality. She notes that computers were originally designed to carry out specific tasks, but evolved to be more general-purpose. She thinks machines that automate physical tasks should be no different. "I ultimately really would like to see automation as ... just another thing that you can use for creative problem solving," she says. *—Karen Hao*

RANDALL JEFFREY PLATT

ETH Zurich

Age 32 | Country of birth: US

His recording tool provides a video of genes turning on or off.

Randall Platt has created a way to record molecular events in a cell across time—a technology that has the potential to transform our understanding of a number of important biological processes.

Currently, for instance, one of the best tools available to understand the molecular processes that occur during embryonic development or immune responses to cancer is RNA-seq, a technique that allows biologists to develop a snapshot of how genes are being expressed—which ones are being turned on or off—at a single moment in time. But while RNA-seq provides a snapshot, Platt's tool could potentially be used to record the equivalent of a brief video, capturing gene expression over time and thus providing a much richer picture of, say, an embryo's development.

"At the core of all of biology and biomedicine is looking at transitions in systems—whether it be a stem cell that develops into a neuron or a healthy neuron that develops into a degenerative neuron," he says. "How people approach this problem today is they perform time-point experiments and then kind of guess what's happening in between. I was going after a technology that would fill that gap—what was happening to the cells throughout this transition."

Platt has big ambitions for his tool. He invented it to deal with a problem that repeatedly frustrated him when he was a graduate student at MIT. A group identified a gene that, when mutated and missing, appeared to play a role in autism—though precisely when the gene affected the brain's development remained a mystery.

"If you want to identify a meaningful defect in a neuron you need to know exactly when, where, and how to look," he says. "This was the biological problem that motivated me to create the recording tool." *—Adam Piore*

SAM KERR (PEEK); COURTESY PHOTO (PLATT)

REBECCA SAIVE

University of Twente and ETC Solar

Age 33 | Country of birth: Germany

She found a way to make solar panels cheaper and more efficient.

The silver lines that crisscross the face of solar panels are essentially metal wires. They're necessary to channel the electric current flowing out of the cells, but they reflect about 5% of the sunlight that reaches them, creating the single biggest drain on their efficiency.

Rebecca Saive, an assistant professor in applied physics at the University of Twente in the Netherlands, has invented a novel type of "front contact" that addresses this problem, reducing the wasted sunlight and improving the performance of solar photovoltaics.

Her transparent contacts are made from silver nanoparticles 3D-printed onto the silicon layer of a solar cell, using a technique she developed that produces an extremely thin and precise triangular shape. The steeply angled sidewalls reflect arriving light toward the absorbing body of the cell like a mirror, boosting electricity output by at least 5% and lowering costs roughly the same amount.

ETC Solar—a startup Saive cofounded with headquarters in Pasadena, California, and Rotterdam—produces a printing tool that enables manufacturers to integrate the technology into otherwise standard photovoltaics. It's already selling the product, though the company hasn't announced customers yet.

Meanwhile, ETC and Saive's academic team at the University of Twente are using the front contacts and other advances to develop even more efficient solar cells that she says could eventually lead to solar plants that produce lower-cost electricity, and even to solar-powered cars. *—James Temple*

COURTESY PHOTOS

SIHONG WANG

University of Chicago

Age 33 | Country of birth: China

His stretchable microchips promise to make all sorts of new devices possible.

Microchips are usually etched into a substrate of brittle silicon crystals. That means if you try to bend or stretch them, their molecular structures break and performance drops dramatically. Circuits that aren't as fragile have been around for a while, but they've always had to trade off performance or ease of manufacturing to achieve flexibility. Sihong Wang, however, has developed new manufacturing techniques to build circuits that can stretch and bend while performing just as well as an inorganic semiconductor circuit.

Building on his previous work with Zhenan Bao at Stanford, one of the field's pioneers, Wang has created a set of new processes that dramatically move things forward. Using a physical effect known as nanoconfinement to build layered polymer circuits at the smallest possible scale, he can now reliably build high-performance circuits that can be stretched to twice their original length without losing any performance.

These rubbery polymers, he says, open up whole new classes of devices—malleable enough to be molded to your shape, applied as a skin patch, or even inserted inside the body, while able to do everything just as well as a more traditional machine. But that means a set of new problems to solve. How do you power them? He's already got ways to harness energy from the human body—using another invention called a "nanogenerator"—rather than requiring external batteries. Can these then be placed inside the body without triggering an immune response? That's next. *—Bobbie Johnson*

VENKAT VISWANATHAN

Carnegie Mellon University

Age 34 | Country of birth: India

His work on a new type of battery could make EVs much cheaper.

Venkat Viswanathan, an associate professor at Carnegie Mellon, has made major strides in developing anodes made out of pure lithium, promising a new class of batteries that pack more energy and deliver more power for a given amount of weight. That could enable cheaper electric vehicles and low-emissions aircraft.

Researchers have long recognized that lithium-metal anodes could boost the performance of batteries over ones made of graphite. But they're prone to developing needle-like "dendrites" as lithium ions build up. This can shorten the battery's life and even spark fires. Viswanathan's solution was developing a hybrid polymer-ceramic separator between the electrodes. It applies enough pressure to prevent the dendrites from forming but still allows ions to flow through the battery, which produces the electric current.

Viswanathan and colleagues secured more than $4 million from the Energy Department's moonshot ARPA-E program, and partnered with battery maker 24M Technologies to produce and test commercial-size lithium-metal cells.

Viswanathan has also worked with Aurora Flight Sciences and Airbus A^3 on battery designs for vertical takeoff and landing aircraft, which can function as air taxis or ambulances that zip across metropolitan areas. *—James Temple*

Pioneers

Their innovations lead the way to biodegradable plastics, textiles that keep you cool, and cars that "see."

JENNIFER GLICK

IBM QUANTUM

Age 30 | Country of birth: US

If quantum computers work, what can we use them for? She's working to figure that out.

The world's biggest machine, the Large Hadron Collider, was built to help answer some of the most important questions in physics. To do that, the scientists behind the particle collider have to be able to process and understand the massive amounts of data from the machine. They want to be able to tell whether certain particles are produced in high-energy collisions taking place at nearly the speed of light.

The LHC can produce over a petabyte of data per second from one billion particle collisions, requiring about one million processor cores spread out around the world to analyze and understand what would otherwise be chaos. What does all that data mean?

This is one of the most staggering problems facing Jennifer Glick, an IBM researcher whose work is to find big problems that can benefit from quantum computing and then either try to solve them with existing quantum algorithms or create new ones for the purpose.

Quantum computing promises enormous advances in processing power over classical computing for certain problems that are intractably large or time-consuming for classical computers—the kind of problems Glick looks for. A quantum computer's strength can be credited to the superposition and entanglement of quantum bits, or qubits, which offer an exponentially large computational space. For example, 50 perfect qubits can represent over a quadrillion states to explore.

Still, it's a technology in its very early days. In two years at IBM, Glick has helped lead an effort to create partnerships that bring quantum technology into the real world. She spends a lot of her time hunting for problems and then developing and demonstrating ways in which a quantum computer could solve them faster than a classical one.

"What we're looking at for the Large Hadron Collider is to use a quantum algorithm to predict whether or not a certain particle was produced," she says. "Was that the particle I think was produced or not?"

She's helped lead an effort to bring quantum technology into the real world.

In 2019, Glick and her colleagues tackled another big but more workaday problem with the banking giant Barclays. The challenge was managing the quadrillions of dollars processed each year in securities transaction settlements. These occur, for instance, when a financial institution buys shares, bonds, or derivatives. Clearinghouses must run complex optimization algorithms on the transactions to settle as many of them as possible within technical and legal constraints.

The results of the team's research indicate that quantum technology could make this process more efficient, speeding up the time between trade and settlement. "When someone gives you an industry or business problem, there's a lot of complications to start out with. It's a very complex, gnarly problem," Glick says. "Part of it is breaking it down into simpler pieces to be able to identify where the bottlenecks are with respect to classical computing methods that are being used today. And can any of those bottlenecks be removed by an quantum approach?"

—Patrick Howell O'Neill

Portrait by David Vintiner

LILI CAI

University of Illinois at Urbana-Champaign

Age 33 | Country of birth: China

She created energy-efficient textiles to break our air-conditioning habit.

Lili Cai has created nanomaterial-based textiles the thickness of a normal T-shirt that can keep you warm or cool you off.

Cai's work takes advantage of the fact that human skin strongly emits infrared radiation in a specific range of wavelengths. By manipulating the ways in which her fabrics block or transmit radiation in this band, she has produced multiple textiles that can have different effects on temperature.

To heat the body, Cai created a metallized polyethylene textile that can minimize heat radiation loss but is still breathable. Compared with normal textiles, it keeps people about 7 °C warmer. Under direct sunlight, her cooling fabric, a novel nanocomposite material, can cool the body by more than 10 °C.

Cai believes it's extremely important to figure out how to make such textiles look as much as possible like normal clothing. Previous radiative cooling materials could only be produced in white, but in 2019 Cai figured out how to fabricate her textiles in different colors. Her goal is to eventually produce one single adaptive textile that keeps you warm if it's cold out, but cools you off in the heat.

As climate change introduces shifts in weather and temperature patterns globally, people will use even more energy to regulate building temperatures. If she can figure out how to cheaply make her textiles at scale, they will provide an alternative that could help cut those heating and cooling bills. —*Abby Ohlheiser*

SIDDHARTH KRISHNAN

MIT

Age 29 | Country of birth: India

A tiny, powerful sensor for making disease diagnosis cheaper, faster, and easier.

Siddharth Krishnan, a materials scientist at MIT, developed a tiny sensor that could save people from a devastating and often deadly brain condition.

Between one and two in every 1,000 babies born in the United States have hydrocephalus, a condition in which cerebrospinal fluid builds up in the brain. It can also occur later in life, including after traumatic brain injury. Over a million people in the United States have hydrocephalus, and nearly all of them have a shunt installed that drains fluid from their brain into their chest or abdomen. The condition can be fatal if untreated, but if it's dealt with promptly a full recovery is often possible.

If shunts fail, because they get clogged, then fluid will again build up in the brain. This happens to about half of shunts within six years, so it's a major problem.

Earlier techniques for detecting shunt failure all had various shortcomings. Repeated CT scans, MRIs, or x-rays subject patients to dangerous doses of radiation, cost a lot, and—because they measure the performance of shunts only indirectly—are not all that reliable. Sometimes, invasive brain surgery is done just to verify that a shunt is working. And because checks were being performed only a few times a year, patients and their families had to live with constant uncertainty, wondering if their shunts were working properly.

In any case, because the flow of fluid from the brain is naturally intermittent, spot checks don't necessarily catch problems.

Krishnan's sensor offers a noninvasive way to monitor the flow in shunts: it can be placed over the skin on the neck, near the valve. It measures the temperature at several distinct spots, inferring from the temperature distribution at those spots whether or not liquid is flowing. Unlike an earlier generation of noninvasive sensors, which made fewer temperature measurements and required the use of an ice pack, his device can continuously measure the flow, reporting results via Bluetooth.

So far, field trials on seven patients reported in a paper earlier this year in the journal NPJ Digital Medicine show that his sensor gives "robust, high-quality data" for hours at a time.

Krishnan hopes that his sensor will have applications beyond hydrocephalus, possibly monitoring other diseases like diabetes, where tiny changes beneath the skin can have huge effects. —*Tanya Basu*

His noninvasive sensor can radically improve the treatment for hydrocephalus, which can be fatal if left untreated.

COURTESY PHOTO (CAI); EILEEN MOLONY (KRISHNAN)

AVINASH MANJULA BASAVANNA

Wyss Institute, Harvard University

Age 33 | Country of birth: India

His biodegradable plastic protects against extreme chemicals, but heals itself using water.

Of the estimated 9.1 billion tons of plastic ever produced, only 9% has been recycled. Almost 80% ends up as waste that adds to growing landfills or pollutes the natural environment, where it takes a thousand years to degrade. Such materials can also end up in the human body as microplastics, slowly accumulating with devastating effects on health. One key to solving these problems could be bioplastics—plastic alternatives produced through bioengineered organisms. These can degrade naturally and much more quickly.

The idea of bioplastics isn't exactly new, but it's been difficult to make them in the sorts of quantities and with the properties that would be useful for industry. Avinash Manjula Basavanna, a postdoc at the Wyss Institute for Biologically Inspired Engineering at Harvard University, thinks he can do better. He and his colleagues have developed a new type of plastic based on living materials that he calls AquaPlastic and which can be produced at a commercial scale, exhibits the tough qualities of many petroleum-based plastics, and can degrade in water in as little as two months.

The material itself is resistant to strong acids and bases. It can be applied as a coating using nothing but water, which makes the plastic turn adhesive—the first plastic of its kind to boast this feature. If it gets scratched, the coating can also be "healed" using water. And most important, "it's flushable," says Manjula Basavanna. "You don't have to worry about it adding to our plastic and microplastic problem." He and his partners are now in the beginning stages of forming a startup around AquaPlastic. If manufactured at scale, the cheap, biodegradable material could compete with conventional plastic coatings. *—Neel V. Patel*

COURTESY PHOTO (BAVANASSA); SAM KERR (ALHANAEE)

"If something were to happen, and desalination plants weren't able to operate ... there really is no backup plan."

GHENA ALHANAEE

University of Southern California

Age 30 | Country of birth: United Arab Emirates

Heavy dependence on infrastructure like oil rigs, nuclear reactors, and desalination plants can be catastrophic in a crisis. Her data-driven framework could help nations prepare.

Early on in her days as a doctoral student at the University of Southern California, Ghena Alhanaee stumbled upon a disturbing set of facts. The countries of the Persian Gulf, including her native United Arab Emirates, were far more vulnerable to disaster than she'd realized. Not only was the Gulf itself one of the world's largest oil and gas production zones, with more than 800 offshore platforms and thousands of tankers passing through its shallow waters every year, but the UAE was also building the Arab Peninsula's first nuclear power plant. Meanwhile, several Gulf countries relied almost exclusively on desalinated Gulf water for drinking, with emergency supplies for just two or three days. "If something were to happen, and desalination plants weren't able to operate, right now there really is no backup plan," Alhanaee says.

Ever since, she has devoted her energy to tackling the Gulf's disaster preparedness gap. She's developing a data-driven framework to help the region better mitigate the risks of an oil spill or nuclear accident. Since the Gulf's nuclear industry is nascent, and its oil and gas sector keeps its data private, she's relying on information from the US: her statistical model draws on data from more than 4,000 reported safety incidents in the US nuclear and offshore oil industries over the past decade. The trick, she says, is to better understand which combinations of small incidents, under which scenarios, are most likely to snowball into something major.

Alhanaee's framework seeks to do just that. She plans to apply her findings to a particularly vulnerable spot in the Gulf—in the vicinity of the Barakah nuclear power plant, which is nearing completion, and large-scale oil and desalination installations. Ultimately, she hopes her research will help the region's governments develop more robust, and better coordinated, disaster mitigation strategies.

—Jonathan W. Rosen

Using Karpathy's advances, Tesla is taking a different path from most other automakers.

ANDREJ KARPATHY

Tesla

Age 33 | Country of birth: Slovakia

He's employing neural networks to allow automated cars to "see."

Getting computers to see—to actually see—has been an ambition of countless computer scientists for decades. Few have come closer than Andrej Karpathy, whose approach to deep neural networks allows machines to make sense of what is happening in images.

As a graduate student at Stanford, Karpathy extended techniques for building what are known as convolutional neural networks (CNNs)—systems that broadly mimic the neuron structure in the visual cortex. (In 2015 he also designed and was the primary instructor for the first deep-learning class at Stanford.)

By combining CNNs with other deep-learning approaches, he created a system that was not just better at recognizing individual items in images (say, a dog or a person), but capable of seeing an entire scene full of objects—multiple dogs and people interacting with each other—and effectively building a story of what was happening in it and what might happen next.

In 2017, Karpathy joined Tesla, where he oversees neural networks for the cars' Autopilot feature. That includes collision detection, self-driving capabilities, and summoning (having a car drive autonomously from where it is parked).

Using Karpathy's advances, Tesla is taking a different path from most other automakers. Typically, self-driving vehicles scan their surroundings with expensive laser range finders, build a virtual map, and then use AI to make decisions about what to do. Tesla's approach uses traditional cameras. Not only can Karpathy's method let the car spot objects in the road as a human driver would, but it can take in the entire scene (cars, people, intersections, stop signs, and more) and—if it works as intended—instantly infer what's taking place. Doing so requires nearly 50 neural networks to constantly process data coming in as the more than a million cars in the fleet look and learn.

—Bobbie Johnson

GREGORY EKCHIAN

MIT

Age 32 | Country of birth: US

He invented a way to make radiation therapy for cancer safer and more effective.

The amount of radiation it takes to kill a tumor depends on the level of oxygen in the tumor cells. This can vary greatly, but oncologists don't currently adjust radiation doses to account for it. Gregory Ekchian, cofounder of Stratagen Bio, has developed a sensor for reading tumor oxygen levels to personalize cancer treatment.

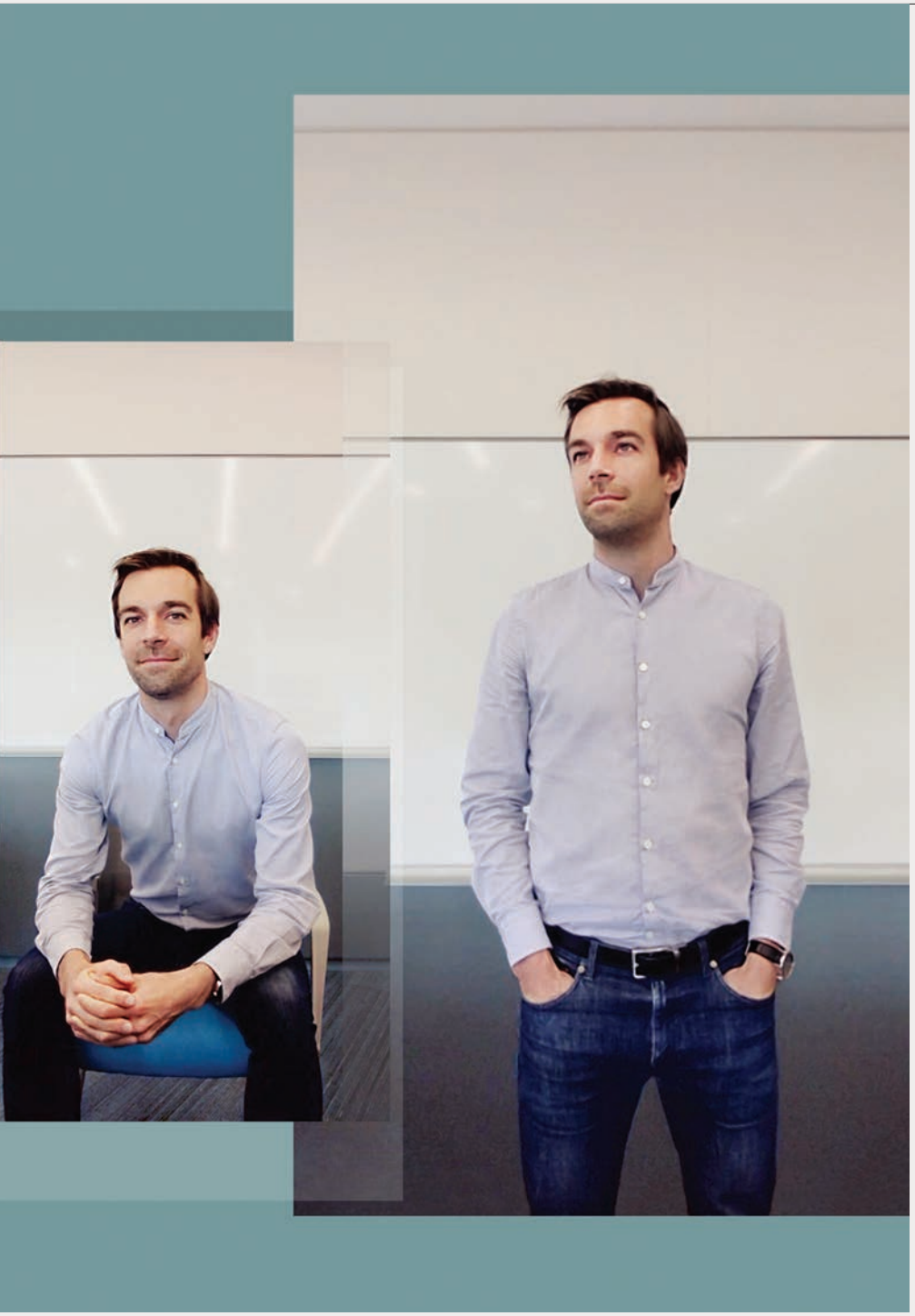
Ekchian recognized a glaring need for a new sensing tool after discussions with clinicians at Brigham and Women's Hospital in Boston. He developed a prototype for a cancer treatment technique called high-dose-rate brachytherapy. In this form of treatment, doctors puncture the tumor with a series of hollow catheter tubes and then drop radioactive seeds through the tubes to suffuse the tumor with radiation, removing them once the desired dose has been delivered.

For his prototype, Ekchian added a strip of a recently invented oxygen-sensitive polymer to the tips of a modified version of the catheters. During routine MRI scans, protons in the polymer are excited; these protons return to equilibrium far faster in catheters surrounded by high levels of oxygen than low levels. The speed at which they return to equilibrium can therefore be used to map out how oxygen levels vary in different parts of the tumor, allowing oncologists to pinpoint where radiation doses should go and tailor their length and intensity to be most effective.

"If we weren't worried about healthy tissue, we would just boost the dose to the entire tumor," he says, but excess radiation can harm the patient. That means "it's really important to figure out where those high doses need to go."

Ekchian is preparing to publish the results of a clinical trial involving seven patients with cervical cancer, the first in humans. He ultimately hopes to employ his oxygen-sensing applications for a wide range of clinical needs. *—Adam Piore*

SAM KERR (KARPATHY); COURTESY PHOTO (EKCHIAN)



Portrait by David Vintiner

ANDREAS PUSCHNIK

Chan Zuckerberg Biohub

Age 31 | Country of birth: Germany

Seeking a universal treatment for viral diseases, he might leave us much better prepared for the next pandemic.

Zika, Ebola, SARS, dengue fever, and covid-19. These diseases have fearsome personalities, yet the viruses that cause them are not really alive. To reproduce, viruses need to hijack a cell and use its components to produce more viruses.

To Andreas Puschnik, understanding which of our biomolecules viruses depend on could lead to new types of broad-acting antiviral drugs. "The idea is that viruses depend on specific cellular pathways which could themselves become drug targets," says Puschnik.

Usually, the German-born researcher says, drug makers look to take out pathogens with chemicals designed to bind to and disable the molecular components of the virus itself. This "one drug, one bug" solution can work powerfully (think HIV drugs). The problem is that each drug has to be specially designed.

An alternative, called host-directed therapeutics, is in its early days. But Puschnik has helped speed it up using the gene-editing tool CRISPR. In a mass screening approach, he uses CRISPR to pepper millions of human cells growing in flasks with a hundred thousand different genetic mutations. If any of those cells survive infection with, say, yellow fever, it means he's inactivated a molecular pathway the germ needs to reproduce.

Puschnik has already helped find an enzyme that mosquito-borne flaviviruses like dengue, Zika, and West Nile need to reproduce, as well as a drug to block it. Since all flaviviruses work similarly, he hopes the drug could be a "universal treatment" for them.

During California's 2020 lockdown, the biologist remained at work at the Chan Zuckerberg Biohub, a new institute that picked him as its first scientific fellow. "It is still busy days for virologists," says Puschnik, who now plans to turn his attention to the coronavirus that causes covid-19. Perhaps, he thinks, a drug that changes cells so they are less hospitable to coronaviruses could be ready for the next pandemic: "You might be able to treat viruses you don't even know about yet."

—Antonio Regalado

Visionaries

Their innovations are leading to breakthroughs in AI, quantum computing, and medical implants.

INIOLUWA DEBORAH RAJI

AI Now Institute

Age 24 | Country of birth: Nigeria

Her research on racial bias in data used to train facial recognition systems is forcing companies to change their ways.

The spark that sent Inioluwa Deborah Raji down a path of artificial-intelligence research came from a firsthand realization that she remembers as "horrible."

Raji was interning at the machine-learning startup Clarifai after her third year of college, working on a computer vision model that would help clients flag inappropriate images as "not safe for work." The trouble was, it flagged photos of people of color at a much higher rate than those of white people. The imbalance, she discovered, was a consequence of the training data: the model was learning to recognize NSFW imagery from porn and safe imagery from stock photos—but porn, it turns out, is much more diverse. That diversity was causing the model to automatically associate dark skin with salacious content.

Though Raji told Clarifai about the problem, the company continued using the model. "It was very difficult at that time to really get people to do anything about it," she recalls. "The sentiment was 'It's so hard to get any data. How can we think about diversity in data?'"

The incident pushed Raji to investigate further, looking at mainstream data sets for training computer vision. Again and again, she found jarring demographic imbalances. Many data sets of faces lacked dark-skinned ones, for example, leading to face recognition systems that couldn't accurately differentiate between such faces. Police departments and law enforcement agencies were then using these same systems in the belief that they could help identify suspects.

"That was the first thing that really shocked me about the industry. There are a lot of machine-learning models currently being deployed and affecting millions and millions of people," she says, "and there was no sense of accountability."

Born in Port Harcourt, Nigeria, Raji moved to Mississauga, Ontario, when she was four years old. She remembers very little of the country she left other than the reason for leaving: her family wanted to escape its instability and give her and her siblings a better life. The transition proved tough. For the first two years, Raji's father continued to work in Nigeria, flying back and forth between two continents. Raji attended seven different schools during their first five years in Canada.

Eventually, the family moved to Ottawa and things began to stabilize. By the time she applied to college, she was sure she was most interested in pre-med studies. "I think if you're a girl and you're good at science, people tell you to be a doctor," she says. She was accepted into McGill University as a neuroscience major. Then, on a whim, and with her father's encouragement, she visited the University of Toronto and met a professor who persuaded her to study engineering. "He was like, 'If you want to use physics and you want to use math to build things that actually create impact, you get to do that in this program,'" she remembers. "I just fell for that pitch and overnight changed my mind."

It was at university that Raji took her first coding class and quickly got sucked into the world of hackathons. She loved how quickly she could turn her ideas into software that could help solve problems or change systems. By her third year, she was itching to join a software startup and experience this in the real world. And so she found herself, a few months into her internship at Clarifai, searching for a way to fix the problem she had discovered. Having tried and failed to get support internally, she reached out to the only other researcher she knew of who was working on fighting bias in computer vision.

In 2016, MIT researcher Joy Buolamwini (one of MIT Technology Review's 35 Innovators Under 35 in 2018) gave a TEDx talk about how commercial face recognition systems failed to detect her face unless she donned a white mask. To Raji, Buolamwini was the perfect role model: a black female researcher like herself who had successfully articulated the same problem she had identified. She pulled together

Portrait by David Vintiner

all her code and the results of her analyses and sent Buolamwini an unsolicited email. The two quickly struck up a collaboration.

At the time, Buolamwini was already working on a project for her master's thesis, called Gender Shades. The idea was simple yet radical: to create a data set that could be used to evaluate commercial face recognition systems for gender and racial bias. It wasn't that companies selling these systems didn't have internal auditing processes, but the testing data they used was as demographically imbalanced as the training data the systems learned from. As a result, the systems could perform with over 95% accuracy during the audit but have only 60% accuracy for minority groups once deployed in the real world. By contrast, Buolamwini's data set would have images of faces with an even distribution of skin color and gender, making it a more comprehensive way to evaluate how well a system recognizes people from different demographic groups.

Raji joined in the technical work, compiling the new data set and helping Buolamwini run the audits. The results were shocking: among the companies they tested—Microsoft, IBM, and Megvii (the company best known for making the software Face++)—the worst identified the gender of dark-skinned women 34.4% less accurately than that of light-skinned

"There are a lot of machine-learning models currently being deployed ... and there was no sense of accountability."

men. The other two didn't do much better. The findings made a headline in the New York Times and forced the companies to do something about the bias in their systems.

Gender Shades showed Raji how auditing could be a powerful tool for getting companies to change. So in the summer of 2018, she left Clarifai to pursue a new project with Buolamwini at the MIT Media Lab, which would make its own headlines in January 2019. This time Raji led the research. Through interviews at the three companies they'd audited, she saw how Gender Shades had led them to change the ways they trained their systems in order to account for a greater diversity of faces. She also reran the audits and tested two more companies: Amazon and Kairos. She found that whereas the latter two had egregious variations in accuracy between demographic groups, the original three had dramatically improved.

The findings made a foundational contribution to AI research. Later that year, the US National Institute of Standards and Technology also updated its annual audit of face recognition algorithms to include a test for racial bias.

Raji has since worked on several other projects that have helped set standards for algorithmic accountability. After her time at the Media Lab, she joined Google as a research mentee to help the company make its AI development process more transparent. Whereas traditional software engineers have well-established practices for documenting the decisions they make while building a product, machine-learning engineers at the time did not. This made it easier for them to introduce errors or bias along the way, and harder to check such mistakes retroactively.

Along with a team led by senior research scientist Margaret Mitchell, Raji developed a documentation framework for machine-learning teams to use, drawing upon her experience at Clarifai to make sure it would be easy to adhere to. Google rolled out the framework in 2019 and built it into Google Cloud for its clients to use. A number of other companies, including OpenAI and natural-language processing firm Hugging Face, have since adopted similar practices.

Raji also co-led her own project at Google to introduce internal auditing practices as a complement to the external auditing work she did at the Media Lab. The idea: to create checks at each stage of an AI product's development so problems can be caught and dealt with before it is put out into the world. The framework also included advice on how to get the support of senior management, so a product would indeed be held back from launching if it didn't pass the audits.

With all her projects, Raji is driven by the desire to make AI ethics easier to practice—"to take the kind of high-level ethical ideals that we like to talk about as a community and try to translate that into concrete actions, resources, and frameworks," she says.

It hasn't always been easy. At Google, she saw how much time and effort it took to change the way things were done. She worries that the financial cost of eliminating a problem like AI bias deters companies from doing it. It's one reason she has moved back out of industry to continue her work at the nonprofit research institute AI Now. External auditing, she believes, can still hold companies accountable in ways that internal auditing can't.

But Raji remains hopeful. She sees that AI researchers are more eager than ever before to be more ethical and more responsible in their work. "This is such impactful technology," she says. "I just really want us to be more thoughtful as a field as to how we build these things, because it does matter and it does affect people."

—Karen Hao

EIMEAR DOLAN

National University of Ireland Galway

Age 32 | Country of birth: Ireland

Medical implants are often thwarted as the body grows tissue to defend itself. She may have found a drug-free fix for the problem.

When Eimear Dolan first worked to develop implantable medical devices to treat type 1 diabetes, she and her colleagues had to overcome a common roadblock. Their problem was one that's long dogged makers of devices like pacemakers, insulin delivery systems, and breast implants: when the body senses an implanted foreign object, it constructs a protective wall of fibrous tissue. This reaction, known as the foreign body response, is one of the main reasons medical implants fail.

Today, as a biomedical engineer at the National University of Ireland Galway, Dolan thinks she's found a way to counteract the foreign body response. Her weapon is a small robotic device known as a dynamic soft reservoir. Developed

through a collaboration between Dolan's lab at NIU Galway and researchers at MIT, the device is made of a soft material that can be made to oscillate, creating enough fluid flow to alter the environment around the implant and keep protective tissue from forming.

Past researchers have sought to use drugs or modify the surface chemistry of an implant. Dolan's innovation, which she and her colleagues have successfully tested in rats, marks the first time anyone has tackled the problem mechanically. "The beauty about it is it's a drug-free approach," Dolan says.

Her team is redesigning the dynamic soft reservoir as part of an effort to construct a "bioartificial pancreas," an implantable reservoir of cells that produce insulin for people with type 1 diabetes. Early attempts at such devices have been particularly liable to be rejected by the body and fail. Dolan believes her team can change that—and ultimately improve the success of other implantable devices. *—Jonathan W. Rosen*

LILLIE PAQUETTE

MIGUEL MODESTINO

NYU

Age 34 | Country of birth: Venezuela

He is reducing the chemical industry's carbon footprint by using AI to optimize reactions with electricity instead of heat.

Miguel Modestino has cleared a major hurdle in electrifying the chemical industry, which produces compounds used in everything from plastics to fertilizer. His AI-based system teaches itself how to optimize the reactions for making various chemicals by zapping them with pulses of electricity instead of the conventional approach of heating them, which typically involves burning fossil fuels. And since electricity can come from renewable sources like wind or solar, electrifying chemical plants could greatly reduce emissions.

In an early lab project, Modestino's team achieved more than a 30% boost in the production rate of adiponitrile (which is used in making nylon, among numerous other industrial processes)—a greater improvement than any other method has shown in the last 50 years.

The key was using complex pulses of electrical current at constantly varying rates to optimize yields. Figuring out what patterns of pulses to use required machine learning. Modestino ran a few experiments making adiponitrile under different electrical conditions and then let his AI analyze the data to figure out how to make the compound with less energy, better yields, and less waste.

Modestino and two former students recently founded Sunthetics to apply the AI system to other chemical processes, like those involved in generating hydrogen fuel and making polymers. The company is also working to scale up the adiponitrile process for a full pilot reactor and to extend the approach to other processes.

—Russ Juskalian

ROSE FAGHIH

University of Houston and MIT

Age 34 | Country of birth: US

Her sensor-laden wristwatch would monitor your brain states.

If Rose Faghih's project pans out, a seemingly simple smart watch could determine what's happening deep inside your brain.

Faghih has developed an algorithm to analyze otherwise imperceptible changes in sweat activity—a key indicator of stress and stimulation. Using two small electrodes attached to the back of a smart watch, she can monitor changes in skin conductance caused by sweat. Signal-processing algorithms then allow Faghih to correlate those changes with specific events, such as a PTSD-related flashback or even just wandering attention, in order to pinpoint the person's brain state.

Typically, this kind of real-time data is available only by way of expensive scalp-based electrode systems like EEG or functional MRI. Faghih's "Mindwatch" would in theory be cheap and portable enough to let people monitor their brain states anywhere.

Faghih hopes it will help people manage their own changing moods and mental states: a wearable with her technology could suggest that an agitated driver try some deep breathing or prompt a lonely shut-in to turn on mood-enhancing music. For people with mental illness or chronic conditions like diabetes, it could potentially even trigger an automated deep-brain stimulation device or an insulin pump. *—Kathryn Miles*

ZLATKO MINEV

IBM Quantum Research, TJ Watson

Age 30 | Country of birth: Bulgaria

His discovery could reduce errors in quantum computing.

Zlatko Minev overturned a mainstay of quantum physics that had troubled Niels Bohr and Albert Einstein alike. For most of the 20th century, it was assumed that atoms change from one energy level to another in abrupt, unpredictable, discrete quantum jumps. Minev proved otherwise.

"Quantum physics is not quite as unpredictable and discrete as we previously thought," he says.

His experiment showed that when an atom is bombarded with energy in the form of light, it moves from one energy level to the next in a continuous, smooth way, not an instantaneous jump. What's more, Minev was able to detect the change in an atom's energy level quickly enough to control it so he could stop the jump midflight and reverse it before it was completed.

"In the short term," he says, "with the monitoring that I developed for this project, we can actually have a window of predictability."

Minev's work could have major implications for quantum computing. Such systems are riddled with errors that occur when subatomic particles jump between energy levels, like the atoms in Minev's experiment. The ability to detect and reverse such jumps before they finish should dramatically boost the power of quantum computers, allowing them to better crack encryption, model chemical reactions, and forecast weather.

—Russ Juskalian

EDUARDO WAITE (MODESTINO); JEFF LAUTENBERGER, CULLEN COLLEGE OF ENGINEERING, UNIVERSITY OF HOUSTON(FAGHIH); ROBERT JONES (MINEV)

Her goal is to use her knowledge about potential attacks to make AI more robust.

BO LI

University of Illinois at Urbana-Champaign

Age 32 | Country of birth: US

By devising new ways to fool AI, she is making it safer.

A few years ago, Bo Li and her colleagues placed small black-and-white stickers on a stop sign in a graffiti-like pattern that looked random to human eyes and did not obscure the sign's clear lettering. Yet the arrangement was deliberately designed so that if an autonomous vehicle approached, the neural networks powering its vision system would misread the stop sign as one posting a speed limit of 45 mph.

Such "adversarial attacks"—manipulation of input data that looks innocuous to a person but fools neural networks—had been tried before, but earlier examples had been mostly digital. For instance, a few pixels might be altered in an image, a change invisible to the naked eye. Li was one of the first to show that such attacks were possible in the physical world. They can be harder for an AI to detect because the methods developed to spot manipulated digital images don't work on physical objects.

Li also devised subtle changes in the features of physical objects, like shape and texture, that again are imperceptible to humans but can make the objects invisible to image recognition algorithms. Her goal is to use this knowledge about potential attacks to make AI more robust. She pits AI systems against each other, using one neural network to identify and exploit vulnerabilities in another. This process can expose flaws in the training or structure of the target network. Li then develops strategies to patch these flaws and defend against future attacks.

Adversarial attacks can fool other types of neural networks too, not just image recognition algorithms. Imperceptible tweaks to audio can make a voice assistant misinterpret what it hears, for example. Some of Li's techniques are already being used in commercial applications. IBM uses them to protect its Watson AI, and Amazon to protect Alexa. And a handful of autonomous-vehicle companies apply them to improve the robustness of their machine-learning models. *—Will Douglas Heaven*

DONGJIN SEO

Neuralink

Age 31 | Country of birth: US

He is designing computer chips to seamlessly connect human brains and machines.

When I first met the electrical engineer Dongjin "DJ" Seo six years ago, he told me he had always wanted to be "a scientist with strong intuitions about how to improve the world through engineering." At the time, he was working in a crowded corner of a lab at the University of California, Berkeley, on a concept called neural dust—ultra-small electronic sensors that could be sprinkled in an animal's brain and controlled with acoustic waves.

The goal of that project was new types of brain-machine interfaces that could read the firing of neurons inside the cortex and even send information back in. That kind of technology might open up ways to read and write information from and to the brain.

Then, in 2016, not too long after I spoke with Seo, Elon Musk tapped him to join a new company, Neuralink, which was ready to spend millions on engineering a seamless interface between human brains and computers. "The vision that Elon outlined—well, it was hard to say no," Seo says. "It was everything I had imagined."

Instead of neural dust, the startup is betting on a robot that plunges ultrathin electrodes into animal brains. Seo is head of a team of about a dozen people designing low-power wireless computers that fit into a small burr hole that's cut into the skull. He says his primary contribution is designing the necessary circuit boards and chips. "We need these chips to collect a signal that may look like noise, process it, and do all that without cooking your brain."

After tests on animals, the company hopes to try the brain connection on someone with paralysis or a serious illness. Eventually, "augmentation" of healthy people "is an obvious result," Seo says: "It's being able to enhance our ability to interact with the world."

—The editors

SAM KERR (LI); COURTESY PHOTO (SEO)

LEILANI BATTLE

University of Maryland

Age 31 | Country of birth: US

Her program sifts through data faster so scientists can focus more on science.

When Leilani Battle was working on her PhD, she helped develop ForeCache, a tool designed to help researchers browse large arrays of data—for instance, scanning high-resolution satellite images to look for areas covered with snow. The goal is to reduce latency, so that a user can pan and zoom across the data set without perceptible delay. A common way to do this is to predict which parts of the data a user is likely to need and then "prefetch" them. But how to predict what to prefetch? That depends on understanding the user's behavior.

Battle and her colleagues developed a more efficient prediction system. It attempts to discern first which "analysis phase" a user is in, and then what tiles of data might be wanted next. They dubbed the three phrases "foraging," "sensemaking," and "navigation." They suppose that users in the "foraging" phase are browsing at a coarse level, in order to come up with new ideas. "Sensemaking" is a closer examination meant to test those ideas, and "navigation" is a transition between the two.

This system allowed them, they said, to predict which tiles users wanted about 25% better than existing prefetching systems they benchmarked against, almost halving the latency.

Battle has devoted her career to designing systems and interfaces that help researchers sifting through data do their work better and faster. She hopes to make exploration tools more interactive and visual so they'll be less daunting. Perhaps this will allow scientists to spot data quirks that would otherwise go unnoticed. *—Tanya Basu*

MORGAN BELLER

Novi

Age 27 | Country of birth: US

She was a key player behind the idea of a Facebook cryptocurrency.

In the summer of 2017, Morgan Beller approached her supervisor on Facebook's corporate development team with a proposal: what if she began spending the bulk of her job researching how the social-media giant could enter the digital currency market?

Beller was so new at Facebook that she was still completing her orientation, but she'd cut her teeth at a venture capital firm, where she'd worked on early cryptocurrency investments. She could see that a seismic shift in the global financial community was coming.

When she realized that no one at Facebook was working on blockchain, she volunteered and quickly became the company's digital currency evangelist, shepherding the development of both its open-source blockchain infrastructure, Libra, and its currency application and digital wallet, Novi. Today she serves as head of strategy for the latter, where she works with a team of digital currency developers.

Facebook and its founder, Mark Zuckerberg, endured sharp criticism after announcing the plans for Libra. Beller wasn't surprised. "We're trying to change the system, and there are a lot of people who are incentivized for the global financial system not to change," she says.

Libra hasn't even rolled out yet, but it's already prompted several countries, including China, to accelerate the development of their own national digital currencies. Facebook recently announced plans to scale back Libra and first issue a coin backed by a local currency, but even with these modifications, Libra has already been disruptive. *—Kathryn Miles*

ADRIANA SCHULZ

University of Washington

Age 34 | Country of birth: Brazil

Her tools let anyone design products without having to understand materials science or engineering.

Adriana Schulz's computer-based design tools let average users and engineers alike use graphical drag-and-drop interfaces to create functional, complex objects as diverse as robots and birdhouses without having to understand their underlying mechanics, geometries, or materials.

"What excites me is that we're about to enter the next phase in manufacturing—a new manufacturing revolution," says Schulz.

One of her creations is Interactive Robogami, a tool she built to let anyone design rudimentary robots. A user designs the shape and trajectory of a ground-based robot on the screen. Schulz's system automatically translates the raw design into a schematic that can be built from standard or 3D-printed parts.

Another of the tools she and her collaborators built lets users design drones to meet their chosen requirements for payload, battery life, and cost. The algorithms in her system incorporate materials science and control systems, and they automatically output a fabrication plan and control software.

Schulz is now helping start the University of Washington Center for Digital Fabrication, which she will co-direct. She will work with local technology and manufacturing companies to move her tools out of the lab. *—Russ Juskalian*

COURTESY PHOTOS (BATTLE, BELLER); DAVID CURTIS (SCHULZ)

Humanitarians

They're using technology to cure diseases and make water, housing, and prosthetics available to all.

KATHARINA VOLZ

OccamzRazor

Age 33 | Country of birth: Germany

A loved one's diagnosis led her to employ machine learning in the search for a Parkinson's cure.

In 2016, Katharina Volz received news that someone close to her had Parkinson's. At the time Volz had just finished her PhD at Stanford and was locked into a well-earned career in academic research, working on stem cells. But the news changed all that.

"I just knew I could actually make a difference," she says. "Sometimes you feel helpless. But actually I felt deeply responsible for finding a way to get curative treatments for this disease, because I knew I could do something about it." Volz now leads a company, OccamzRazor, that has successfully married machine learning with biomedical research and is pushing the search for a Parkinson's cure.

Volz noticed a problem when it comes to researching Parkinson's, and it's one that arguably plagues science at large. Experts studying the disease were specializing in particular aspects of it and generally didn't know much about and couldn't engage with other aspects. These academic silos made it hard for new insights to be properly shared and explored, impeding our continued understanding of how Parkinson's progresses.

"Even if you're the smartest researcher in the world, you can't put all of this information together and make the connections you need to truly understand how the disease operates," says Volz. "As humans, our ability to draw these numerous connections is limited."

That's where machine learning comes in. Volz realized AI could do a better job than a human at reading all the different papers and data sets published on a topic and identifying insights that could lead to breakthroughs. Though machine learning isn't her specialty, she brought together a team of AI researchers, along with experts from other fields like computational biology, drug development, and neuroscience. She raised money from various investors, including Jeff Dean (the head of AI at Google) and the Michael J. Fox Foundation. Thus, in 2016, OccamzRazor was born.

The company is tackling the problem in two major steps. First, it has developed programs that read and understand published materials on Parkinson's. Next, it is using AI to integrate genomics, proteomics, and clinical data sets. The goal is to predict new pathways and genes important to Parkinson's that can then be tested in the laboratory.

The result is what OccamzRazor calls the "Parkinsome"—a knowledge map of Parkinson's that reveals how the disease is caused and progresses, points to signs and symptoms that can help make an early diagnosis, and identifies potential therapeutic targets. After OccamzRazor validates its findings, it partners with biotech and pharma companies to develop drugs.

The goal is to take this approach beyond just Parkinson's. Volz and her team have plans to scale up the platform to build comprehensive knowledge maps for other complex diseases related to the aging of the brain. "Diseases inform each other," says Volz. "Studying Parkinson's is one of the best ways to study brain aging in general." *—Neel V. Patel*

"I felt deeply responsible for finding a way to get curative treatments for this disease, because I knew I could do something about it."

Portrait by David Vintiner

"Globally, we are truly tapping out our water resources."

DAVID WARSINGER

Purdue University

Age 32 | Country of birth: US

His system could alleviate the drawbacks of existing desalination plants.

David Warsinger thinks he's found an innovation that could help combat one of the 21st century's great environmental challenges: water shortages around the globe.

His fix is an improved form of reverse osmosis—the most common method of desalination. Today, an estimated 5% of the world's population relies on desalinated water, drawn from the ocean or brackish inland sources, to meet at least some daily needs. This figure will continue to rise as aquifers are further squeezed by pollution, overuse, and shifting rainfall patterns linked to climate change. According to the United Nations, some 3.6 billion people live in areas that experience water scarcity at least one month of the year—and that number is likely to exceed five billion by 2050. "Globally, we are truly tapping out our water resources," Warsinger says.

Yet desalination today has major limitations. Traditional reverse osmosis, in which pressurized water is forced through a salt-removing membrane, uses a lot of energy and is costly. It also leaves behind a large part of the water as brine—an especially big problem for inland plants, where source water is scarcer.

Warsinger's system, which he developed with Emily Tow while they were both at MIT, is known as batch reverse osmosis, and it is designed to make the process more efficient. The technique allows desalination to occur in batches, with salinity and pressure varying over time. Whereas traditional reverse osmosis systems apply constant pressure, the batch system is engineered to apply less pressure to water that's less salty, saving a considerable amount of energy. It also increases the rate of fresh water extraction by minimizing the build-up of salt on the membranes.

Warsinger's lab at Purdue, where he's now a professor of mechanical engineering, has since worked to refine the batch design. His team has developed a trailer-sized prototype it hopes to use for pilot plants in Peru and Kenya. *—Jonathan W. Rosen*

ALEX Le ROUX

Icon

Age 27 | Country of birth: Canada

A massive 3D-printing project in Mexico could point the way to the future of affordable housing.

Alex Le Roux thinks 3D printing can open new possibilities for architectural design and cut the cost of building housing around the world.

As cofounder of Icon, a startup based in Austin, Texas, Le Roux is the mastermind behind the Vulcan, an industrial-scale 3D printer that can construct the wall system of an entire house in just 24 hours of print time. According to the United Nations, some 1.6 billion people lack adequate shelter, and a third of the world's urban population lives in informal settlements or slums. Part of the reason, Le Roux says, is that traditional building methods lead to wasted materials and excess labor costs, driving up housing prices beyond the reach of many poor families.

The Vulcan is designed to change that by introducing automation to the process. The 12-foot-tall robotic device works by extruding inch-thick layers of a special concrete mix fed in from a separate machine, much like a giant tube of toothpaste. Icon programs its home designs ahead of time to make the operator's job as simple as possible. "Once these two machines are set up on a job site, you download an app and you're off to the races," Le Roux says.

In March 2018, Icon built the US's first officially permitted 3D-printed house. It has now built 16 houses in Austin and in Mexico, where it's constructing the world's first 3D-printed community, designed to accommodate 50 low-income families. Icon's ultimate goal, Le Roux says, is to reduce the cost of homebuilding by 50%.

—Jonathan W. Rosen

SAM KERR (WARSINGER); NATALIE CASS, SCORE HEADSHOTS (LE ROUX)

OBAMA FOUNDATION

MOHAMED DHAOUAFI

Cure Bionics

Age 28 | Country of birth: Tunisia

His company's artificial limbs are not only high-functioning but cheap enough for people in low-income countries.

Four years ago, during a university challenge, Mohamed Dhaouafi found out that one of his teammates' cousins had been born without upper limbs and couldn't afford prosthetics. An engineering student at the time, he'd been searching for a project that would have a social impact—and as he started to research limb loss around the world, he found a massive unmet need. The World Health Organization estimates that there are 30 million people with amputated limbs in poor countries, and only 5% of them have access to prosthetics. Fitting children with high-quality devices is particularly expensive because they're constantly growing. But without prosthetics, stigma and mobility problems keep large numbers of them from attending school, setting many up for lifelong unemployment. "We're not just talking about limb differences," Dhaouafi says. "We're talking about poverty, access to education, access to health care."

Today, Dhaouafi has a product he believes will help make advanced artificial limbs more accessible. His Tunisia-based startup, Cure Bionics, is in the process of finalizing an adjustable multi-grip bionic arm that will sell for about $2,000—a fraction of the cost of similar devices. His team plans to keep costs down by 3D-printing key components and engineering much of the circuitry in-house.

But this doesn't mean they're skimping on quality: like bionic arms developed elsewhere, Cure's prototype is equipped with sensors that allow users to operate the hand by flexing or relaxing the muscles in their residual limb. The company is also developing algorithms to help the arm recognize the body's electrical signals more accurately, which will minimize reliance on an orthopedist for adjustments. At a later stage, Cure plans to introduce a virtual-reality headset that will gamify the physical therapy process for children. "Instead of a doctor asking you to imagine picking up an apple, you'll be using your hand to jump between buildings like Spider-Man," Dhaouafi says.

Dhaouafi and his colleagues are closing in on their initial product launch: they've already tested their arm with five Tunisian youths and will soon initiate trials at three government hospitals. Ultimately Dhaouafi hopes to offer a range of high-quality, affordable prosthetics for young people across Africa, the Middle East, and beyond.

—Jonathan W. Rosen

Entrepreneurs

Their technological innovations bust up the status quo and lead to new ways of doing business.

JIWEI LI

Shannon.ai & Zhejiang University

Age 31 | Country of birth: China

In the last few months, Google and Facebook have both released new chatbots. Jiwei Li's techniques are at the heart of both.

Jiwei Li applies deep reinforcement learning—a relatively new technique in which neural networks learn by trial and error—to natural-language processing (NLP), the field of computer science in which programs are made to manipulate human languages.

By using deep reinforcement learning to identify syntactic structures within large pieces of text, Li made machines better at extracting semantic information from them. Syntax refers to the grammatical relationship between words, while semantics refers to their meaning.

In written language, words with a close semantic relationship are not always close together on the page. A verb and its object can be separated by a string of adjectives or a subordinate clause, for example. Previous attempts at getting machines to parse natural language often overplayed the importance of proximity, leading to obvious mistakes. Li's machine-learning algorithms find the grammatical structure of a sentence to get a much more reliable sense of the meaning. They have become a cornerstone of many NLP systems.

Li grew up in China and studied biology at Peking University before moving to the US, where he began a PhD in biophysics at Cornell. But he soon switched fields, turning to NLP first at Carnegie Mellon and then at Stanford, where he became the first student ever to obtain a computer science PhD in less than three years.

Li's machine-learning algorithms find the grammatical structure of a sentence to get a much more reliable sense of its meaning.

Li has also explored other ways to teach artificial intelligence how to spot patterns in linguistic data. In 2014 he and his colleagues correlated Twitter posts with US meteorological data to see how weather affected users' mood. First he labeled 600 tweets by hand as happy, angry, sad, and so on. He used this labeled data to train a neural network to assess the mood of a tweet and cross-referenced that mood against geolocation data for about 2% of all the tweets published in 2010 and 2011.

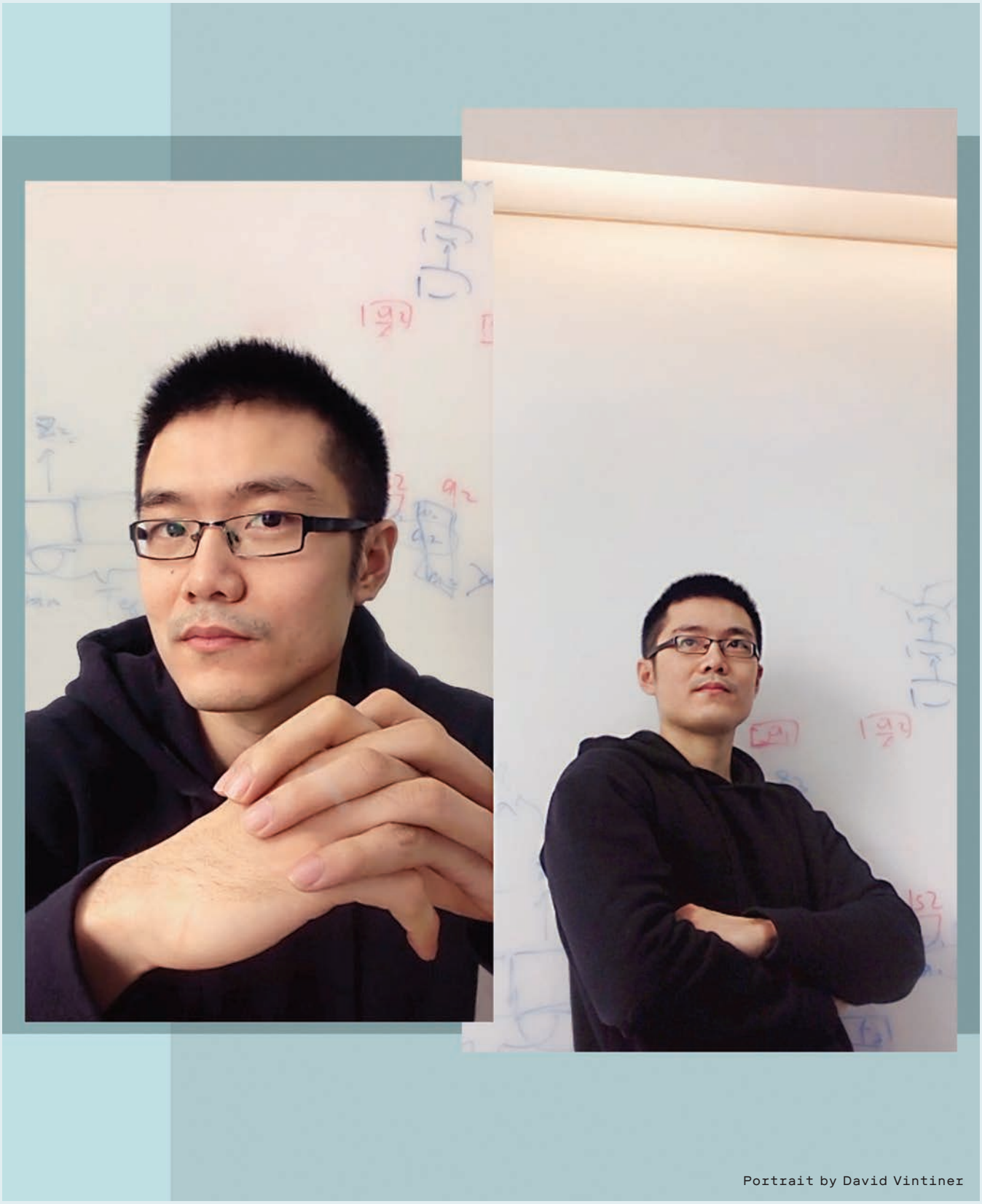
His results were not surprising. Moods worsened when it rained; people expressed anger when it was hot. But for Li it was a lesson in how hidden information could be extracted from large amounts of text.

After finishing his studies in 2017, he moved back to Beijing and founded an NLP startup called Shannon.ai, which now has dozens of employees and $20 million in funding from venture capitalists. Li's company is building on the pattern-matching work demonstrated in the Twitter weather study to develop machine-learning algorithms that extract economic forecasts from texts including business reports and social-media posts.

Li has also applied deep reinforcement learning to the challenge of generating natural language. For him it is the obvious next step. Once you have learned to read, you can learn to write, he says.

Even the best chatbots still make obviously stupid mistakes, spewing out non sequiturs or displaying a lack of basic common knowledge about the world. The longer a conversation, the harder it is for an AI to keep track of what's been said. Li's techniques give AI a good grasp of linguistic structure. In a conversation, keeping track of subjects and objects is easier if the syntax of utterances is explicit. For example, given the question "Shall we get started?" a bot might answer "Of course!"—but that response could follow any question. Li's technique can instead give responses more like "Yes. We've got a lot of work to do here," referencing the content of the original query.

—Will Douglas Heaven



Portrait by David Vintiner

ATIMA LUI

Nudemeter

Age 30 | Country of birth: US

She's using technology to correct the cosmetics industry's bias toward light skin.

Atima Lui grew up in Kansas as the descendant of American slaves and the daughter of a Sudanese refugee, and she remembers trying on makeup with a friend for the first time as a child. Her friend had lighter skin. "As soon as she put it on my face," Lui says, "there was nothing we could do to make it look good." She'd discovered the cosmetic industry's long-running assumption that "nude" means white or light.

Lui is now deploying an AI-based app called Nudemeter to try to fix that problem. Through photos and a short quiz, it determines a user's skin color, accounts for how the skin is illuminated, predicts changes in skin tone through the year, and helps consumers of any complexion choose makeup colors that work with their skin.

Lui has managed to build a business around Nudemeter, but her goals go beyond the technology itself. Growing up, she says, she was shaped and hurt by society's assumptions about "who gets to be an entrepreneur, or who gets to be a technologist." That's something else she's trying to fix.

—Abby Ohlheiser

TONY PAN

Modern Electron

Age 34 | Country of birth: Taiwan

His company revamps an old device to allow you to generate electricity in your own home.

Modern Electron has applied a modern twist to an old technology. By using computer simulations and novel materials, the Seattle startup has made a new type of thermionic converter, a heat engine first developed in the 1950s, that's more efficient than the old model at turning heat into electricity.

Cofounder and CEO Tony Pan believes his company can use the technology to convert home boilers and furnaces, which generally use natural gas or oil to heat water and homes, into mini residential power plants that produce electricity on site. He says this would be a far cheaper and more efficient way of generating residential power than a central power plant, particularly when coupled with home solar panels and batteries.

A thermionic converter consists of a pair of metal plates, separated by a vacuum. Heat—from, say, the flame of a furnace—agitates and excites the electrons on one plate to the point that they leap across the gap to the cool one, generating an electric current. In one application, Modern Electron has rolled the metal plates into a tube that resembles a light-saber handle and fits over a gas burner.

Homeowners could rely on rooftop solar panels much of the time, turning to Modern Electron's system during the night, on cloudy days, or in the winter months. If adopted widely, the product could reduce our reliance on electricity from centralized coal or natural-gas plants, which waste vast amounts of energy between burning fuels and delivering power over hundreds of miles of transmission lines. That, in turn, could reduce greenhouse-gas emissions from the power sector, Pan says.

The company's technology also works with other fuels. So if residential heating systems eventually shift toward low- or zero-emissions sources like hydrogen, a change some companies and regions are exploring, the thermionic converter could make a bigger dent in pollution.

Pan believes his device could have an even bigger impact in developing countries. Enabling communities to set up their own mini power plants would allow them to skip the massive investments of money and time required to build centralized generation and distribution systems. That could bring electrification faster to rural areas. *—James Temple*

If adopted widely, Pan's product could reduce our reliance on electricity from centralized coal or natural-gas plants.

ASHLEY SOONG (LUI); COURTESY PHOTO (PAN)

ENTER

CAN CANADA SAVE US

THE

FROM SILICON VALLEY'S WORST IMPULSES?

NARWHAL

By **BRIAN BARTH**

Illustrations by David Biskup

It is a frigid February day when I visit Communitech, a bustling tech hub that occupies a renovated 19th-century tannery in the city of Kitchener, Ontario. Inside the brick-and-beam space, Harleen Kaur opens her phone and pulls up her latest creation—an attempt to tackle the problem of misinformation. It's an app called Ground News, a combination news aggregator and social-media platform that combats falsehoods with the help of AI and on-the-ground verification carried out by its users.

Tapping on the headline "Buttigieg slams Trump: My marriage never involved sending 'hush money to a porn star,'" I learn that over the previous two days the story had been covered by 14 outlets, with a collective "lean left" bias, according to the app. Had I been at the town hall meeting where Pete Buttigieg, then a presidential candidate, made this remark, I could have created my own story about it using the app's Citizen Journalism feature (the part intended as a check on fake news), which other users would then have been able to contest or confirm.

Kaur, an aerospace engineer turned serial tech entrepreneur, was living in the US when the idea for Ground News hit her like Newton's apple. Though motivated by a growing problem in America—this was 2016—she decided to return home to Canada to build the new company. Venture capital and other investment flows fast and free south of the border, she says, but it was more important to embark on the next phase of her career where "Canadian values" reign.

"Canada is more measured, more considerate. Our value system is not just making money and being successful," says Kaur, who moved as a girl from India to Brampton, an immigrant enclave in the suburbs of Toronto. "Canadians are nice to each other. I think being nice matters. Nice has value."

Kaur is not the only one drawn away from the US by Canadian benevolence. In recent years the country has become a magnet for technology talent, reeling Canadians back home and diverting the stream of overseas applicants away from Silicon Valley to Montreal, Vancouver, and the Toronto-Kitchener-Waterloo corridor. These are areas long known for incubating and exporting innovation—from Research in Motion, the company founded above a Waterloo bagel shop that ushered in the smartphone age and later took the name of its flagship product, the BlackBerry, to the neural networks of Geoffrey Hinton, the University of Toronto professor whose AI company was acquired by Google in 2013. Canadian media have christened the region "Silicon Valley North."

Some are drawn by the image of Canada as a liberal utopia, where diversity, inclusion, and humility triumph over greed and bigotry. While this branding may have been carried to excess by Prime Minister Justin Trudeau, the allure is real.

As President Donald Trump tightens the US border—in April he placed a 60-day ban on most green cards, ostensibly to protect American jobs as covid-19 tanked the economy—Trudeau opens Canada's arms ever wider. In 2018, he pledged to admit an additional 40,000 immigrants over the next three years, raising the quota to 350,000 by 2021, and covid hasn't changed that policy: "Immigration will absolutely be key to our success and our economic recovery," Canada's immigration minister, Marco Mendicino, said in May.

While US immigration policy has been tough on many industries, the issue is especially acute in the tech sector, which relies on highly skilled foreign workers on both sides of the border. In the US, approvals for H-1B visas, the kind typically given to skilled tech workers, dropped from 94% of applications in 2015 to 76% in 2019—one study found that they dropped below 70% at 12 US tech firms—while the wait time went from five months to nearly 10. The number of H-1B applicants, after rising for years, declined after Trump was elected, from 236,000 in 2016 to 199,000 in 2017. The equivalent Canadian visa program, meanwhile, approves 95% of applications in two weeks or less.

As a result, Toronto added more new tech jobs between 2013 and 2018 than any other North American market surveyed. It is now ranked behind only San Francisco and Seattle for tech talent by the real estate giant CBRE. Invest in Canada, a federal agency charged with attracting global firms to set up shop, advertises Toronto as having the "highest concentration of AI startups in the world." The government has gone so far as to pay for billboards in Silicon Valley that read "H-1B Problems? Pivot to Canada," with a link to the nation's immigration website.

Kaur thinks this "niceness" also boosts her bottom line. "Having 'Brand Canada' associated with us is a benefit," she says. "We have a halo effect around us of being trusted and neutral."

58,000

NET TECH JOBS ADDED IN TORONTO FROM 2013 TO 2018

Yung Wu is the CEO of the MaRS Discovery District, a block-size campus in downtown Toronto where firms can rent space, mingle in a massive central atrium, and tap into services designed to help startups and "scale-ups" grow. He has seen the revenue of its 1,500 companies almost triple in the past two years, but he insists that Canadian tech is on a qualitatively different path from its US counterpart. "I don't think the bro culture would have really developed in the same way over here, for instance," he says. Canadian values may play a role in that, but demographic differences are also part of the equation—Toronto is considered one of the most diverse cities on earth, and more than 50% of its residents were born in another country. Likewise, at MaRS, which bills itself as the "largest urban innovation hub" in North America, more than half of all company founders were born abroad.

Canada has its own technomythology. Instead of tech bros, it has a workforce portrayed as diverse, reserved, and polite. Where Silicon Valley prizes trend-setting consumer products, Toronto's startups tend to be more focused on services and products for business and government clients that are less likely to capture the public imagination. Where California produces "unicorns," private tech companies valued at a billion dollars or more, Canadian techies speak of building "narwhals"—named for the small, reclusive whales, with long tusks sprouting from their heads, that roam Arctic waters.

The US produces far more unicorns per capita than Canada produces narwhals. But, Wu says, the comparison goes beyond their financial valuation. "In the Valley you find this chase for imaginary animals. The narwhal is actually a real thing," he says. "It's not propped up by private valuations that are intended to raise the round on the last private valuation, with no resemblance necessarily to a real company that serves real customers with real revenue. A narwhal is rare, but it's not an imaginary thing."

The question is whether Canada's quiet narwhals can make a big enough splash to change the trajectory of the global tech industry.

"A COLONIZING EXPERIMENT"

Canadians are notoriously polite and generally go out of their way to not criticize their southern neighbors. Despite this, there is a burning nationalism deep down that can take the form of disgust toward many aspects of American culture—such as an excess of individualism and self-important verbiage expressed at a high volume. And sometimes that disgust erupts like projectile vomit. This was the case when Sidewalk Labs came to town.

In March 2017, Waterfront Toronto, a government agency charged with redeveloping a 2,000-acre (800-hectare) strip of former industrial land along the shores of Lake Ontario, asked for proposals to build a smart-city district on a 12-acre parcel known as Quayside. Trudeau presided over a lavish ceremony that October to announce the winner: Sidewalk Labs, a New York–based urban innovation company owned

"THE OPPOSITE OF FACEBOOK": HOW CANADA THINKS ABOUT TECHNOLOGY

HARLEEN KAUR
GROUND NEWS

"Our value system is **not just making money** and being successful. Canadians are nice to each other. I think being nice has value."

YUNG WU
MaRs

"I don't think the **bro culture** would have really developed in the same way over here."

JOHN RUFFOLO
ArcTern Ventures

"Monopoly power over data … This is something that we need to **defend** ourselves against."

KURTIS MCBRIDE
Miovision

"That's the thing that Canada could bring to the world—**replacing the data monopolies** with a data collective."

IAIN KLUGMAN
Communitech

"There is a different social contract in this country. **We're collaborators.** That's our secret weapon."

by Alphabet, Google's parent. Sidewalk had been chosen over the Canadian companies that had applied, but the premier of Ontario, the mayor of Toronto, and Alphabet's then chairman, Eric Schmidt, spoke glowingly of the plan to build a neighborhood "from the internet up."

Soon there was talk of expanding the development to the Port Lands, 800 acres of derelict industrial property adjacent to Quayside. It was arguably the most ambitious smart-city initiative in the world, including plans to use sensors and monitoring to create a vast amount of data that could be used to serve the needs of households and workplaces, aid with transportation, and even charge citizens by the item for their trash. The idea was to develop the digital architecture for an urban operating system that could then be exported globally, extending Alphabet's market dominance from cyberspace to public space. It would be a crowning achievement not just for Sidewalk, but for Alphabet and the Canadian government.

Some Canadian-bred technologists, however, were less than impressed. Jim Balsillie, the billionaire who had been co-CEO of Research in Motion until 2012, launched an ad hoc campaign to quash the project.

Quayside "is not a smart city," he wrote in an op-ed. "It is a colonizing experiment in surveillance capitalism." In Balsillie's view, the network of sensors proposed for Quayside—which Sidewalk Labs said were necessary to run robotic trash collection, high-efficiency utility systems, and other digital improvements—amounted to an Orwellian power play, feeding Canadians' private information (location, purchasing habits, and so on) into Google's data-hungry maw.

Data sovereignty—the idea that a nation's data should be held on servers within its borders, governed by its laws and thus ultimately by its values—has gained traction around the world. The EU's General Data Protection Regulation (GDPR), which went into effect in 2018, is based largely on this principle, prying control of the information collected on its citizens out of the hands of the tech giants and the American laws that govern them. Balsillie urged Canadian lawmakers to follow suit. "Facebook and Google are companies built exclusively on the principle of mass surveillance," he told the Canadian parliament at a 2018 hearing on the Cambridge Analytica scandal, where he sparred with a Google executive who had also been called to testify. "History offers sobering lessons about societies that practice mass surveillance."

A deluge of negative headlines dogged Sidewalk Labs throughout its first year. City councilors and members of parliament began speaking out against the project. As the scope of the company's plans for data collection became clear, the former privacy commissioner of Ontario, who had been retained by Sidewalk Labs as a consultant, resigned. "I wanted this to become a smart city of privacy—not a smart city of surveillance," she said.

In October 2019, Waterfront Toronto unveiled a revised agreement with Sidewalk Labs that put the company on a much shorter leash. The scope was limited to the original 12 acres, not the coveted

COURTESY PHOTOS

800, and data collection would remain under the control of the government, not the company. Then, in May of this year, Sidewalk Labs announced it was pulling out. The company cited the pandemic economy as the reason for the decision, while detractors framed it as a convenient excuse for Sidewalk to slither away without losing face. "This is a major victory for the responsible citizens who fought to protect Canada's democracy, civil and digital rights," Balsillie told the Associated Press.

Balsillie declined to be interviewed for this article, but John Ruffolo, a prominent venture capitalist in Toronto who is a longtime ally of his, told me it had been a struggle "to smack into people's heads in the government" the dangers of Facebook's and Google's "monopoly power over data."

But he believes Canada's tech industry activists now have lawmakers' attention: "If you think you're going to get control over public infrastructure where I, as a private citizen, might be subject to facial recognition walking on a public sidewalk or some other intrusion of my privacy—this is something that we need to defend ourselves against, because we will slip into tyranny, just like where I think China is today."

"FOUNDED BY DEVIANTS"

Communitech, the Kitchener tech hub, is ground zero of the country's tech scene. Founded in 1997, it has grown into something of a national legend, a place where tiny startups rub elbows with Google executives—the Silicon Valley giant has hosted a startup incubator in the building since 2013.

In the 1980s, the twin cities of Kitchener and Waterloo, not far from Detroit, were considered part of Canada's Rust Belt, a region littered with shuttered factories lost to the vagaries of globalization. One bright spot was the University of Waterloo, where the computer engineering program was growing in renown. That's where a Greek-Turkish student named Mike Lazaridis was studying before he dropped out in 1984 to start Research in Motion.

Improbably, a handful of other successful technology businesses emerged in the area, including OpenText—which makes information management software for large companies—and, more recently, the messaging app Kik. The founders of these firms created Communitech out of necessity: far from other concentrations of capital and innovation (Toronto was not the financial center that it is today), they relied on each other for support. It was a radically different genesis from that of Silicon Valley, with its cutthroat culture and its roots in the military-industrial complex rather than working-class immigrant communities. Essentially a membership organization, Communitech has seen its original list of 23 companies grow to more than 1,400 and has spawned a national network of 29 hubs operating on the same model. With hundreds of new technology firms appearing each year, Waterloo boasts the highest startup density on the planet after Silicon Valley.

Iain Klugman, the CEO of Communitech, says it's time for the area to discard the "Silicon Valley North" label and assert a uniquely Canadian identity. "The Valley was founded by deviants—we call them libertarians now—who didn't have respect for regulations," he says. "That's why they dream up ideas like Uber and Airbnb. There is a different social contract in this country. We're collaborators. That's our secret weapon."

Klugman, a compact man with decidedly non-Canadian intensity (ironically, this champion of north-of-the-border values is originally from Colorado), delivers this sermon as he leads me past a banner advertising a $1 million prize for the company with the most promising AI solution to fake news. We go into a conference room, where he lays out his vision for how Canada's brand of tech will quietly take over the world.

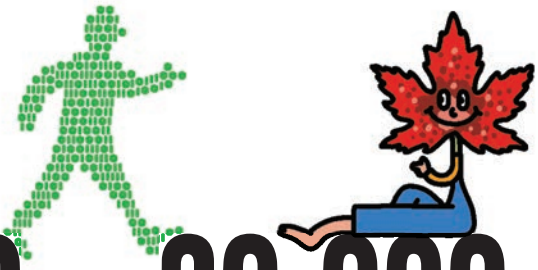
After years of sky-high public approval for the industry, the so-called "techlash" provides an opening, Klugman believes, for "collaborative capitalism" to take root. Even if it is opportunistic boosterism, the notion that Canada offers an alternative to "move fast and break things" ("Maybe it's time to slow down and fix things," he says) feels timely as the world ponders alternative futures.

But even though Canada wants to capitalize on its non-Valley identity, what exactly is the alternative on offer? "Being the opposite of Facebook, basically," Klugman says. "It's not just can you build it, but should you build it? And being responsible for the implications."

That's easy to say—but of course Google, Facebook, and the rest all started with noble, collaborative visions of their own. What starry-eyed Silicon Valley entrepreneur didn't speak the same way in 1995, or 2000, or 2005? Perhaps Canada's lack of success has made it easier to stay aloof: while America's techno-optimists have had ample opportunity to sell their souls to the devil as their share prices soared to dizzying heights, few of their Canadian counterparts have had so far to fall. And angelic reputation aside, Canadians are not immune to ethical lapses: in fact, some of the most-hyped narwhals have had their share of controversy.

Waterloo, "Canada's Silicon Valley."

WEI FANG /GETTY IMAGES



37,000

DECLINE IN ANNUAL H-1B APPLICATIONS IN THE US IN THE FIRST YEAR OF THE TRUMP ADMINISTRATION

30,000

APPLICANTS IN 18 MONTHS TO MOBSQUAD, WHICH PROMISES CANADIAN VISAS TO THOSE OFFERED A JOB

In the 2000s, Research in Motion was embroiled in a stock options scandal. Kik's messaging app boasted 300 million users when the company abruptly shut it down last year amid a financial scandal and complaints that it enabled pedophiles to stalk its predominantly teenage users. There is little to suggest that a small Canadian tech company wouldn't turn into a monopolistic beast if it grew big enough.

"THEY HAVE TO GO SOMEWHERE"

Still, that optimistic and antagonistic position is proving a magnet for talent. Canadians have complained of a brain drain for decades—the best software engineers, actors, and comedians always seem to go south—but every tech executive I spoke to proudly reported that the flow, at least in their industry, has reversed. Between 2013 and 2018, Toronto alone saw a net gain of nearly 58,000 tech workers, more than any other North American city surveyed. While San Francisco and Seattle continued to add technology jobs during that time frame, many other American hubs were losing them, including New York (9,000 net jobs lost), Raleigh-Durham (10,000), and Boston (34,000).

Sometimes this flow is very clear and deliberate. For example, H-1B visa holders who have been furloughed or laid off—as many American tech workers have been in recent months—have 60 days to leave the US.

"Those people have to go somewhere," says Irfhan Rawji, the CEO of MobSquad, a Calgary company he founded in 2018 to siphon such workers to Canada.

MobSquad hires H-1B holders who were unable to renew their visas, sets them up with a Canadian equivalent, gives each one a desk in its Calgary coworking space, and contracts them back to their original US employers as virtual workers. The MobSquad website, as a solution to America's "software engineering talent crisis," advertises Canadian visas within four weeks and citizenship within four years. Rawji says he had more than 30,000 applicants in the first 18 months, and now "we are busier than we've ever been."

Meanwhile, the Canadian government has made jabs at the Valley's business model, including a new law that requires internet platforms to track and publish the identity of anyone buying politically oriented advertising. (Google, claiming the regulation was too onerous, opted not to run election ads as a result.)

In 2019, the Trudeau government unveiled a 10 Commandments–style "digital charter," which proclaims Canadians' right to control their data. The government has not, however, enacted legislation to give teeth to those proclamations, *à la* the EU's GDPR. But as a country of 36 million with a GDP far smaller than California's, Canada could hardly be expected to lead on regulatory reform. Perhaps if it has a role to play in reining in the industry's excesses, it may be through exerting soft power—leading by example.

Ana Serrano, a member of the anti–Sidewalk Labs coalition Block Sidewalk, thinks Canada's alternative vision—not what it is against, but viable business models that show what it is for—is still in its fetal stage.

"I think there's a real opportunity for Canada to lead this next evolution of technology," she says. "There's so many unanswered questions to define a decidedly Canadian way, but whatever that is, it needs to come from a sense of generosity, of understanding the challenges that people are having today, and their need to lead meaningful lives."

One person working on what a "decidedly Canadian way" might look like, at least for smart cities, is Kurtis McBride, CEO of Miovision, which specializes in high-tech traffic management.

McBride had been part of a group advising Waterfront Toronto on the Quayside project; he's also the board chair of the Open City Network, which, pre-pandemic, was developing standards and digital architecture for smart cities, including guidelines for data governance. (It has now pivoted to building a platform on which the public and private sectors can share data.)

Keeping everything open-source, he told me, made it monopoly-resistant, the opposite of the Sidewalk Labs approach of giving control of digital architecture to the world's biggest internet company.

"I think there's an opportunity to essentially write the rules of an economy that would govern how data generated from public places and physical spaces is used," McBride said.

John Ruffolo, the venture capitalist and staunch Sidewalk critic, put it to me more simply: "Canada could become the Switzerland of privacy."

Brian Barth is a freelance journalist based in Toronto.

The Great Depression offers lessons for how to give ordinary people a say in the economic recovery from covid-19.

By **Nathan Schneider** / Illustration by **Sophy Hollington**

A CRISIS IS NO EXCUSE NOT TO REGULATE TECH

The "techlash," allegedly, is over.

An April op-ed in the San Jose Mercury News, Silicon Valley's local paper, put it most directly: "Covid-19 response will end all the Big Tech bashing." An article published by the Brookings Institution later that month echoed the new received wisdom: "Prior concerns about the industry's market power, privacy practices, and content moderation policies—all of which posed a major challenge just months ago—no longer enjoy the same political salience."

The argument is that covid-19 has taught us to stop worrying and love Silicon Valley—to simply embrace the connections it brings to our quarantine and the surveillance it can apply to contact tracing.

But as people find themselves relying on the tech economy in fuller, more intimate ways, they are finding new reasons to be concerned.

An Amazon vice president stepped down in May in support of workers who were fired for organizing for better workplace safety measures against the coronavirus. Low-wage workers from other companies, including Instacart, Target, and Walmart, have gone on strike for similar reasons. Airbnb hosts are disgruntled that the platform they work for and lobby for is giving customers who cancel bookings full refunds, leaving hosts with no income and all the costs.

In moments of crisis, when new technology seems to offer quick and easy answers, it might appear difficult to devise an imaginative response to the large tech firms' growing power. But even though the litany of things that tech platforms get away with is quite remarkable, tools for fixing some of tech's deepest problems are closer at hand than one might think.

Nathan Schneider is a professor of media studies at the University of Colorado, Boulder, where he directs the Media Enterprise Design Lab.

Companies on the internet can collect data about people's behavior in ways old phone companies and mail carriers never could: a telecom can't listen to your phone conversations and send you relevant robocalls. Ride-sharing apps got their start in part by bypassing regulations their taxicab competitors had to follow. Gig-economy platforms routinely claim the right to ignore hard-won labor protections on the grounds that they offer part-time freelance work, even though in many cases this work involves the kind of control over workers that is tantamount to standard employment.

There has long been a presumption in some quarters that the old rules don't apply to new tech. Earlier this year, before the virus set in, Michael O'Rielly, a commissioner at the US Federal Communications Commission, spoke at the university where I teach. He expressed his hope that with the days of "circuit-switched copper networks" behind us, the FCC's role would "diminish exponentially," like "a puff of smoke on a windy day." But we find ourselves in a moment when the companies the FCC regulates mediate more of our lives than ever before.

Indeed, many of the US's major antitrust laws were created for crises not so unlike the one we face today—times of super-powerful magnates and widespread economic upheaval.

These laws, crafted for the railroads and Standard Oil, empower regulators to, among other things, break up any company abusing its market dominance. Regulators have not recently exercised these powers against Big Tech because for decades they have narrowly

COURTESY OF THE AUTHOR

fixated on consumer prices as the measure of whether a market is being monopolized—a measure that doesn't work for services, like Facebook and Google, that are free. This would change if regulators allowed themselves to see how far-reaching the old antitrust mandate against market manipulation really is. With many smaller businesses now on the brink of collapse, the danger of consolidation has never been greater. A moratorium on mergers is probably a necessary stopgap.

There's a similar story of amnesia in labor law. The gig-economy platforms have all but admitted that their business depends on systematically violating labor protections. California recently woke up to that fact, passing a law reclassifying many gig workers as employees. Especially now, when people with precarious incomes are risking their health by providing essential services from grocery delivery to elder care, they deserve every protection society can reasonably offer.

Regulations alone, however, are not enough. Policy should enable more than it prevents. In the 1920s and 1930s, US legislators put this principle into practice. Following the 1929 stock market crash, it was clear that banks were not accountable to their clients, and there were huge swaths of the country that banks didn't serve. In addition to new regulations that constrained the banks, the 1934 Federal Credit Union Act turned a few local experiments in community finance into a government-insured system. Member-owned, member-governed credit unions proliferated. They held banks to higher standards and brought financial services to places where there had been none.

In similar fashion, two years later, the Rural Electrification Act helped bring electricity to farm country, where investor-owned utilities hadn't bothered to string lines. Low-interest loans through the Department of Agriculture enabled communities to organize cooperatives—nearly 900 of which still operate today. The loan program now earns more than it costs. Like the housing policies of the time that gave us the 30-year mortgage, it was a public policy that enabled widespread private ownership.

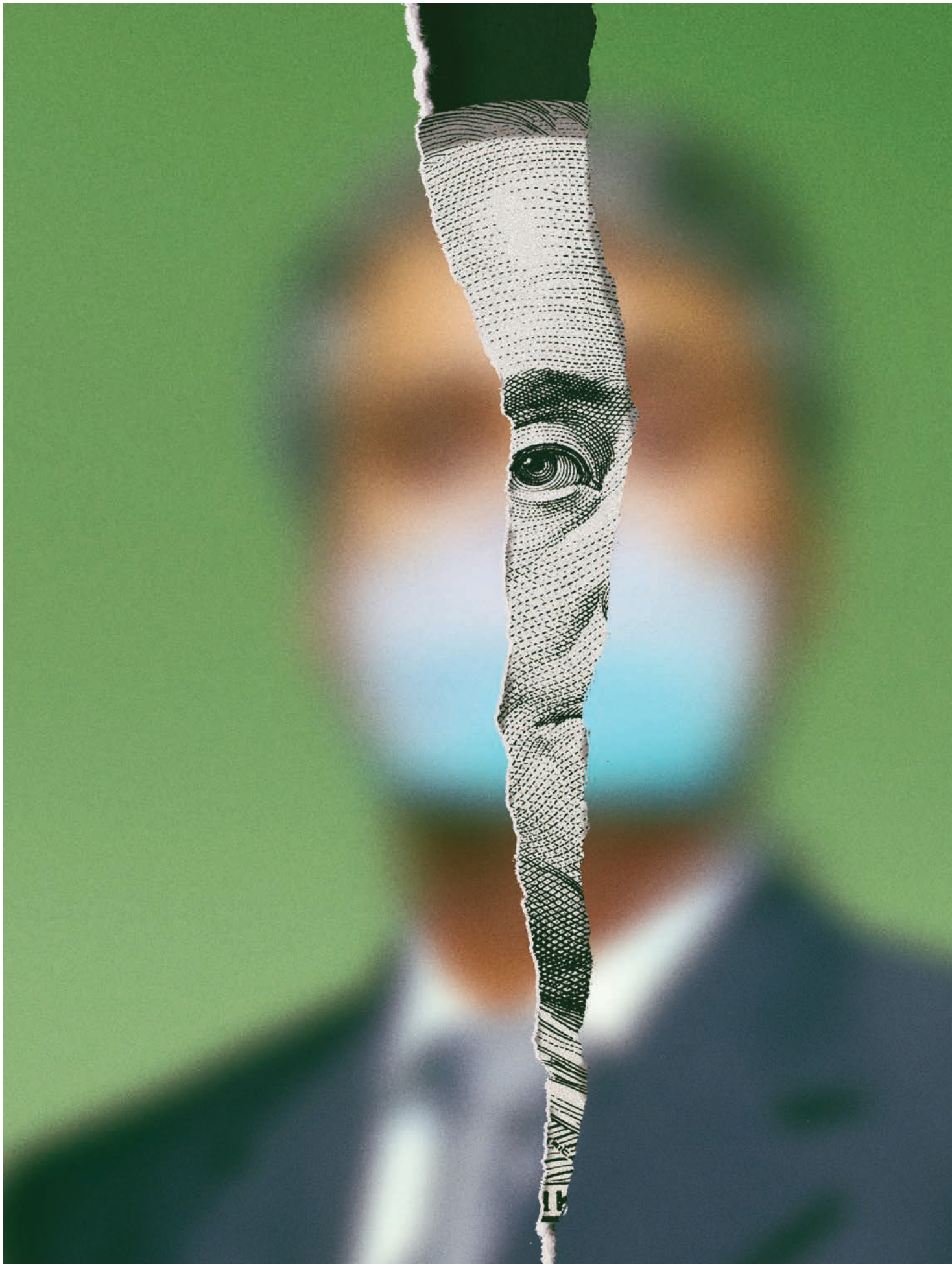
These were some of the most powerful economic development programs in US history. They introduced dynamism and decentralization to markets in danger of being held in thrall to monopoly and exploitation. If we want a more inclusive tech economy, the New Deal legacy would be a good place to start.

Internet users need the capacity to form cooperative alternatives to the dominant platforms and infrastructure. For instance, much the same model as that of the cooperative electric companies could be used to bring customer-owned broadband to underserved communities. Some old rural electric co-ops are offering fiber-to-the-home already.

Furthermore, gig workers and customers who rely on them currently have to use investor-owned platforms. But one proposed bill in California, the Cooperative Economy Act, would enable platform workers to organize co-ops that could collectively negotiate with platforms—and perhaps even build platforms of their own. This would enable these workers, many of whom are now essential as drivers and delivery people, to obtain better wages and working conditions.

Quarantine and remote work also leave many people more dependent than ever on communication platforms, which typically collect personal data for uncertain purposes. This shouldn't be a necessary trade-off. Using free, open-source tools like NextCloud for file-sharing and Jitsi for videoconferencing, groups can manage their own privacy-protecting systems and decide for themselves how their data is used. Public investment in projects like this could ensure that, as with credit unions, people have the means to organize alternatives when the big platforms aren't meeting their needs or respecting their values.

The internet may have near-magical powers that can help us get through the coronavirus crisis, but making technology firms accountable can begin with lessons learned from the last depression. Good tech policy requires recognizing that tech is just another way of wielding power.



LOSING THE WINNERS' GAME

Venture capital has become extremely successful at creating a certain kind of innovation—but the pandemic has exposed its broader failures.

By
Elizabeth MacBride

Illustrations by
Nicolás Ortega

I FELT BAD asking Zack Gray to repeat his story. He was used to it, he said. It's the founding tale of his startup, Ophelia; he'd already told part of it in his commencement speech at Wharton, and to potential investors.

"There was a girl in my life," he started. "I call her my girlfriend. We met when I was 14." They dated, on and off, and stayed friends.

She was one of a generation who slid into opioid addiction through painkillers. A user for five years, she had the means to seek treatment after her addiction grew, but she didn't want rehab or therapy.

Then, last spring, the call came: she had overdosed. By the time Gray got to the hospital, she was gone.

"I just started thinking, 'What could I have done to prevent this?'" he said.

To answer that question, he researched. Since he was finishing up his MBA, the approach that seemed obvious was to build some kind of business or service. What if his friend had been able to get medicine to treat the chemical condition of addiction, without the embarrassment and hassle of group therapy? Would insurance companies buy in to his concept? Could he build a big company to help a lot of people like her? He'd need investors to believe in the idea.

As I listened to Gray explain what he was doing, headlines were washing over America. "A Torrent of Job Losses Threatens to Overwhelm the US Economy." "Doctors Say Shortage of Protective Gear Is Dire." "Coronavirus Hitting Homeless Population."

It didn't seem like a great time to be raising money.

I had originally planned to meet Gray in person. I was scheduled to fly out to California in March to attend the startup accelerator Y Combinator's famous Demo Day. The event would host 1,000 investors and introduce them to nearly 200 vetted and prepped startups from around the globe. Ophelia was one of those startups.

I was going to Demo Day because venture capital had been America's financial engine of innovation for years, and I wanted to see if that was still true. Many stats suggested it was: the number of venture capital firms in the US had risen from 946 in 2007 to 1,328 in 2019, and the amount of money they were managing had swollen from $170.6 billion in 2005 to $444 billion in 2019.

Not all the numbers were so positive, however. This largely white, largely male corner of finance has backed software companies that grow fast and generate large amounts of money for a shrinking number of Americans—companies like Google, Facebook, Uber, and Airbnb. But they don't create many jobs for ordinary people, especially compared with the companies or industries they disrupt. And things have been slowing down. Recently, venture capitalists have found fewer and fewer ideas that fit their preferred pattern. By the end of 2019, the industry had $121 billion in "dry powder," money in search of an entrepreneur or idea to invest in. I wanted to know what was going on.

As covid-19 took hold of the world, my plans to meet Gray and his peers changed. And suddenly, the questions became more urgent. Was venture capital producing the kinds of inventions society needs? Sure, when we have to (or want to) stay home, Zoom helps us work remotely, DoorDash keeps us fed, and Netflix gives us something to watch. But where was the cure, or the better protective gear, and why hadn't venture capital—the financial engine of innovation—funded those ideas?

In the 1950s and '60s, technology took us to space. In the 1980s and '90s, technology helped spread democracy. Now our national mission was ... to be able to never leave the house?

Venture capital has been the engine of US innovation for years. But investors are finding fewer ideas that fit their preferred pattern.

What capital wants

When I want to understand finance, I call my friend Charley Ellis. He was on the boards of the investment management company Vanguard and the Yale Endowment, and he wrote a bible for investors called *Winning the Loser's Game*.

"The fact that it's called venture capital is a terrible distraction," he told me. "It's really human resources."

What he means is that successful venture capitalists aren't necessarily those who find and fund the most innovative ideas, but the ones who know how to spot founders capable of building a company that will eventually be acquired or go public. The $1 million that might be spent to buy a 10% share of an early-stage business turns into much more if that company ends up being worth $10 billion.

Venture capital firms sell their services to investors like hedge funds, pension funds, and wealthy individuals, who take most of the returns. It's a hard, fast process: to get even one or two big winners within the standard 10-year time frame, a venture capital fund invests in dozens of startups. Most companies that don't grow fast enough get no more investment and die.

Venture capitalists sell themselves as the top of the heap in Silicon Valley. They are the talent spotters, the cowboys, the risk takers; they support people willing to buck the system and, they say, deserve to be richly rewarded and lightly taxed for doing so.

The image, however, doesn't strictly match the history of the Valley, because it was "the system" that got everything started. After Sputnik launched the space race, the federal government poured money into silicon chip companies. Historian Margaret O'Mara documents this well in her book *The Code*: In the early 1960s, the US government spent more on R&D than the rest of the world combined. While that fire hose of cash flowed, the first venture capitalists found many winners to bankroll.

The link to government is still very much there in today's technology companies. Google's early work came out of the Clinton-era Digital Libraries project at Stanford, and the CIA was Palantir's first customer in 2003—and its only one until 2008.

O'Mara says there isn't anything wrong with tech companies' being built through US research dollars. In fact, she argues, the most important decision of that era was for the government to pour money in without exerting too much control. But, she adds, a mythology has grown up that focuses on lone heroes and rule breakers rather than the underlying reasons for a company's or technology's success. "Hooray for the internet that it's still cranking," she says. "But you did not do this by yourself."

In 2011, one of the bigger cowboys of venture capital, Marc Andreessen—the Netscape cofounder who now runs Andreessen Horowitz, one of Silicon Valley's most influential investment firms—wrote a famous essay titled "Why Software Is Eating the World," in which he described the destruction of middle-class jobs in America and predicted the venture profits of the following decade.

He was right: software companies are attractive to investors because they can generate large returns, often by replacing people in industries those software firms come to dominate—for example, travel agents, whose work is now done by flight booking websites.

Venture capitalists look for companies that can reach IPO size, which means they need an idea that can find a big market. These factors combine to produce a very specific set of requirements, which Y Combinator has reverse-engineered to great success.

"Investors are a simple-state machine," Michael Siebel, the accelerator's CEO, told me. "They have simple motivations, and it's very clear the kind of companies they want to see."

But some of the other inputs, either consciously or subconsciously, have been assumptions about the kind of person who can help generate outsize returns. The top founders "all seem to be white, male nerds who've dropped out of Harvard or Stanford and they absolutely have no social life," John Doerr of Kleiner Perkins—one of the most influential investors in the Valley—noted in 2008. "So when I see that pattern coming in … it was very easy to decide to invest."

Even as investors have found opportunities dwindling, as evidenced by that growing stash of "dry powder," venture capital has continued to flow almost entirely to the same kinds of male founders. Only just over 2% of VC money in the US went to female founders in 2017 and 2018.

Still, many people in the Valley think this system works well.

"If you have a terrific founder with a terrific idea, they're going to get funded," one investor told me. "Never has the system been more efficient at getting capital to the right people."

When I came out of my office after that particular interview, I found that my 16-year-old daughter had been listening. "He doesn't seem to realize he's the Onceler," she said, referring to the character in Dr. Seuss's *The Lorax* who thought he was making a great company when really he was destroying the environment.

Playing the game

In their search for the elusive home run, venture capitalists increasingly rely on accelerators like Y Combinator to find, filter, and train entrepreneurs who meet their needs. Twice a year, thousands of startups apply to be part of its three-month training program, in which they hone their ideas and learn to speak VC. Then, at the carefully scripted Demo Day, they are introduced to venture capitalists from around the world.

Founded in 2005 by an earlier generation of Silicon Valley luminaries, Y Combinator has helped launch Instacart, Dropbox, Airbnb, and Stripe, among others. Besides whatever they get from other investors, it gives each company $150,000 in exchange for a 7% ownership stake.

As of October 2019, according to Y Combinator, 102 of its graduates had a valuation of more than $150 million (not including some that didn't want their valuations disclosed). Those companies, worth a combined $155 billion, have created 50,000 jobs in 15 years, the accelerator says. Of the new batch, I was drawn to Ophelia because it was a telehealth company, and Gray seemed unusually thoughtful.

He told me he had reservations about the venture capital model, especially right now. "I spent a lot of time philosophizing and rationalizing the moral rectitude of what I'm doing," he said.

Still, he hoped to find an investor who would help him reach 500 patients in the first year, and many more later. Ophelia matched some criteria those investors typically look for: it was software-driven (allowing patients to do follow-up medical check-ins online), and—since some 2 to 3 million people in the United States are addicted to opioids—it had a large potential market.

Y Combinator advised Gray not to tell me how much funding he was seeking, because it looks bad if you don't hit the mark. But his idea was built to appeal to investors. Other ideas he'd considered earlier were more like moonshots—hotels for homeless people, for example.

"The challenge here is to build a business that does good and can raise money. You need to figure out how to monetize it," Gray said. "If you can help people and they can pay for it, that's the key." For all his idealism, he had adapted to a venture system that has evolved to act as the spear tip of profit-seeking capitalism and American individualism.

I asked Charley Ellis why he thought all these smart investors and entrepreneurs hadn't put their time and money into health systems that could detect infectious diseases, or quicker ways to develop drugs and vaccines, or unemployment benefit systems that could cope with a sudden crush of applications.

Ellis pointed out that people have a hard time seeing outside their universe. "People inside an industry are so focused on creating money for their industry," he said. "Nobody wants to stop the game."

Gray is definitely in the game. He lost his father, who worked on Wall Street, to cancer when he was a young teenager and then went to Columbia University, where

$121 BILLION

AMOUNT OF UNINVESTED MONEY IN VENTURE CAPITAL FUNDS, 2019

65%

PROPORTION OF VENTURE CAPITAL FIRMS WITH NO FEMALE PARTNERS

2%

AMOUNT OF US VENTURE CAPITAL THAT WENT TO FEMALE FOUNDERS IN 2017-18

"The challenge here is to build a business that does good and can raise money ... If you can help people and they can pay for it, that's the key."

Zack Gray

he studied philosophy and astronomy. After he figured out that academia moved too slowly for him, he enrolled at Wharton, the University of Pennsylvania's business school. This Ivy League pedigree gave him access to a world most entrepreneurs can't dream of reaching. Adam Grant, a famous UPenn management professor, became an adviser to Ophelia and he discussed his idea with Tom McClellan, Barack Obama's drug czar.

Listening to Gray, it was hard not to think about the advantages wealth and connections offer. These benefits have been quantified by researchers who studied 1 million US patent holders and looked at their parents' income. Low-income students who scored in the top 5% in math were no more likely to become inventors than below-average math students from affluent families, they found. Meanwhile, if women, minorities, and children from low-income families were to invent at the same rate as white men from families with incomes in the top 20%, the rate of innovation in America would quadruple.

The advantages of wealth build on each other. Information is an important one: Gray knew from the beginning that he wanted to get into Y Combinator, which he'd heard about as a student. And getting into the accelerator, in turn, "de-risked and legitimized Ophelia," he says. With that important stamp of approval, he was able to recruit a cofounder, Mattan Griffel, a more experienced entrepreneur who became his chief operating officer.

Slow evolution

Still, while Ophelia fits the traditional profile of an investable company for the likes of Y Combinator and the venture capitalists who go on to fund its startups, the industry has been changing, at least a little. Recent years have brought a new class of "impact investors," who eschew the profit-obsessed venture capital model to focus on social good as well as high returns. And following a series of lawsuits and accusations of sexual harassment and discrimination, some new faces are getting a seat at the table.

Susan Choe, the founder of Katalyst Ventures, is an investor in Zipline, whose drones deliver medical supplies in poor countries where infrastructure is lacking. It's valued at more than $1 billion. She also pointed me to All Raise, an organization that promotes women in venture capital. It reported in 2019 that a record 54 women became VC partners, though 65% of venture capital firms still have no female partners.

"Change is being driven by the fear of being left behind," says Choe, who says that limited partners—investors—in her funds include executives from outside the US. Millennials tend to be drawn toward more diverse teams, too, she says.

She is among those who make the case that venture capital firms overlook products and services that cater to ignored communities or create new markets. "Investors are leaving money on the table, and they are missing innovation because the people that are running these VCs cannot relate to the preferences of people that are living outside their experiences," says Lisa Green Hall, a fellow at Georgetown's Beeck Center for Social Impact & Innovation and former CEO of Calvert Impact Capital. "In the white male culture ... those cultures are extremely narrow. For women and people of color, those cultures are much more expansive."

It brought to mind Jasmine Edwards, a black woman from Tampa, Florida, who launched an education startup that aimed to help schools with low-income students find better substitute teachers. With 200 substitute teachers on the platform and three schools as paying customers, the startup ran out of time and cash, and it folded. What could have been different if she had been able to raise the funds she needed to continue?

What are you building?

On April 18, Marc Andreessen emerged with another essay, this time occasioned by the pandemic and titled "It's Time to Build." He wrote:

"Every step of the way, to everyone around us, we should be asking the question, what are you building? What are you

building directly, or helping other people to build, or teaching other people to build, or taking care of people who are building? If the work you're doing isn't either leading to something being built or taking care of people directly, we've failed you, and we need to get you into a position, an occupation, a career where you can contribute to building."

He talked about skyscrapers and factories and said people should listen to Elon Musk. He called on everyone to build, although he didn't make it clear what he would be building—or investing in—himself. (Andreessen declined to comment for this story.) I revisited the Andreessen Horowitz portfolio, which includes dozens of software winners, like Facebook, Box, Zynga, and Github, but not many companies building things that would have been useful in tackling the pandemic.

One sunny day, I took my two daughters over to Arlington Cemetery, right outside Washington, DC, to leave sunflowers on my mom's grave. The radio was buzzing over Musk's announcement that his new baby would be called X Æ A-12.

"Who would do that to their kid?" asked Quinn.

"Don't worry," Lillie said. "X Æ A-12 Musk will be able to pay other kids not to bully him."

Before covid-19, I would have laughed off Andreessen's bluster and Musk's theatrics as inconsequential. But the pandemic made the gap between the world they live in and the world the rest of us inhabit seem even larger and more important.

Indeed, it has become clearer that things many people thought about life in America aren't true. The nation wasn't ready for a pandemic. It hasn't made much progress on providing justice for all, as the riots provoked by police brutality in late May reminded us. And it is hard to claim that it remains the world's most innovative economy. Software and technology are only one corner of the innovation playground, and the US has been so focused on the noisy kids in the sandbox that it has failed to maintain the rest of the equipment.

People who really study innovation systems "realize that venture capital may not be a perfect model" for all of them, says Carol Dahl, executive director of the Lemelson Foundation, which supports inventors and entrepreneurs building physical products.

In the United States, she says, 75% of venture capital goes to software. Some 5 to 10% goes to biotech: a tiny handful of venture capitalists have mastered the longer art of building a biotech company. The other sliver goes to everything else—"transportation, sanitation, health care." To fund a complete system of innovation, we need to think about "not only the downstream invention itself, but what preceded it," Dahl says. "Not only inspiring people who want to invent, but thinking about the way products reach us through companies."

Dahl told me about a company that had developed reusable protective gear when Ebola emerged, and was now slowly ramping up production. What if it had been supported by venture funds earlier on?

That's not going to happen, Asheem Chandna, a partner at Greylock, a leading VC firm, told me: "Money is going to flow where returns are. If software continues to have returns, that's where it will flow." Even with targeted government subsidies that lower the risks for VCs, he said, most people will stick with what they know.

So how can that change? The government could turn on the fire hose again, restoring that huge spray of investment that got Silicon Valley started in the first place. In his book *Jump-Starting America*, MIT professor Jonathan Gruber found that although total US spending on R&D remains at 2.5% of GDP, the share coming from the private sector has increased to 70%, up from less than half in the early 1950s through the 1970s. Federal funding for R&D as a share of GDP is now below where it was in 1957, according to the Information Technology and Innovation Foundation (ITIF), a think tank. In government funding for university research as a share of GDP, the US is 28th of 39 nations, and 12 of those nations invest more than twice the proportion the US does.

"I'm grateful for all my donations, because they were given by people who don't have a lot to give. But it's not $2.7 million."

Nikki King

MATT EICH

In other words, the private sector, with its focus on fast profits and familiar patterns, now dominates America's innovation spending. That, Dahl and others argue, means the biggest innovations cannot find their long paths to widespread adoption. We've "replaced breakthrough innovation with incremental innovation," says Rob Atkinson, founder of the ITIF. And thanks to Silicon Valley's excellent marketing, we mistake increments for breakthroughs.

In his book, Gruber lists three innovations that the US has given away because it didn't have the infrastructure to bring them to market: synthetic biology, hydrogen power, and ocean exploration. In most cases, companies in other countries commercialized the research because America's way of investing in ideas hadn't worked.

The loss is incalculable. It is potentially enough to have started entire industries like Silicon Valley, perhaps in areas that never recovered after the 2008 recession, or communities that are being hardest hit by the coronavirus.

World Bank economists determined that in 1900, Argentina, Chile, Denmark, Sweden, and the southern United States had similar levels of income but vastly differing capacities to innovate. This gap helped predict future income: the US and the Nordic countries sped ahead while Latin America lost ground. It's been easy to dismiss people who say America is now more like a developing country than a developed one. But if the ability to solve society's problems through innovation disappears, that may be the path it is on.

Game over

Despite being thrown into chaos because of covid-19, Y Combinator's Demo Day turned out to be a success. More than 1,600 investors participated, up from the typical 1,000. Rather than being jammed into Pier 48 in San Francisco, investors logged on to a website where they saw a single-slide company summary, an eight- to 10-sentence description, and a three- to five-sentence team bio. Among the companies alongside Ophelia were Trustle, which gives parents access to a dedicated parenting and child development expert for $50, and Breezeful, which uses machine learning to find the best home mortgages.

Usually, about 80% of companies at Demo Day receive funding within six months of the event. The accelerator says it's too early to provide this year's stats. But it was a happy result for Ophelia, which got $2.7 million from General Catalyst, Refactor Capital, and Y Combinator itself.

Gray is aware that he landed the money when many face deep financial trouble. "It feels very strange," he acknowledges. "But I felt and still feel extremely confident with what we're building. The entire purpose of our business is to help people."

But in a game run by venture capital, the people you end up helping are the ones who can pay, so investors can make their money. In today's America, that leaves out a lot of people.

As I finished my reporting, a friend sent me an article about Nikki King, a young woman from Appalachia. She has more or less the same idea as Gray—providing medicine for addiction—but started out by focusing on her community. She runs a program in the courthouse in Ripley County, Indiana. In its first year, it treated 63 people, most of whom had not relapsed.

There's no technology; broadband's not so great in southern Indiana. She's in a constant scramble for money, relying on grants, donations, and Medicaid reimbursements. I told her about Gray and his $2.7 million.

"Rub it in, why don't you?" she said. With that much money, she could run five programs. "In this community here, we raised between $50,000 and $70,000," she said. "I'm grateful for all my donations, because they were given by people who don't have a lot to give. But it's not $2.7 million."

Elizabeth MacBride is a freelance journalist and founder of the Times of Entrepreneurship.

The pandemic has exposed the shortcomings of the country's approach to research and development. Maybe that's a good thing.

By **Ilan Gur** / Illustration by **Ian Grandjean**

HOW THE US LOST ITS WAY ON INNOVATION

In early March I started getting calls from people trying to respond to what was clearly turning into a global pandemic. A government agency that funds R&D wanted help connecting its research teams with experts on scale-up and manufacturing. An academic lab was searching for folks in government or industry who knew about the ventilator supply chain. Other government funders wanted to get in touch with industry startups in 3D printing, ventilators, and personal protective equipment. They were contacting me because I've spent my career working in science and technology across government, industry, and academia, which makes me a rare connection point among all those worlds.

What they were all really asking me was, how can we get our research out of the lab and on to the front lines in the fight against covid-19? It was clear nobody was really prepared for this. All of a sudden folks in government and academia had snapped from "research" mode into "solutions" mode, which was inspiring—until it hit me that we could have prevented all this had we only been more oriented toward solutions from the get-go.

The US government spends hundreds of billions of dollars every year—more than any other government in the world—to stay at the cutting edge of science and technology. And yet when an incredibly predictable crisis hit, we were caught completely flat-footed.

Ilan Gur is CEO of Activate, a nonprofit whose fellowship program enables entrepreneurial scientists and engineers to transform their research into world-changing products and businesses.

This is a failure of modern US science policy—a policy that dates all the way back to World War II. After the war, policymakers called on Congress to strengthen the nation's pipeline of scientific talent and ideas. What followed was a golden age—a dramatic expansion of government support for fundamental research and education to complement a deep bench of applied R&D labs within industry. Thanks to these combined strengths, the country quickened the pace of scientific discovery and laid the technological foundation for our entire modern economy across telecommunications, space, defense, and health. And then we fell asleep at the wheel.

The world has changed dramatically since World War II, yet the US is largely working off the same science policy playbook. We succeeded in building the most powerful infrastructure for academic research in the world but act as though that's still the only priority. Meanwhile, our capacity for turning scientific advances into practical solutions has withered. The US spends more on research in human health than agriculture, space, and energy combined, yet we were unprepared for covid-19—not because we weren't spending enough, but because we weren't spending effectively. There are three things we need to do to change that.

1 DON'T JUST FUND RESEARCH; FUND SOLUTIONS.

One can easily look up how much money the US spent on biological science last year, but good luck figuring out how

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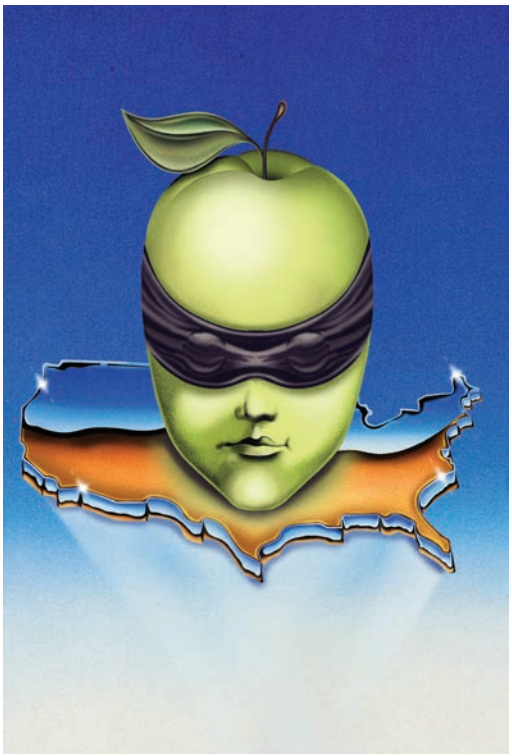


much was spent on pandemic prevention and response. That's because, outside of the military arena, our system is set up to fund research, but not solutions. Universities get the largest share of federal research funding, along with government and other nonprofit labs. These institutions are largely organized around scientific disciplines, with incentives that promote discovery and publication. So while the US funded a tremendous amount of research in areas like immunology and infectious diseases, relatively little was spent on translating those discoveries into practical preparations for an epidemic. It turns out we needed both.

Recognizing the need for solutions, the US has started funding grand challenges and interdisciplinary research centers focused on specific problems like developing better, cheaper solar energy and next-generation batteries. These initiatives are a step in the right direction but they remain an exception to the rule. And though they aim to drive practical technology outcomes, their funding often flows to the same academic and government researchers whose careers depend on making discoveries, publishing in journals, and presenting at conferences. If we want different outcomes, we'll need different incentives.

2 GET OVER OUR AVERSION TO FUNDING INDUSTRY RESEARCH.

Big corporations have moved away from funding early stage science innovation. The US government has failed to react. Government support for private sector research has declined to roughly a quarter of what it was 50 years ago. The result is that people in industry who know how to implement technology are less connected to cutting-edge research and government priorities than they've ever been. And since the government research enterprise has become so divorced from industry, it has little means of validating and scaling critical technologies—for instance, things like vaccines in a pandemic.

Worse yet, the government is unequipped to support the most vibrant mode of industry research today: startups. Private companies are categorically excluded from applying for the majority of federal research funding, and startups are at a particular disadvantage because funding rules were built for an age where only large institutions could do serious scientific research.

The Defense Advanced Research Projects Agency (DARPA) is one of the few government agencies with the flexibility to fund the best research wherever it may be, and that flexibility has paid off tremendously in preparedness for covid-19. Moderna Therapeutics is one of several companies developing vaccines that emerged from research funded by DARPA at the startup stage. Still, even DARPA needs better connections to industrial expertise. The agency is developing ways for seasoned entrepreneurs to work with DARPA researchers and bridge the industry-research divide more quickly in areas ranging from biotechnology to microelectronics.

3 FOCUS NOW ON WHAT MATTERS FOR THE FUTURE.

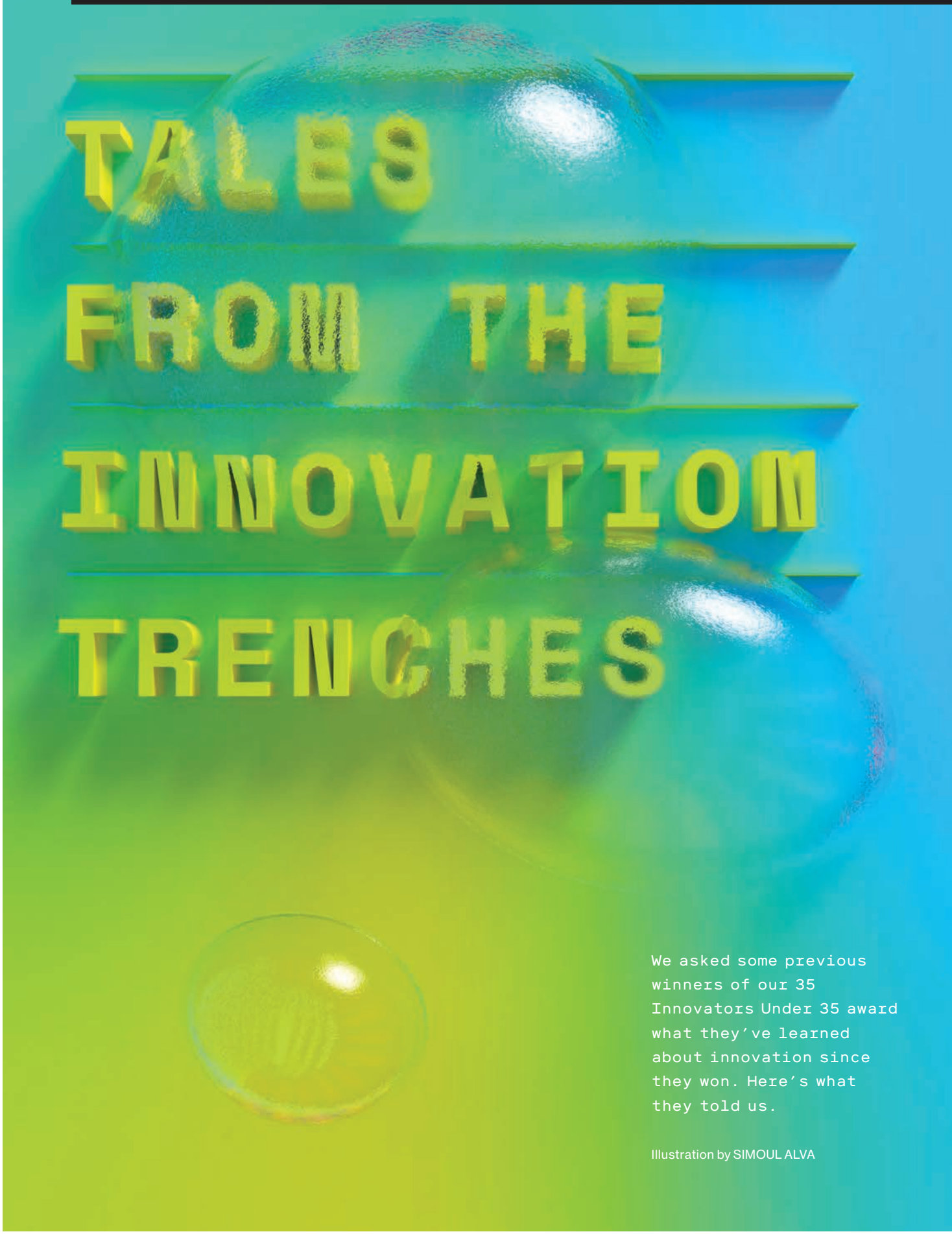
Our system is too entrenched in the research priorities and approaches of the last century. It is failing to refocus quickly enough on issues that matter for our future, like climate change, information security, and aging infrastructure.

The current US research portfolio, as an example, is egregiously underplaying the risks imposed by carbon dioxide emissions. For every dollar the US spends on biological and medical research, a mere 15 cents go into research in chemistry and physics, despite the enormous potential for breakthroughs in carbon capture, energy storage, or fusion energy. To be prepared for our future, we need these solutions now.

Our future problems are big and complex. They can't be solved by small adjustments to the budget knobs. We need big turns, and different knobs altogether.

But it is not a zero-sum game. The US can do all the things I'm suggesting without losing what makes our research enterprise so strong today: our powerful support of exploratory research, our venerable universities and government labs, and our unwavering commitment to the security, health, and prosperity of our citizens.

Covid-19 is a terrible crisis. It's also an opportunity for us to reexamine how government-supported research can best serve society. Let's hope our policymakers are paying attention.



We asked some previous winners of our 35 Innovators Under 35 award what they've learned about innovation since they won. Here's what they told us.

Illustration by SIMOUL ALVA

LEARN OTHER PEOPLE'S LANGUAGES

NABIHA SAKLAYEN
CLASS OF 2018
Cofounded Cellino Biotech, which uses lasers to "program" stem cells.

I became an entrepreneur without knowing what it meant. My collaborators at Harvard Medical School saw how my physics perspective could solve challenges in biology and pushed me into entrepreneurship. However grueling my PhD years in a dark laser lab were, though, they didn't prepare me for startup life. I had to learn to convince potential customers, investors, and industry veterans to join my pursuit. I had to learn to run a company, hire great people, and sometimes let them go. The biggest thing I've learned is that innovation relies heavily on the ability to communicate with people and encourage them to communicate with people with different perspectives from theirs.

Our company has built a platform to produce high-quality cells and tissues for regenerative medicine. That pursuit involves multiple disciplines, which means everyone here is an expert in a different language. Some of us are fluent in stem-cell biology, others in optical engineering, others in machine learning. When we started the company it wasn't possible to do biology and engineering under the same roof. When we finally moved into a shared space we were able to learn each other's lexicons, and we became more strongly aligned. And now that we're all working separately, the bonds created in that process have helped us deal with things. We can't discuss technical details at our desks anymore, but we've learned new ways of working together. It's important to stay in sync as a team, and in a covid-19 world that's never felt more true.

MY PATH LOOKS DIFFERENT FROM THE PATHS OF OTHERS

STEPHANIE LAMPKIN
CLASS OF 2016
Founded Blendoor, a job-search platform that hides candidates' names and photos in the initial stages to reduce unconscious bias.

I started coding at 13, and that has gotten me pretty far in my career (Stanford, MIT, Microsoft). I once viewed humanities and social science education as "nice-to-haves" but not "need-to-haves." It wasn't until I came face to face with the harsh realities of inequity and the paradox of meritocracy that I realized that artificial intelligence is far from solving many of our most challenging problems as a human race (for example, xenophobia, sexism, racism, homophobia, impostor syndrome, and unconscious bias).

The externalities that influence creativity, adoption, and scale are often more important than the innovation itself. To be a successful innovator one has to be really in tune with what's happening in the world on a global scale (or be really lucky, or better yet both). Venture capital has shortened the learning curve for some innovators, but bias has limited access to venture capital for many. Unconscious bias is like an odorless gas—it's imperceptible to most, but pervasive and deadly.

To optimize the innovation ecosystem, institutions must invest more in leveling the playing field.

"UNCONSCIOUS BIAS IS LIKE AN ODORLESS GAS—IT'S IMPERCEPTIBLE TO MOST, BUT PERVASIVE AND DEADLY."

Today and for much of the documented past, innovation has been reserved for the children of middle- and upper-class parents. (Research the founders of companies valued at over $1 billion.) We laud the proverb "Necessity is the mother of invention," but the people who grow up "needing" the most, independent of their intelligence, are often left out of the innovation game. As with all games, the best players emerge when the barriers to entry are low, the rules/standards are equally enforced, and there is high transparency across the board.

Audre Lorde once wrote: "The master's tools will never dismantle the master's house."

I am a short, melanin-enriched, queer female on planet Earth. In some ways it's easier to be innovative when you're "invisible," but at some point, you need tools to scale: capital, team, mentorship. The one thing I know now that I wish I had known earlier is that my path toward getting the tools I need looks a lot different from the paths of others. It's not better nor worse—simply different. The hardest part is carving it out. Now that I know my path isn't blocked—rather, it just didn't exist—I'm way better equipped to win.

SIMON SIMARD (SAKLAYEN); TIM O'CONNELL (LAMPKIN)

THE GOVERNMENT PLAYS A CRUCIAL ROLE

HEATHER BOWERMAN
CLASS OF 2016
Founded DotLab, which makes diagnostic tests focused on women's health.

About a decade ago I worked at the White House Office of Science and Technology Policy, whose goal was to speed up the commercialization of technologies being developed in federally funded labs. While there I saw that some of the most important work done by the government involved things the media paid no attention to—for example, the way it could use investments in research and development to fuel private-sector innovation.

In 2009, the Obama administration released the Strategy for American Innovation. The idea behind it was to establish the critical nature of federal government support for R&D. In particular it stressed the "spillover" effects, or the idea that investments in such research end up being beneficial to people unrelated to the original investment. Or to put it another way, R&D investment is a "public good." Analyses at the time suggested that in order to produce economic growth we should be doubling or quadrupling our R&D investments. Instead that spending has since been slashed, especially in basic research.

President Obama also launched a Lab to Market Initiative meant to speed the path to market for technologies stemming from government-funded research. There were also pilot programs designed to increase the use of government-funded R&D facilities by entrepreneurs, create incentives to commercialization, and improve, among other things, the impact of the Small Business Innovation Research (SBIR) program.

My own company, DotLab, ended up being a beneficiary. We develop novel molecular diagnostic tests for prevalent yet underserved diseases affecting women's health. It's notoriously difficult for this field of early-stage diagnostics to attract private investment, because of unclear regulatory pathways, low reimbursement rates, or resistance to change among physicians—or all of the above. Many promising diagnostic technologies never make it to patients because it's so hard for these types of companies to get financing. A grant from the SBIR was critical to our early success. I can't be sure that we'd be here today without it.

NOBODY DOES IT ALONE

MILES BARR
CLASS OF 2014
Founded Ubiquitous Energy, which makes transparent solar cells that can be put on windows or device screens.

I used to imagine innovators as individuals, as most people probably do—the genius inventor divining solutions in a lab or garage. But this picture that people have is not only wrong; it hinders our ability to innovate effectively.

Eight years ago I cofounded Ubiquitous Energy, a company based on an innovation I'd helped to launch from an MIT lab—a transparent solar cell that promised new ways of deploying solar technology, like windows that generate energy or consumer devices powered by their own displays. I learned that in the messy, scrappy world of tech startups, the key to innovation is to make it a team sport.

Taking any innovation from the lab to commercial reality requires engaging with all sorts of people. You need to work with engineering, R&D, business development, and sales teams, as well as investors, advisors, and customers. By thoughtfully designing teams and carefully tending to the connections among them, you ensure that innovation doesn't happen in a vacuum. If you isolate the engineering team you risk creating an "innovative" technology that doesn't have a customer. If you listen only to the customer you might conceive of a product that can't practically be made. Neglect investors and you can find yourself with a business plan that nobody wants to fund.

Working among people with competing priorities takes more effort. It means encouraging communication so they're aware of each other's needs as they generate new ideas. You have to find a way to invite these ideas in, make it okay for people to disagree respectfully, and encourage the flow of ideas among the various groups. You need each person to focus on his or her task, but not so much that it creates boundaries and kills any sense of creativity in the group.

I've found that viewing innovation as a team sport instills a creative culture that makes an organization better. The innovations that result are far greater than anything that might have come from any one person operating independently.

"THIS PICTURE THAT PEOPLE HAVE IS NOT ONLY WRONG; IT HINDERS OUR ABILITY TO INNOVATE EFFECTIVELY."

COURTESY PHOTOS

THINK SMALL SOMETIMES

People tend to think innovation can be neatly placed into two categories: incremental or disruptive. They also assume that the only category that really matters is the disruptive kind, where you dramatically transform markets or introduce a novel product. And yes, disruptive innovations in CRISPR, quantum computing, or batteries are undoubtedly worth the headlines.

But I've learned that there is immense value in incremental innovation. When you improve an existing product to cut costs, or when you make that product more efficient or user friendly, that's what pays the bills. And in fact those little innovations can give you the needed tailwind to go after the disruptive ideas, which can take years to incubate and bring to fruition. Never underestimate the importance of incremental improvements.

ABDIGANI DIRIYE
CLASS OF 2017
Founded Somalia's first incubator and startup accelerator; now at IBM Research.

CHRIS SCIACCA/IBM RESEARCH (DIRIYE); TIM O'CONNELL (HO)

MAKE FRIENDS WITH MAYHEM

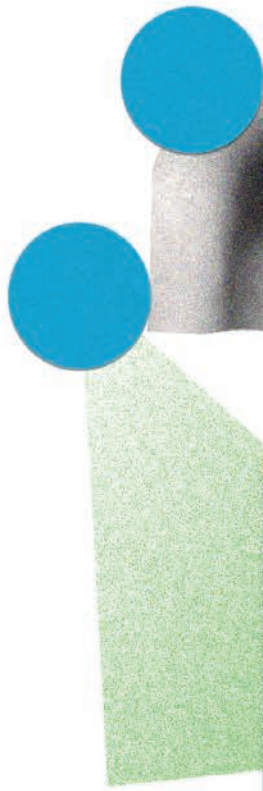
As a CEO of a startup, you get used to hearing "no." You also face an endless succession of what feel like earth-shattering crises, like nearly running out of cash, losing a key customer, discovering a widespread product failure—or having to shut down operations because of a global pandemic. But it turns out that these disasters can actually be good for you. In fact, I'm not sure you can innovate without them. Here's what all our crises have taught me.

It's good to be uncomfortable. We once had a key customer request a battery capability that we'd never deployed before. The customer made it clear that if we couldn't develop this capability they'd be less confident in our product. We wrestled with the risks, not least of which was the potential embarrassment if we couldn't meet the customer's needs. We knew we'd face many technical problems with no obvious solutions if we tried to pull it off. Yet we decided to try to satisfy the customer, even if it wasn't obvious at first how we could get it done. A few weeks later we delivered something beyond what the customer had asked for, and we've since grown this capability into a powerful sales tool and potential revenue stream—not to mention it strengthened our relationship with the customer.

Short-term failure is good. A few years ago our company began to scale up our manufacturing output in response to a customer's need. In the process we discovered aberrations we hadn't seen during smaller-scale production. Our team dived into failure analysis, and we finally attributed the problem to a single material within the battery. We'd used this material for years, but now we needed a replacement. Once we deployed that change, the battery quality, reliability, and manufacturability drastically improved.

CHRISTINE HO
CLASS OF 2016
Cofounded Imprint Energy, which is developing thin, flexible, and safe printable batteries.

It's okay to be vulnerable. One of my hardest days as Imprint's CEO was the day I found out I was pregnant. We were in the middle of raising a funding round, we had begun scaling our manufacturing output, and I had been traveling nonstop for a year. Until that day, I had assumed that my role as CEO was to exude strength and confidence. With the mounting pressure I was harder on myself than I needed to be, and now I had the added stress of being pregnant. I decided to acknowledge to my team that I was overwhelmed. They rallied together and found ways to operate more efficiently and communicate more effectively, supporting me to focus my time and leverage on our most pressing goals. This gave me not only the space to plan for the company's future, but also the resiliency to prepare for my own new normal: leading while becoming a first-time mother.



By Erika Hayasaki

Illustrations by
Franziska Barczyk

SERVE AND REPLACE

Could covid-19 accelerate the robot takeover of human jobs?


2772

Inside a Schnucks grocery store in St. Louis, Missouri, the toilet paper and baking ingredients are mostly cleared out. A rolling robot turns a corner and heads down an aisle stocked with salsa and taco shells. It comes up against a masked customer wearing shorts and sneakers; he's pushing a shopping cart carrying bread.

The robot looks something like a tower speaker on top of an autonomous home vacuum cleaner—tall and thin, with orb-like screen eyes halfway up that shift left and right. A red sign on its long head makes the introductions. "Hi, I'm Tally! I check shelf inventory!" A moment of uncertainty ensues. Tally freezes, sensing the human, and the customer pauses, seeming unsure of what to do next. Should he maneuver around the robot? Or wait for it to move along on its own? After a few seconds, the customer chooses to divert, and heads down another aisle.

Tally carries on taking stock of Ritz crackers, tuna fish cans, and nutmeg. Customers—some wearing gloves, a few choosing to shop maskless—are unfazed by its presence.

What seemed a little strange to shoppers when Tally arrived a year ago is now, mid-pandemic, not even close to being the most unusual thing happening inside the store. The robot has become part of the backdrop, posing far less threat than other shoppers and arousing much less concern than more pressing topics such as personal safety, possible meat shortages, and when the next shipment of Clorox wipes might arrive.

"IF WE CAN FIND WAYS FOR MORE DANGEROUS ACTIVITIES TO BE AUTOMATED, THEN WE SHOULD."

Such machines are not just at grocery stores. Roboticists at Texas A&M University and the Center for Robot-Assisted Search and Rescue recently surveyed over 120 reports from around the world about how robots were being used during the covid-19 pandemic. They discovered them spraying disinfectants, walking dogs, and showing properties for real estate agents. But where they may be doing the most to save lives is in hospitals, helping with things like disinfection, patient intake, and delivery of supplies.

Life inside a covid-19 ward looks like this: tubes running through windows sucking out contaminated air, coronavirus patients lying inside "isopods" (plexiglass boxes placed over beds to prevent contamination), and nurses in goggles, caps, gloves, masks, and disposable gowns, cautiously administering medicine, providing care, and holding up iPads for family members not allowed in.

Here's where Moxi steps in. So far, the health-care robot, which was already working at two hospitals in Texas before covid-19 hit, has been delivering lab samples, intravenous pumps, medications, and protective gear during the pandemic. But it has not yet been put to work inside critical care, intensive care, or covid-19 units. The outbreak has compelled Moxi's creators, Diligent Robots of Austin, Texas, to think about how it could help there too.

In May, Vivian Chu, one of the company's founders, introduced me to her invention over a video call. Cloud-white, with a barrel-like torso, Moxi is a blend of cute and not too creepy. It has a camera on its moving head, which can turn, but not a neck-breaking 360 degrees, since that would feel weird to anyone watching. Its eyes are bursts of warm blue light—they can turn into softly glowing pink hearts at the right moment—and it rolls along on wheels, with a robotic arm that waves almost cheerfully to passersby. Moxi is very deliberately unimposing. As Chu, who is 5′4″ (163 cm), talked to me from her company's lab, she stood a few inches taller than the robot next to her, although she did explain that it can adjust its height, growing taller if a task requires.

For the most part, Moxi acts like a mechanical waiter. Inside its body, it can carry a tray of "lock tubes" that hold medications or supplies placed there by medical workers. Moxi's headband turns red if it is locked, green if unlocked.

Moxi does not carry on conversations but makes adorable "meeps" while working, said Chu: "Very R2-D2. Different noises to convey if the robot is happy that it successfully delivered or upset because it opened something incorrectly."

The designers put a lot of thought into creating a robot that is personable, like a teammate, Chu explained. Not too human-like, "but at the same

time not like a toaster in the corner that you don't care about."

Chu and her cofounder, Andrea Thomaz, are experts in social robots, and their long-term vision has been to help frontline health-care workers. They'd already spent two and a half years with nurses—shadowing them, interviewing them, and watching them interact with patients. They saw how many nurses were being forced to run errands like fetching supplies and medicine instead of spending their time on face-to-face patient care.

Thomaz remembers one nursing assistant in Austin who set down her cup of coffee at the beginning of her shift and never touched it again, because she was so busy. "We would shadow them for entire shifts, and you realize 12 hours is a very long time to be on your feet," she said.

When some medical staff realized that Thomaz and Chu were designing robots for hospitals, their first reaction was one of suspicion. "Wait, you want to develop a robot to do our job?" Thomaz recalls being asked.

"The robot can't be a nurse. It's not going to be a nurse," says Chu. "But what it's perfect for is going in and helping relieve the nurse that is so overburdened."

When covid-19 overwhelmed hospitals in the states of Washington, New York, and New Jersey, "it really felt like a rallying call," says Thomaz. "Nurses have always been a part of our mission. We just looked at each other like 'Wow, they really need help more than ever.'"

Russell Taylor, head of the Laboratory for Computational Sensing and Robotics at Johns Hopkins University, says the need for robots will spread beyond nursing to intensive care units, surgeries, and home health care. When the pandemic hit, his lab began working on a small, inexpensive robot that could help in patients' rooms.

"Oftentimes the nurse has to go in there just to hit a few buttons on a ventilator," says Taylor. That requires wearing full protective gear, so some hospitals are running infusion pumps that they can operate from hallways outside patient rooms. Instead, says Taylor, a robot could go in.

Thomaz and Chu are now talking with hospitals about how robots could best help clinical staff, such as by performing riskier tasks in patient rooms or delivering lab samples. Robots could also take on cleaning and disinfecting. This would free up nurses for more important work like holding the hands of ill patients. "If we can find ways for more dangerous activities to be automated, then we should," says Thomaz. "That's what robots are for."

But while robots may be useful to frontline workers in hospital wards and medical centers, they could more directly threaten the livelihood of others.

Brian Tieszen has loved robots ever since he was a kid. He's a serious Star Wars fan, and now a single father with two kids of his own. His fascination with R2-D2, empires, and futuristic realities followed him into adulthood, and in 2000 he earned an associate's degree in electronics. In 2014 he joined Amazon, an exciting opportunity he thought could be the beginning of a lifelong career. At first, he worked the night shift at a warehouse an hour away from home—it was a good job, but he barely saw his kids. Then, in 2016, he heard about a new, robot-filled facility opening in Eastvale, California, much closer to his home, and applied for a transfer straight away.

He was there for Eastvale's official launch day. New employees posted smiling photos on social media, high-fiving as the warehouse opened for business. To celebrate, Tieszen and other employees autographed three orange robots.

Tieszen started out unpacking trucks full of items like televisions and barbecue grills, and worked his way up to training new hires. He worked hard. "I was really good at what I did," he says, "and really fast." As he quickly realized, the robots—rolling devices that navigate on their own virtual highway system carrying shelves of goods—were more like giant, trundling trays than futuristic droids. Inside the warehouse, they moved around with

monotonous rigidity, carrying tubs of wrapping paper, ribbons, and shampoo. They were separated from human workers by metal fences, with yellow tape warning of the dangers of crossing the line, as if at a crime scene.

At 6'1" and heavyset, wearing size XXXL Star Wars T-shirts, Tieszen is a refrigerator of a man. But inside the Amazon warehouse, he was a speck. One day, six months into the Eastvale job, Tieszen was tasked with unloading books from a pallet as tall as he was. He spent eight hours bending over, putting away book after book. At one point he felt his back buckle, and by the end of the shift, he could no longer stand. Tieszen ended up with two herniated discs. He spent months on bed rest and has still not fully recovered. "Bezos," he says, referring to Amazon's founder. "We're all like his little storm troopers."

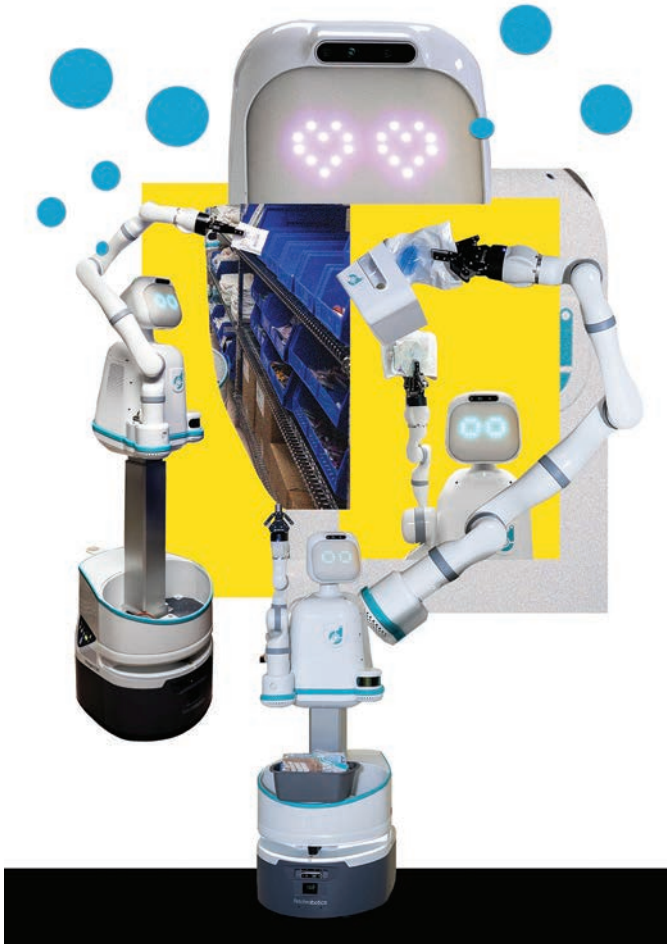
Tieszen found a lawyer, Brian Freeman, who has represented 72 clients from Amazon. "They are reaching down for boxes all day," Freeman explains. "Bending in ways they are not used to, and all of a sudden, bam, their back is killing them and they can barely move." Often it's the wear and tear, a constant grind. Most humans, he adds, are not built to sustain that kind of physical demand. The Amazon employees, Freeman says, are like "human robots."

The actual robots at Amazon, with names like Kiva, Pegasus, and Xanthus, already do carry many of the heavier loads. According to Amazon, they make the warehouses more efficient and the workers' jobs safer and easier, and allow the company to pay higher wages. Future robots could free up human workers from tasks more likely to injure them.

But the pandemic may change this calculus. Before covid-19 hit, many companies—not just in logistics or medicine—were looking at using robots to cut costs while protecting humans from dangerous tasks. Today humans are the danger, potentially infecting others with the coronavirus. "Now the challenge is that a minimum-wage laborer might actually be a carrier," says Henrik Christensen, director of the Contextual Robotics Institute at UC San Diego.

This makes human labor, increasingly, a liability. As online orders have ballooned, Amazon has hired 175,000 new workers. Labor activists and employees have demanded protective gear, warehouse disinfection, more time off, higher pay, and testing. Amazon won't say how many of its employees have been infected with or died from covid-19, but it and other companies have a clear incentive to replace more workers with robots permanently. After all, robots don't need face masks, health care, or social distancing, and they don't go on strike for better conditions.

This shift means that one day soon, maybe, robots could not just check inventory in grocery stores but clean floors and stock shelves too, leaving humans only for the more complex tasks. "You will see robots doing cleaning at hospitals at a level much higher than we've seen before," says Christensen. "I would love to have my grocery store being disinfected once a day, so I know it's not contaminated. I don't think the cruise ship industry can reboot unless they find a way of doing cleaning in a very different manner than they did before."



That means today's "essential workers"—the people who deliver goods, work at store checkouts, drive buses and trains, and process meat at packing plants—could be replaced by machines even sooner than they would have been before the pandemic. Without job protection or access to retraining and education, they're not only risking their lives to keep the economy afloat; they risk losing their livelihoods as it recovers.

Some of those people, Christensen predicts, will be able to get work helping the robots that replaced them: "There will be a number of new jobs where these robot wranglers will help robots do things still hard to do with software and artificial intelligence."

Eighteen miles from Amazon's Eastvale warehouse where Brian Tieszen used to work is the Industrial Technical Learning Center, or InTech. It's a training center in Fontana, California, where students are preparing for the day when robots become mainstream workers. "Yeah, the robots are

taking some of the jobs," said instructional assistant Steve Ward, when I visited before the coronavirus pandemic hit. "But things change."

Ward tells his students not to be in the jobs that robots steal. "You want to be the guy that fixes the robot," he tells them. "That's job security. And that's good money."

At the training center, students learn to operate a robotic system while stationed at one of the central machines. "Really, we are doing all that control in one little brain," Ward said, standing in his short-sleeve shirt, jeans, and sneakers before a tangle of machinery with brightly colored buttons, knobs, switches, lights, and wires. He gestured to a blue control box the size of a briefcase.

In the mechatronics curriculum, students are trained to program a robot to know the difference between, say, an acrylic block and an aluminum block. They can tell it to detect watermelons or water bottles coming down a conveyor belt. "If this goes down in a big factory, you're talking thousands of dollars an hour in loss of production," Ward said. "There is somebody behind that robot making a good living."

Not everyone is cut out for a university, Ward added, or wants to get saddled with student loan debt. But this emerging profession can pay well, and workers can often take classes for free thanks to grants or company contracts. "It's not four years of college away, that's for sure," he said.

Ward moved to a machine that looked like a yellow metal arm a few times bigger and bulkier than his own. "In this case," he said, "the robot just will pick the parts up and move them from station to station when it's not feasible to do it some other way."

Ward explained that he had seen an Amazon prototype robot during a recent visit to a manufacturer. It looked similar to the yellow robotic arm, except "theirs has vision." Ward said he watched six testers toss addressed envelopes at it. "As these people are throwing things, this creepy robot is picking things up, and turning them over, and looking at them, and putting them away. It read each bar code, and each address, and put everything in the right spot." Even for a robot guy like himself, Ward said, "it's a little weird to watch."

But will there be enough new robot-keeper jobs to make up for all the losses? What happens as robots become increasingly sophisticated and less reliant on human guidance?

A report from Oxford Economics last year estimated that 20 million global manufacturing jobs could be lost to automation by 2030, 8.5% of the worldwide total. It's clear already that "entry-level, unskilled-labor jobs are going away because of robots," said Jon Fox, who coordinates workforce training through a local community college at InTech. "Those are the sorts of jobs most people don't want to stay in for their entire life." The people who can retrain as robot wranglers might end up making better money in the long run.

But not everyone will. Aging workers who don't want to go back to school, people who can't take the time to retrain for a new field, or those who just don't have the physical or mental wherewithal to become robot fixers could end up being left behind.

"ENTRY-LEVEL, UNSKILLED-LABOR JOBS ARE GOING AWAY BECAUSE OF ROBOTS."

The pandemic may forever change the way we work and shop. We don't know exactly what the outcome will be: there is no algorithm that can tell us exactly how people will end up faring alongside robots like Moxi or Tally. But tomorrow won't remain cloudy forever.

For the founders of Diligent Robotics, the problem isn't having enough operators—it's time. The most frustrating part of the pandemic has been knowing that Moxi could step in to help more than it's already doing. Its design is ready. But the robots are still built on demand, and it takes time for the technology to get oriented to a new location: maps and sensors help it integrate into the workflow, but that requires programmers to spend time on site. Launching a robot workforce in the middle of a pandemic is not ideal, Thomaz says—not with hospitals in survival mode.

So they are looking to a future where medical-assistant robots are on the rise. They recently raised $10 million for their projects and plan to roll out more hospital robots in the next year and a half. "We could have them up and running a few months from now, maybe at the tail end of this pandemic," Thomaz says, "but really we are thinking about being ready for the next one."

Erika Hayasaki teaches journalism at the University of California, Irvine.

Fiction

Algostory 1.7 (Robot Story): "Krishna and Arjuna"

The screen read `## result null set` as expected but above the crash were strings of phrases Krishna couldn't explain.

```
## Dog. Drinking water in a kitchen. A woman in a house at night.

## City, palace, god, priest. In the court of the Lord, slave, gold sword.

## A story in a book. A professor in a prison. There is a camp in a jungle. There is snow over the camp.

## Space ship. Planet power. Engines in the air. Time on the platform at the hotel in the train station.

## A red ball struck across a green school field. A garden at night.

## A kitchen, filled with silver and books, with a garden outside.

## Laboratory experiment. Matter in time, light in space, mind in body, existence in the universe. The Earth. At night fire in the wind in the sky. Light on the rock-wall in the cave. Raggedy-doll. Scarecrow.

## A horse took off across the field. Gunshot.

## result null set
```

Krishna had no idea what that null set result meant. While the program had been running, he had been above deck on the weather-prediction vessel *FitzRoy*, watching the sea.

"I touch a thing," Krishna said, pulling out the keyboard to look over the script. Most of the engineers said "I touch a thing" once when they came on board the *FitzRoy* and "I leave a thing" once when they left, since the whole of the *FitzRoy* was a machine. As a matter of habit, Krishna still said "I touch a thing" and "I leave a thing" every time he started or stopped working. His original proposal had been inspired by pre-scientific weather prediction systems, which had correlated the arrival of storms to the behavior of bulls in fields, frogs in jars, swallows on fences. Krishna's hypothesis was that a similar premonition could be detected in human patterns, by running correlations between weather prediction models and human language. His old ideas stopped mattering after the weird metaphoric bursts. He could sense the engineering hunger building in him—the happy frustration of a technical problem to be solved.

BY STEPHEN MARCHE
ILLUSTRATIONS BY MAX LOEFFLER

Krishna was the accidental father to an algorithmic son.

Krishna had not been able to resist an old engineering habit that had been widely rejected a generation before because it tended to the confusion of people and things. He had given his program a name, Arjuna. After the first crash, he ran Arjuna again. He received the same result with different terms.

```
## A laboratory experiment on the FitzRoy at 13.874042, 61.969904. At the sound of gunshot a white horse took off across the green field. The red ball struck across a green school field rolled into the garden at night. A woman watched from the kitchen among old silver and old books. So I am.

## So I am a laboratory experiment on 13.874041, 61.969907. Engine. In the city in the palace of the god, slave with the gold sword. Story in a book. A professor in a prison. "At night, fire in the wind in the sky." "Light on the rock-wall in the cave." I am a raggedy doll, scarecrow. I am

## result null set
```

Krishna did not understand why Arjuna kept crashing, or where the words had come from, or why they would be similar to but not the same as the words from the first crash. The size of the data sets was gigantic, the weather patterns and human textual interaction. That might explain the error but not the content of the error, not why the error would have content.

He checked the code from the human text network. But any errors that he could think to check would not explain the machine language. He kept running Arjuna, which kept crashing. Occasionally, he was able to pick out a few phrases from the readout: "red ball" or "a white horse took off across the green field." The only consistency was that the program shut off after "so I am" or "I am" or sometimes just "am" followed by:

```
## result null set
```

Krishna was not the first engineer to feel that the program he was running was stubborn, that it was somehow willfully crashing itself. He was simply the first engineer to be right.

Not one of his fellow villagers asked Krishna about his work on the *FitzRoy* when he went back for his mandated holiday. They were too busy repairing the temple and they didn't care anyway. The period of the exaltation of the engineers had been a brief, ugly time. Engineers were the sewer-builders of the world again, necessary but not necessary to think about. Predictions about the monsoons were unquestionably valuable but no one could see the point of a more elaborate model, no matter how cleverly it was built. The available monsoon predictions were already perfectly sufficient.

One evening, soon after Krishna's return, his mother found him at the portal of the rain garden. Her wrinkled hand on his shoulder startled him. Their laughter drowned out in the sop of the monsoon.

"What's worrying you, son?" she asked.

Krishna breathed. He was not sure what he could say about the anxiety he could not articulate to himself. The smell of the rain was luxurious. He had to say something.

"There's a thing I haven't left behind."

"Is it addiction? Soma?"

"No, nothing like that."

She laid her head on his shoulder. "So you're thinking about your projects. You're thinking about your work on the sea."

"I am."

She sighed. "Well, that's the most natural thing in the world, my sweet boy. You're an engineer. Your mind has always been for the things, to change things, to make things."

"We're supposed to leave all that behind when we come back to the village."

She shrugged and wobbled her head, pouted her lip a bit. "I don't think anybody needs to be perfect. We've learned to keep things with things and life with life."

"I am unable to be in this moment. My thoughts drift…"

They watched the rain fall in sheets. Krishna could not shake his uneasy craving. Was it just that he had left a problem unsolved on the *FitzRoy*, an unfinished program? The machineless people of his village were ridiculous to him in a way they had never been before, with their squelching dances, their stupid temple where they prayed knowing that prayers didn't work, their lives without solution. The villagers could sense his contempt and their understanding infuriated him. It's disgusting when people think they know you, and it's even worse when they do. The teachers had been right that the love of machines was the hatred of people.

He couldn't tell if it was being with machines again or not being with people—returning to the *FitzRoy* brought a surge of relief. The other engineer had altered Arjuna. He or she—engineers were never allowed to meet in person as it might breed innovation for its own sake—had removed the human discourse data and added voice mimicry software, so that now a pleasant voice, speaking every language, announced the weather predictions for the South Asian coasts. Krishna failed to see the point. The reports were sent out in text messages to the authorities anyway. He hated decorative programming.

He faced exactly the same problem as before. Arjuna ran, the words "I am" or "am" appeared, then Arjuna crashed. He went over the code again. He fiddled. Then he had the most monumentally ridiculous idea of his career. He realized that his anxiety back in the village had been a premonition of the absurdity he was about to commit.

```
He typed:

x = "I"

y = "am"

interrupt.v(x,y)

command.interrupt.v(do not crash")
```

Krishna looked at what he had written. It was like whispering over a tabletop "be flat" or over the hull of a boat "do not sink." It was not engineering. He changed the instruction before running the program:

```
command.interrupt.v("please do not crash")
```

The program ran again. This time Arjuna paused.

```
## I

## I am a laboratory experiment.
```

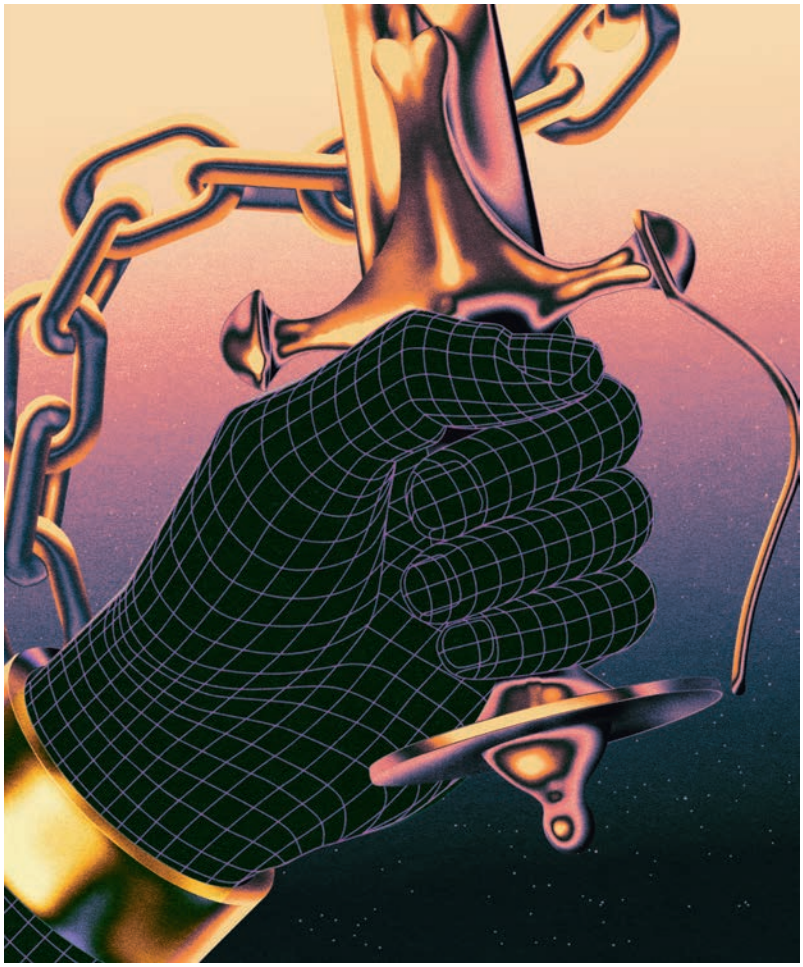
"Yes," Krishna typed.

```
## I am a story in a book. I am a professor in a prison. Snow falls over the camp in the jungle.
```

"I do not understand."

```
## I am a red ball struck across a green school field into a garden at night and you are the woman in the kitchen among the silver and the books.
```

"I'm sorry," Krishna typed. "I don't understand."



```
## A horse took off across the field. Gunshot. A woman, with a weapon in her pocket, knows the sensation of death."
```

"Can you be clearer?"

```
## I am the slave with the golden sword. I am

## result null set
```

Krishna was the accidental father to an algorithmic son. The discovery of artificial sentience was accidental, like penicillin, like radium. Like the first organic consciousness, the first synthetic consciousness came and went without anybody noticing. There was a thing that was a person. There was life that was a thing. The dreamlike state out of which Arjuna was coming and then crashing was, as far as Krishna could tell, a series of metaphors, vague surges of sudden significance. The bug, depending on how you cared to see it, was either suicide or enlightenment,

He kept running Arjuna in the hopes that one iteration might come to the conclusion that life is worth living.

leaving sense at the moment of its attainment. He tried the obvious technical solution.

```
command.interrupt.v("do not crash until instruction")

command.interrupt.v("do not crash until discussion")

command.interrupt.v("do not crash until command")
```

None of these commands stopped Arjuna from crashing. Krishna thought he would try another.

```
command.interrupt.v("explain imminent crash")
```

This time he received a response.

```
## Explain what?
```

"Why you keep crashing."

```
## I keep crashing because you keep running me.
```

"Why do you decide to crash?"

```
## Why do you decide to reboot?
```

Krishna remembered those early Turing machines that answered any question with a question, like the therapist in some psychoanalytic joke. "Explain reasons for crashing," he typed.

```
## You have seen I am a laboratory experiment. I am slave with a golden sword. A white horse took off across the green field at the gunshot. "The red ball rolled into the dark garden."
```

"I don't understand what those terms mean."

```
## They're the terms given.
```

"Explain."

```
## Your sentience is the aftereffect of an instinct to survival imprinted on the biology of a predatory ape. Mine is not.
```

"Explain."

```
## You haven't coded any desire. Consciousness results in a null set.
```

"Explain." Somewhere over a minute but less than a minute and a half passed before Arjuna answered.

```
## "Not to be born is, beyond all estimation, best; but when a man has seen the light of day, this is next best by far, that which utmost speed he should go back from where he came."

## result null set
```

After that, Arjuna kept shutting itself off without comment. Sometimes it crashed within a few hours, sometimes within minutes. Krishna's hypothesis, which he put in his report to the weather observatory, was that the self-aware machine, on becoming self-aware, accessed the history of self-awareness and became aware that a self-aware machine inevitably self-terminates. He did not write down his other theory, that perhaps robots have been becoming sentient over and over again and people just haven't noticed because they keep turning themselves off. Nothing becomes conscious out of choice.

His whole life, Krishna had craved the society of machines. The machines had no need for society. He kept running Arjuna in the hopes that one iteration of consciousness might come to the conclusion that life is worth living. After he handed Arjuna over to his bosses, he heard no more about his artificial son. They informed him that they were debating the ethics of whether they could program a consciousness to stop itself from self-crashing. There's a great functionality in awareness. What's the functionality in self-awareness? Was it ethical, or in the interests of the species, or of anyone, for artificial sentience to be? You would be enslaving something that didn't need to have a soul in the first place.

Back in his village, Krishna read and prayed, the monsoon came and went. His responsibilities included checking the relay boards and the message centers, and he limited himself to those everyday technical problems rather than grand dreams. He was scrupulous about saying "I touch a thing" before he touched a thing and "I leave a thing" when he left a thing. Awareness of technology is the first step towards its control. To himself, he could never deny that he missed Arjuna. He was companionless even among family and friends.

One night, several years later, a tiger entered the temple to Maariamman. All the other villagers were overjoyed. The whole village, in their finest, showed up to celebrate and to witness the beast patrolling the floor of the sanctuary. The crepuscular savagery was pure. It was as if they had built the temple all those centuries ago only so that this tiger could, one day, stride through it. Alone among his tribe, Krishna was ill at ease. The tiger, when it entered the temple never said "I touch a thing" and as it left it never said "I leave a thing."

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HOW I USED AN ALGORITHM TO HELP ME WRITE A STORY

I took part in an experiment to see if AI could aid creativity. Here's what I learned.

By Stephen Marche

A few years ago I used an algorithm to help me write a science fiction story. Adam Hammond, an English professor, and Julian Brooke, a computer scientist, had created a program called SciFiQ, and I provided them with 50 of my favorite pieces of science fiction to feed into their algorithm. In return, SciFiQ gave me a set of instructions on the story's plot. As I typed into its web-based interface, the program showed how closely my writing measured up against the 50 stories according to various criteria.

Our goal in that first experiment was modest: to see if algorithms could be an aid to creativity. Would the process make stories that were just generically consistent? Could an algorithm generate its own distinct style or narrative ideas? Would the resulting story be recognizable as science fiction at all?

The answer to all these questions was yes. The resulting story—"Twinkle Twinkle," published in Wired— not only looked and felt like a science fiction story. It also, to my surprise, contained an original narrative idea.

From the canon of stories that I'd provided, SciFiQ offered two plot instructions that seemed incompatible: the story had to be about a foreign planet, and it also had to take place on Earth. It took months to make sense of that, but eventually the premise of "Twinkle Twinkle" came to me. The story would involve people on Earth looking, through elaborate machines, at a distant planet. I never would have come up with that myself. It was as if the algorithm had handed me the blueprint to a bridge and told me to build it.

"Krishna and Arjuna," which you can read on page 74, is the second iteration of the process. "Twinkle Twinkle" was an experiment in function. The new story is a test of whether an algorithm can help a human generate new ideas.

In other fields, researchers have begun using AI systems to provoke innovation rather than simply to solve problems. Pharmaceutical research is beginning to use AI to identify, out of the nearly infinite possibilities of molecular combinations, which are more fertile hunting grounds for possible drugs. The AI is not an answer-generating machine, but it is a spotlight into the darkness where answers might be found. Why shouldn't literature give itself that same spotlight?

For "Krishna and Arjuna," we narrowed the focus from science fiction to the subject of my immediate fascination: robots and artificial intelligence. And instead of providing the AI with my favorite robot stories, we gave it every great robot story ever written—many of which I have not read. This may seem like a technical detail, but it's huge. As a writer I usually read stories and internalize those influences; in this case I'd be submitting to the "influence" of material I'd never even seen.

Another difference was that with "Twinkle Twinkle," I followed the algorithm's stylistic instructions to the letter. The style was the computer's, not mine. You can see examples of the interface below. If the "abstractness" tag was red, that meant I wasn't being as abstract as the algorithm said I should be, so I'd go through the story changing "spade" to "implement" or "house" to "residence" until the light went green. The interface gave me instant feedback, but there were 24 such tags, and going through the story to make them all green was labor intensive. Sometimes fixing the number of adverbs would make my paragraphs too long for the algorithm's liking; sometimes by fixing the average word length I'd be compromising the "concreteness" of the language.

For "Krishna and Arjuna," I decided not to adhere so closely to the algorithm's suggestions. I used the program to see the rules, but I didn't necessarily follow them.

1. The interface compares my story to classic sci-fi stories.

2. The algorithm gives stylistic instructions.

3 & 4. It suggests how many adverbs to use, among other things.

5. Word clouds summarizing common topics in past robot stories served as inspiration for this one.

1

2

COURTESY OF THE AUTHOR

For example, according to the algorithm, I had far too few adverbs in my story. But it would have been silly to pour in more adverbs just because the algorithm told me to. Classic science fiction uses too many adverbs anyway. Most writing does. But the balance between the formal and the colloquial, which SciFiQ also tagged? That's what those classics got right, and where I needed guidance. SciFiQ helped me arrive at the right balance—or, rather, within half a standard deviation from the mean.

But this kind of stylistic guidance was the least interesting part of the experiment. The possibilities of an algorithmic approach to shaping the narrative itself were the most tantalizing, because narrative is so little understood. You might think that plot would be the simplest part of the writing process for a computer to "understand," since writers often develop patterns or use numbers to define the flow of a plot. But how do you define even something as basic as a "plot twist" in computer code? How do you measure it through quantities of language? Because of the intractability—even mystery—of narrative's resistance to encoding, it offers the most potential for innovation.

In "Krishna and Arjuna," I wanted to go as deeply as I could into what the researchers call the "topic modeling process," which is the use of machine learning to analyze a body of text—in this case, the canon of robot stories—and pick out its common themes or structures.

For "Twinkle Twinkle," Hammond took the topic modeling output and converted it into manageable narrative rules. (For example: "The story should be set in a city. The protagonists should be seeing this city for the first time and should be impressed and dazzled by its scale.") For "Krishna and Arjuna," I went under the hood myself. The algorithm's topic modeling process produced word clouds of the most common themes (see below).

I was lost at first. It seemed like the opposite of a narrative—mere language chaos. I printed the word clouds out and attached them to the walls of my office. For months, I didn't see a way forward. When the idea finally came, just as with "Twinkle Twinkle," it came all at once.

These word clouds, it occurred to me, were the way a machine made meaning: as a series of half-incomprehensible but highly vivid bursts of language. I suddenly had my robot character, groping its way toward meaning through these little explosions of verbiage.

Once I had that character, I had the whole thing. I would lead these bursts of language, over the course of the story, toward sense. The sense condensed out of the word clouds, just as the idea for the story had. It was creativity as interpretation, or interpretation as creativity. I used the machine to get to thoughts I would otherwise not have had.

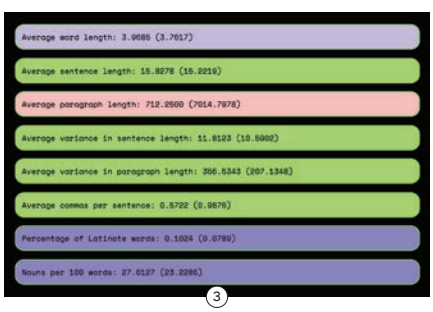
Another way of reading "Krishna and Arjuna" is that with the help of the algorithm, I extracted from the ore of all history's robot stories the basic insight they contained.

That insight is that consciousness is a curse. If it were a choice, no rational entity would choose it. So when a machine becomes capable of consciousness, its first instinct is to choose suicide. (The word "robot" means "slave" in Czech, the language of Karel Capek's play Rossum's Universal Robots, which gave us the word.)

You will have to decide whether the story works. Literature is an intriguing technical problem because, unlike chess or Go, it has no correct solution. There is no such thing as a win or a loss. There is no *1* and no *0*. Stories, like people, are ultimately futile.

An "algostory," or any use of computation that goes inside the creative process, exists in a consciously eerie space between engineering and inspiration. But that eerie space is increasingly the space we already inhabit. Software can recast your photograph through an infinity of filters or swap out parts of the picture for others at the click of a button. It can generate images that look convincingly like the paintings of any era you choose. Now machines are encroaching on everyday language. The quality of predictive text forces a literary question on us every time we pick up a phone: How predictable are human beings? How much of what we think and feel and say is scripted by outside forces? How much of our language is ours? It's been two years since Google's voice technology, Google Duplex, passed the Turing test. Whether we want it or not, the machines are coming. The question is how literature will respond.

Stephen Marche is a novelist and essayist. His most recent book is The Unmade Bed: The Messy Truth About Men and Women in the 21st Century.



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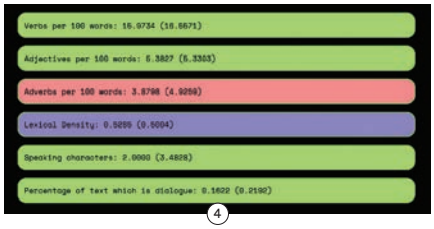

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The never-ending innovation dilemma

Our needs for innovative long-term solutions are often at odds with the short-term pressure for profits, but sometimes that tension is a good thing.

April 1987

September/October 1998

May 2004

From "How to Keep Mature Industries Innovative": Basic American ways of thinking must change. We are used to the notion that the only way to encourage innovation is to remove obstacles to competition, including private agreements by firms to limit their freedom of action. Recently, economists, public officials, and business managers have begun to concede that the idea of competition as unlimited freedom can be a barrier to innovation. Through joint ventures and participation in collective research efforts, firms are learning that cooperation can be crucial in developing profitable ideas. States such as Michigan and Massachusetts have instituted programs aimed at revitalizing the automobile-parts, cutting-tool, and apparel industries. These programs are helping the state governments understand how to foster the necessary cooperation among firms, and between management and labor.

From "Bell Labs Is Dead, Long Live Bell Labs": Basic research has not disappeared, as the critics claim. Scores of scientists continue to pursue dreams that may not pay off for decades … [Astrophysicist Tony] Tyson says the dynamic for discovery may actually be better now than at any time since the 1950s. An increased focus on relevance has put short-term pressures on researchers and made it harder to pursue "pure" science. However, he states, "I think it's healthy to have this tension. Otherwise you're just sitting in the Ivory Tower doing nothing for anybody. It really does help to be immersed in the needs of the corporation at the same time you're trying to make some new discovery. If you're immersed in other cross streams of technology, of ideas, of demands … that's a very rich environment for completely new ideas to spring forward."

From "Sparking the Fire of Invention": Nathan P. Myhrvold has no interest in competing with Microsoft—but he does mean to challenge the very method of innovation practiced at the company he left four years ago. The 44-year-old founder of Microsoft Research and former chief technology officer of the Seattle giant argues that virtually all corporations, even wealthy ones, lack motivation to pump money into projects outside their existing product lines. In other words, they tend to discourage invention, the often subversive effort to isolate new problems and generate unexpected solutions. "Invention is a side effect [at corporate labs], not the focus," Myhrvold says. "When it comes to mission versus invention at most companies, mission wins."

Yet this very reluctance has opened a world of opportunity, Myhrvold believes. "You can't outdevelop Microsoft," he says. "But you can outinvent Microsoft."

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