MIT Technology Review

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Number 6

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2023

AI and consciousness

Unbreakable encryption

21st-century shop class

Plastics. Politics. Twitter. And other hard problems.

With contributions from

Jennifer Doudna

Bill Gates

Katie Notopoulos

Annalee Newitz

Mark Zuckerberg

Priscilla Chan

Lina Khan

& more

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MIT Technology Review Insights

The Green Future Index 2023

The Green Future Index 2023 is the third edition of the comparative ranking of 76 nations and territories on their ability to develop a sustainable, low-carbon future. It measures the degree to which economies are pivoting toward clean energy, industry, agriculture, and society through investment in renewables, innovation, and green policy.

The index ranks the "green" performance of countries and territories across five pillars:

- Carbon emissions
- Energy transition
- Green society
- Clean innovation
- Climate policy

KEY

- Green leaders
- The greening middle
- Climate laggards
- Climate abstainers

↑ Countries that have gone up in the ranking since last year

↔ Countries that have retained the same ranking as last year

↓ Countries that have gone down in the ranking since last year

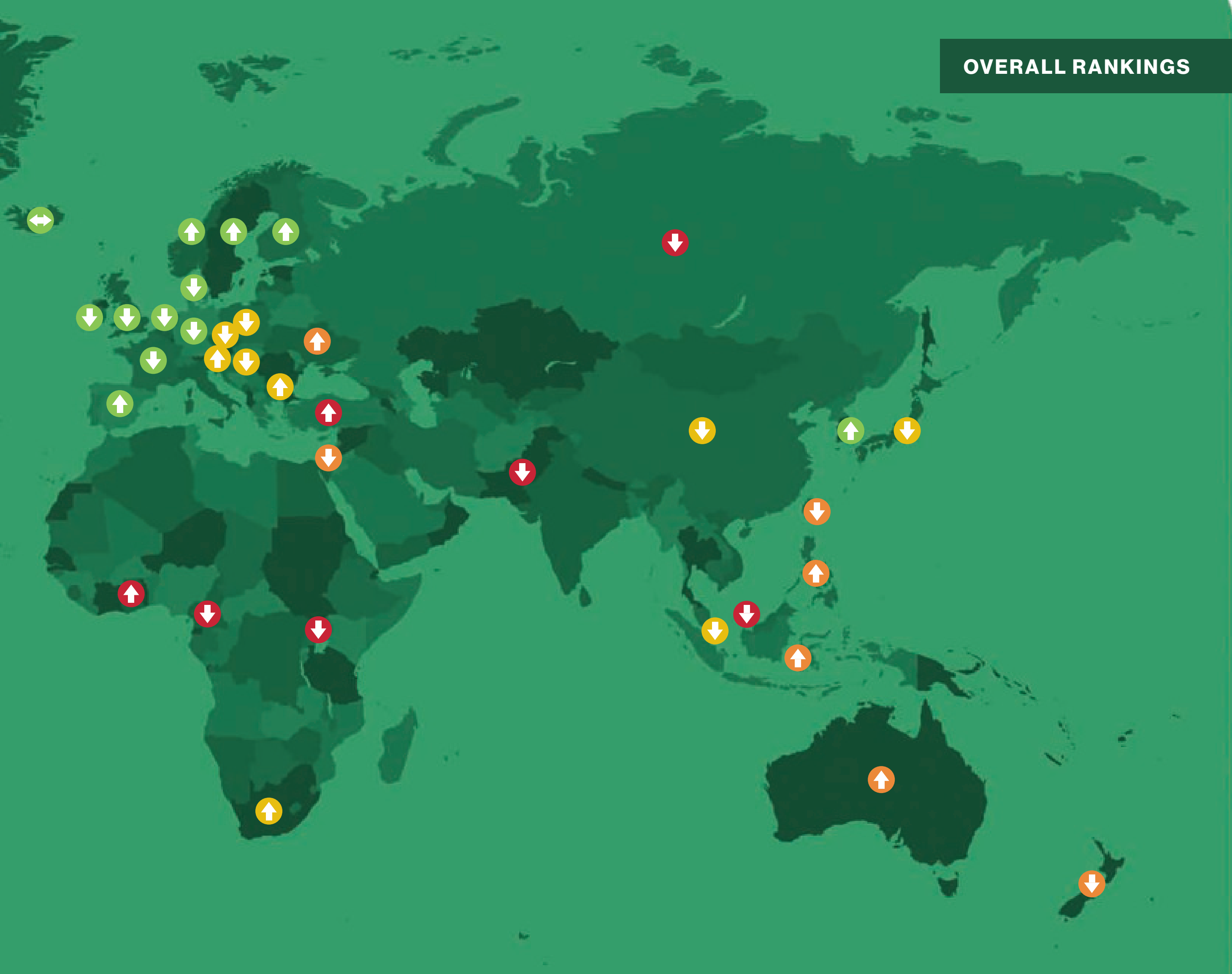
Overall top 10

Rank 2023		Rank 2022	Territory	Score/10
1	↔	1	Iceland	6.69
2	↑	6	Finland	6.68
3	↑	5	Norway	6.37
4	↓	2	Denmark	6.34
5	↑	9	Sweden	6.33
6	↓	3	Netherlands	6.22
7	↓	4	United Kingdom	6.12
8	↑	10	South Korea	6.00
9	↓	7	France	5.99
10	↑	13	Spain	5.92

- Iceland's government is working to streamline the construction of wind farms and will put forth new legislation to that effect in 2023.
- Luxembourg is the only country with significant movement toward the Green Leaders: it showed considerable state resolve in decarbonizing its economy.
- South Korea's 2022 carbon neutrality spending nearly doubled to ₩12t (U.S. $9.2b), and it adopted the Carbon Neutrality Act.

Scan the QR code to experience the interactive index, view the data, and download the full report or visit technologyreview.com/gfi

OVERALL RANKINGS



While the index ranks 76 countries, this map only features a selection of the overall data.

Green society top 10

Rank 2023		Rank 2022	Territory	Score/10
1	↑	3	**Ireland**	7.64
2	↓	1	**South Korea**	7.37
3	↑	4	**Germany**	7.14
4	↓	2	**Singapore**	7.06
5	↑	11	**Denmark**	6.82
6	↓	5	**United States**	6.81
7	↔	7	**Taiwan**	6.80
8	↑	9	**Czech Republic**	6.79
9	↑	12	**Sweden**	6.76
10	↓	6	**Iceland**	6.74

- Ireland's score reflects its world-leading progress in reforestation.
- Three Asian economies – South Korea, Singapore, and Taiwan – have strong government resolve to define sustainability targets and coordinate outcomes with civil society.
- EU members collectively benefit from its policy resolutions to speed up low-carbon societal and economic activities.

For all of history we've turned to technology, again and again, to help us solve our hardest problems. Technology gave us warmth and light when it was cold and dark. It helped us pull fish from the sea and crops from the earth so we would not be hungry. It enabled us to cross over the oceans and fly through the skies, shrinking vast distances down to routine travel. It's given us vaccines and treatments and cures. It has made virtually every fact and all of human knowledge available to us instantly on demand. We can speak to each other in entirely different languages and be understood using nothing more than a slim slab of glass and metals in our pocket.

Sometimes technology can seem like a miracle. Of course, it is nothing more than human achievement. Yet like all things human, our creations can be deeply flawed. As a result, we have also used tech to unleash horrors on ourselves, intentionally and by accident.

We have employed it to broadcast hateful rhetoric and divisive ideologies. We have fine-tuned our machines to kill each other in ever greater numbers and with ever more efficiency. It is our technology that took the carbon from out of the ground and put it in the sky. Our technology that poisoned the water and the air, that made deserts out of forests, and that wiped entire species off the planet.

Technology is an engine for problems, for solving them and for creating entirely new ones—and then we perversely turn to even newer technologies to try to solve *those*. In this issue, we step back from this cycle. We explore big questions and hard problems and ask: What role can—and should—technology play going forward?

Our cover is inspired by Douglas Main's terrifying story on plastics (page 22). There's an adage that says every piece of plastic ever made still exists. While that isn't entirely true, as Main vividly describes, it is pretty darn close. We're not reducing how much is made—precisely the opposite. Reuse is negligible. Recycling isn't working. Meanwhile, plastic is absolutely everywhere, and in absolutely everything, including our own bodies. What are we going to do about it?

AI epitomizes the sometimes fraught relationship we have with technology. It has the potential to massively benefit society—and yet it could cause incalculable harm if we get it wrong. As its development races ahead, Grace Huckins has written a powerful, even poetic exploration of AI consciousness (page 30). What would it take, and what would it mean, for an AI to become conscious? How would we know? What would we owe it?

David W. Brown takes on the challenge of spacecraft design and the struggle to make smaller, cheaper missions that can still tell us meaningful new things about the solar system (page 52). If we are going to make the most of the resources we devote to space exploration, we'll have to grapple with the hard limits of physics—and think hard about what we can, and want to, do.

Some of our hardest problems come down to human nature, and our capacity and sometimes outright desire for conflict. Social media and online communications are lousy with trolling, disinformation, harassment, and hate speech. Katie Notopoulos argues that the solution for much of this is to end our fixation with free services and move to smaller, distributed platforms that put more power in users' hands (page 64).

One hard problem most of us have likely faced is the experience of interacting with government services online. A decade after the famously botched launch of Healthcare.gov, Tate Ryan-Mosley explores why it is still so hard for the government to get tech right (page 46). Her reporting takes us to New York City, which has had some manner of success—in part by going with the lowest tech possible.

And finally, we asked some of the smartest minds out there what they consider the biggest problems that aren't getting enough attention right now. You'll find their responses starting on page 39, and many more online at techreview.com/hardproblems.

Thanks for reading,
Mat Honan

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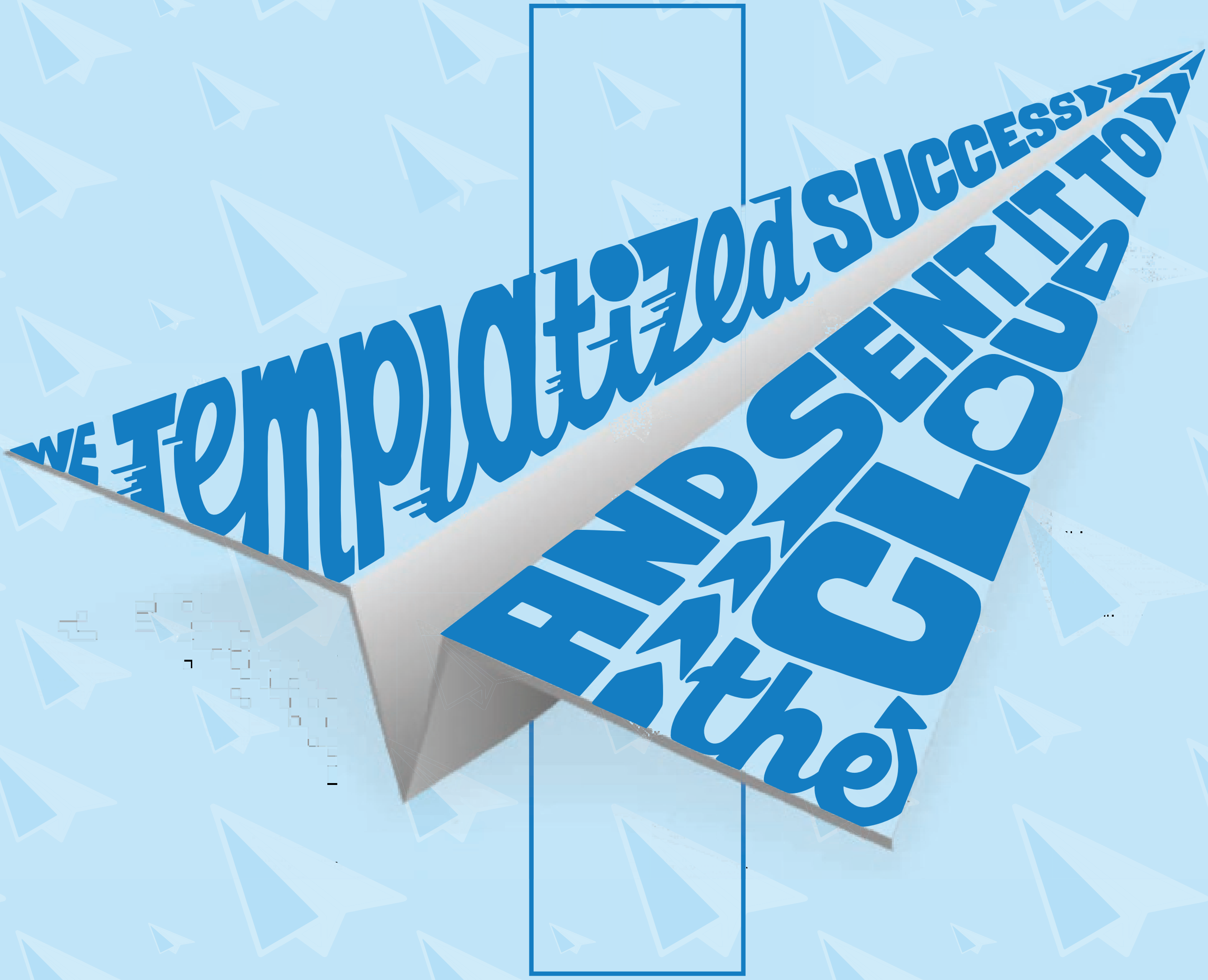
ROBYN KESSLER


We templatized success
and sent it to the cloud

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“We’ve upgraded everything else in our society—why not democracy?” –p. 40

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The hard problems issue

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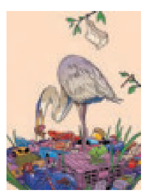


Cover illustration by Michael Byers

The Download

How AI can help us understand how cells work—and help cure diseases

A virtual cell modeling system, powered by AI, will lead to breakthroughs in our understanding.

By Priscilla Chan & Mark Zuckerberg

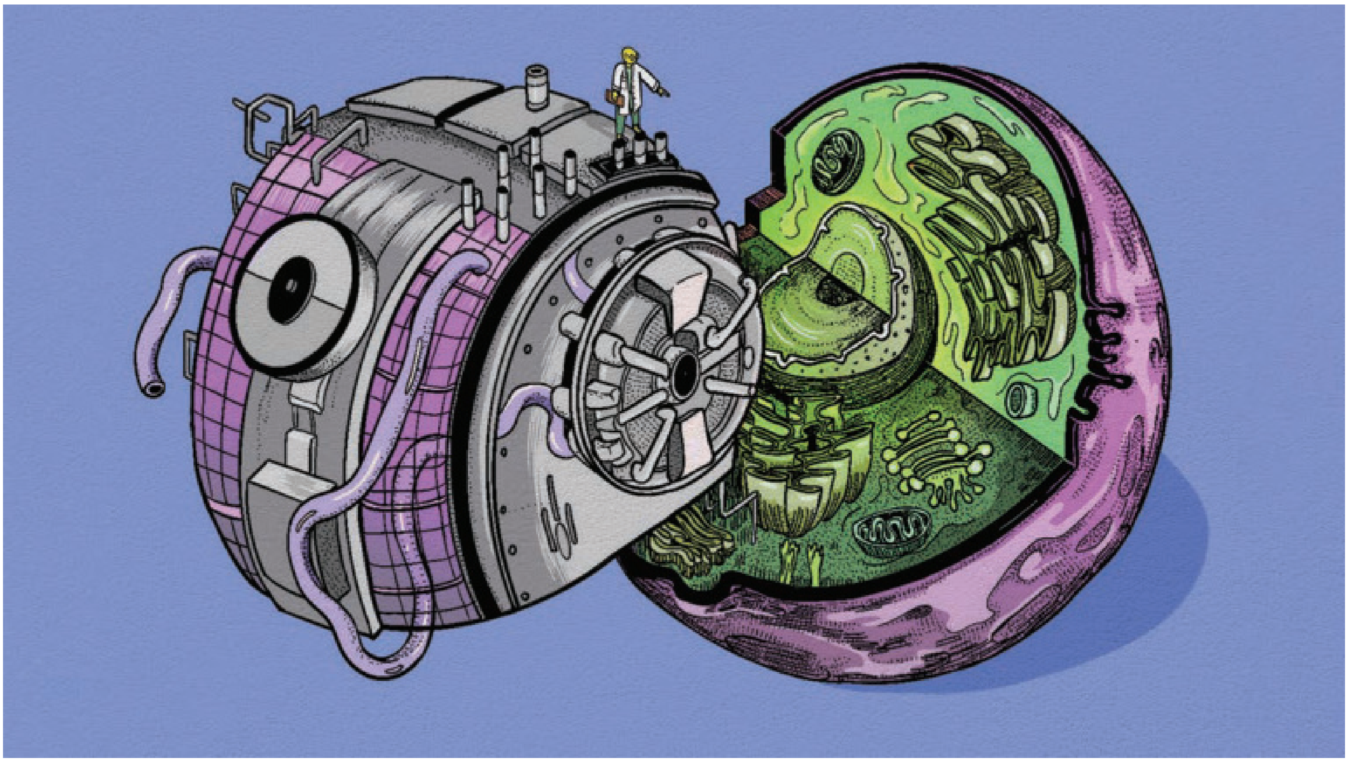
As the smallest living units, cells are key to understanding disease—and yet so much about them remains unknown. We do not know, for example, how billions of biomolecules—like DNA, proteins, and lipids—come together to act as one cell. Nor do we know how our many types of cells interact within our bodies. We have limited understanding of how cells, tissues, and organs become diseased and what it takes for them to be healthy.

AI can help us answer these questions and apply that knowledge to improve health and well-being worldwide—if researchers can access and harness these powerful new technologies.

Imagine if we had a way to represent every cell state and cell type using AI models. A "virtual cell" could simulate the appearance and known characteristics of any cell type in our body—from the rods and cones that detect light in our retinas to the cardiomyocytes that keep our hearts beating.

Scientists could use such a simulator to predict how cells might respond to specific conditions and stimuli: how an immune cell responds to an infection, what happens at the cellular level when a child is born with a rare disease, or even how a patient's body will respond to a new medication. Scientific discovery, patient diagnosis, and treatment decisions would all become faster, safer, and more efficient.

At the Chan Zuckerberg Initiative, we're helping to generate the scientific data and build out the computing infrastructure to make this a reality—and give scientists the tools they need to take advantage of new advances in AI to help end disease. ▸



EVA REDAMONTI

The data

Advances in AI coupled with large volumes of scientific data have already predicted the structure of nearly all known proteins. DeepMind trained AlphaFold on 50 years' worth of carefully collected data, and in just five years, they solved the mystery of protein structure. ESM, another AI system, which was developed at Meta, is a protein language model—trained not on words but on over 60 million protein sequences. It is used for a wide range of applications, like predicting protein structures and the effects of mutations from single sequences.

A virtual cell modeling system will also require large amounts of data. Since 2016, CZI has supported researchers globally in efforts to generate and annotate data about cells and their components, built tools to integrate these large data sets, and made them widely available for researchers to learn from and build upon.

A global consortium of researchers has been building a reference map of every cell type in the body, and our San Francisco Biohub is creating whole-organism cell atlases. Together, these data sets are yielding the first draft of the open-source Human Cell Atlas, which will chart cell types in the body from development to adulthood. Our SF Biohub and the Chan Zuckerberg Imaging Institute are partnering on OpenCell, which maps the locations of different proteins in our cells.

Researchers are also using machine-learning models like Geneformer and scGPT to explore large amounts of data about genes and cells—including data generated from CELLxGENE, the open-source software platform that CZI's science and technology teams created to speed up single-cell research. Similarly, with a new prototype data portal for cryo-electron tomography, our Imaging Institute and our science and technology teams are engaging machine-learning experts to develop automated annotations of microscopy data. This will speed up data processing time from months or even years to just weeks.

We are making the data as representative as possible to make sure scientific breakthroughs benefit everyone. This effort includes incorporating pediatric data into the Human Cell Atlas, filling gaps in our knowledge about the cellular mechanisms of diseases that arise in childhood. With our Ancestry Networks grants, we are also supporting researchers generating reference data about cells based on tissue samples from Black, Latino, Southeast Asian, and Indigenous people, among others from understudied racial, ethnic, and ancestral backgrounds.

Already, research teams have made discoveries using these well-curated data sets. One discovered that the broken gene linked to cystic fibrosis is expressed by a type of cell scientists had never come across before, while another identified the respiratory cells that are most vulnerable to SARS-CoV-2. Others are using the data to discover new options for splicing genes to potentially correct disease-causing mutations in specific cells.

These discoveries are the first step in developing treatments for diseases—and we believe that AI can significantly speed up researchers' rate of discoveries going forward.

The compute

To create a virtual cell, we're building a high-performance computing cluster with 1000+ H100 GPUs that will enable us to develop new AI models trained on various large data sets about cells and biomolecules—including those generated by our scientific institutes. Over time, we hope, this will enable scientists to simulate every cell type in both healthy and diseased states, and query those simulations to see how elusive biological phenomena likely play out—including how cells come into being, how they interact across the body, and how exactly disease-causing changes affect them.

Our computing cluster won't be as large as those used in the private sector for commercial products, but once it's up and running, it will be one of the world's largest AI clusters for nonprofit scientific research. This will be an important resource for academic teams that are ready to use data sets in new ways but are held back by the prohibitive cost of accessing the latest AI technology. Like our other tools, these digital cell models, and their associated data and applications, will be openly accessible to researchers worldwide.

The people

Generating these data sets, building this computing cluster, and using AI for biology is the kind of multidisciplinary, collaborative effort that defines our work.

Our Biohub Network has brought together experts from different disciplines and institutions to tackle some of science's biggest and riskiest challenges, which couldn't be solved in traditional academic settings. Through projects like CELLxGENE, researchers around the world have helped build a single-cell data corpus—a testament to how effectively a shared resource for open science can grow with more collaborators contributing resources and brainpower.

When CZI first launched our science work in 2016, we committed to a big goal: helping the scientific community cure, prevent, or manage all disease by the end of this century. We believe this goal is possible and will be significantly advanced if leading scientists and technologists work together to make the most of the opportunities created by AI. We can start by unlocking the mysteries of our cells, and that can lead to work that helps end many diseases as we know them. ■

Priscilla Chan is cofounder and co-CEO of the Chan Zuckerberg Initiative. Priscilla earned her BA in biology at Harvard University and her MD at UC San Francisco.

Mark Zuckerberg is cofounder and co-CEO of the Chan Zuckerberg Initiative. He is also the founder, chairman, and chief executive officer of Meta. Mark studied computer science at Harvard University.

JUAN RUIZ PARAMO/GETTY IMAGES

Replicating nature's strongest material

Material inspired by limpet teeth could be a stronger and more sustainable alternative to Kevlar in bulletproof vests.

By Fanni Daniella Szakál

For a long time, spider silk held the top spot as the strongest biological material on the planet, inspiring researchers and startups worldwide to manufacture an artificial version. But not so long ago, spiders were pushed off their silky pedestal by the common limpet, a small marine snail dotting the shores of Western Europe.

When limpets graze on algae, they scrape trails in the rocks with their radula, a tongue-like feature lined with small teeth. The trails hint at the strength of those teeth, but it wasn't until 2015 that science put a number to it, measuring their tensile strength—the most stress a material can bear without breaking—at about five gigapascals, the highest among all natural materials.

The extraordinary mechanical properties of limpet teeth come from their composite structure: a flexible scaffold made of chitin (a common substance found in insects, crustaceans, and other organisms), reinforced with nanocrystals of a form of iron oxide called goethite.

Exploiting the strength of such a material could offer solutions to some engineering challenges. "There are a lot of applications of technology that are limited by the strength and toughness of materials," says Nicola Pugno, a researcher at the University of Trento in Italy, who was involved in the 2015 study.

Weaker and more fragile materials limit the lifetime of objects, and they can also prevent us from building new things for more extreme applications "because at a given point, we'll reach the failure of the material," says Pugno.

While the appeal of replicating a particularly strong natural material is clear, figuring out how to do it is less so. "First you have to re-create these very fine structures in the lab, and then you have to find ways of production that are close to industrial manufacturing," explains Zunfeng Liu, a researcher working on artificial spider silk at Nankai University in Tianjin, China.

In 2022, researchers at the University of Portsmouth in the UK created the first artificial limpet teeth using a curious approach: they manufactured a chitin scaffold via electrospinning, a method of producing small fibers from a solution using electricity, and then used cell cultures derived from the limpet radula to add the iron oxide crystals. "I'll be honest—I did not expect this to work as well as it has, because it's just so out there," says Robin Rumney, lead author of the study.

Rumney and his colleagues are currently working on refining and scaling up production of the artificial limpet teeth with hopes of building body armor. If they succeed, limpet-inspired armor could be a stronger and more sustainable alternative to present-day bulletproof vests made of Kevlar, a material that requires a toxic manufacturing process and is difficult to recycle. Rumney also hopes to one day produce sustainable plastic substitutes, making use of the tons of chitin the fishing industry discards as waste.

For now, Rumney is just excited to analyze a recent gift from the British Antarctic Survey: a box of a different species of limpets from Antarctica with golden-colored, metallic teeth. Normally, generating metal compounds in the lab requires extreme temperatures. That these limpets are able to do it below 2 °C is remarkable. "If we could adapt this technology of taking metal out of seawater," Rumney says, "on the one hand we could get access to useful metals, and on the other hand to clean water." ■

Fanni Daniella Szakál is a marine biologist turned science journalist based in Europe.

A race for autopilot dominance is giving China the edge in autonomous driving

Electric-vehicle makers and AI companies are taking Tesla-like self-driving features to China, but they're still out of reach for most consumers.

By Zeyi Yang

Toward the end of a nearly 15-minute video filmed in the southern Chinese city of Guangzhou, William Sundin, creator of the ChinaDriven channel on YouTube, gets off the highway and starts driving. Or rather, he allows himself to be driven. For while he's still in the driver's seat, it's the car now steering, stopping, and changing speed—successfully navigating the busy city streets all by itself.

"It's a NOA [navigate on autopilot] function but for the urban environment," he explains to the people watching him test-drive the XPeng G6, a Chinese electric-vehicle model. "Obviously this is much more difficult than simple highway NOA, with lots of different junctions and traffic lights and mopeds and pedestrians and cars chopping and cutting lanes—there's a lot more for the system to have to deal with."

His final assessment? The navigation system isn't perfect, but it's pretty "impressive" and a preview of more advancements to come.

Beyond a simple product review, Sundin's video is giving his followers a close-up view into a production race that has sped up among Chinese car companies over the past year. And whether they are electric-vehicle makers or self-driving startups, they all seem fixated on one goal in particular: launching their own autonomous navigation services in more and more Chinese cities as quickly as possible.

In just the past six months, nearly a dozen Chinese car companies have announced ambitious plans to roll out their NOA products to multiple cities across the country. While some of the services remain inaccessible to the public for now, Sundin tells MIT Technology Review, "the watershed could be next year."

Similar to the so-called FSD (for "full self-driving") features that Tesla is beta-testing in North America, NOA systems are an increasingly capable version of driver-assistance systems, able to autonomously stop, steer, and change lanes in complicated urban traffic. This is different from fully autonomous driving, since human drivers are still required to hold the steering wheel and be ready to take over. Car companies now offer NOA as a premium software upgrade to owners willing to pay for the experience, and who can afford the models that have the necessary sensors.

A year ago, the NOA systems in China were still limited to highways and couldn't function in urban settings, even though most Chinese people live in densely populated urban areas. As Sundin notes, it's incredibly challenging for NOA systems to work well in such environments, given the lack of separation between foot traffic and vehicles, as well as each city's distinctive layout. A system that has learned the tricks of driving in Beijing, for instance, may not perform well in Shanghai.

NOA systems are an increasingly capable version of driver-assistance systems, able to autonomously stop, steer, and change lanes in complicated urban traffic.

As a result, Chinese companies are racing to produce more city-unique navigation systems before gradually expanding into the rest of the country. Leading companies including XPeng, Li Auto, and Huawei have announced aggressive plans to roll out these NOA services to dozens or even hundreds more cities in the near future—in turn pushing one another to move faster and faster. Some have even decided to release NOA without extra costs for the owner.

"They are launching it quickly in order to create awareness, to try to build credibility and trust among the Chinese consumers—but also, it's FOMO [fear of missing out]," says Tu Le, managing director of Sino Auto Insights, a business consulting firm that specializes in transportation. Once a few companies have announced their city navigation features, Tu adds, "everyone else needs to follow suit, or their products are at a disadvantage in the Chinese market."

At the same time, this fierce competition is having unintended side effects—confusing some customers and arguably putting other drivers at risk. And

underneath the automakers' ubiquitous marketing campaigns, many of these features simply remain hard to access for those who don't live in the pilot cities or own the high-end models.

It's also not full self-driving—at least not yet.

The autonomous driving industry divides its technological advancements into six levels, from 0, where humans control the entire driving process, to 5, where no human intervention is needed at all.

Beyond 0, there are really only two levels in use today. One is the type of system in robotaxis, led by companies like Cruise, Waymo, and the Chinese giant Baidu, which offer level 4 technology to passengers but are often limited to certain geographical boundaries. The other level is the NOA system, exemplified by Tesla's FSD or XPeng's XNGP. They are only level 2, meaning human drivers still need to monitor most tasks, but the technology is much more accessible and is now available in auto vehicles sold around the world.

There's no standard for how safe the tech needs to be before it is sold to consumers.

It's easy to believe that commercially available vehicles are closer to fully autonomous than they actually are, because Chinese car companies have given their NOA products all kinds of misleading or meaningless names. Li Auto, for example, follows Tesla's tradition and calls it NOA, while NIO calls it NOP (Navigate on Pilot) and NAD (NIO Assisted and Intelligent Driving). Huawei calls it NCA (Navigation Cruise Assist) and Baidu calls it Apollo City Driving Max.

Confused yet?

Apart from just being hard to remember, the different names also mean a lack of consistent standards. There's no guarantee that these companies are promising the same things with their similar-sounding products. Some might cover only the major beltways in a city, while others go into smaller streets; some use lidar (a laser-based sensor) to help improve accuracy, while others only use cameras. And there's no standard for how safe the tech needs to be before it is sold to consumers.

"Many such concepts are invented by Chinese companies themselves with no reference or background," says Zhang Xiang, an auto-industry analyst and visiting professor at Huanghe Science and Technology College. "What are the standards for achieving NOA? How many qualifications are there? No one can explain." ■

Zeyi Yang covers technologies in China and East Asia for MIT Technology Review.

STEPHANIE ARNETT

A library in India for everyone

The Servants of Knowledge collection on the Internet Archive is digitizing rare documents—and expanding access to them.

By Ananya

On a bright sunny day in August, in a second-floor room at the Gandhi Bhavan Museum in Bengaluru, workers sit in front of five giant tabletop scanners, lining up books and flipping pages with foot pedals. The museum building houses the largest reference library for Gandhian philosophy in the state of Karnataka, and over the next year, the large assortment of books—including the collected works of Mahatma Gandhi, a translation of his autobiography, *Experiments with Truth,* into the Kannada language, and other rare items—will be digitized and their metadata recorded before they join the Servants of Knowledge (SoK) collection on the Internet Archive.

This digitization push is just the latest for the SoK, which was established about four years ago with a volunteer effort to preserve hard-to-find resources. It has since expanded to include partnerships with various libraries and archives throughout India.

Today, the SoK collection is a searchable library of books, speeches, magazines, newspapers, palm leaf manuscripts, audio, and film from and about India in over 15 languages. The collection is a truly open digital library containing public-domain and out-of-copyright works on science, literature, law, politics, history, religion, music, and folklore, among many other topics. All content is open access, searchable, downloadable, and accessible to visually challenged people using text-to-speech tools. Volunteers and staff continue to expand the collection, scanning about 1.4 million pages per month in various locations across Bengaluru, and more collaborations are in the works.

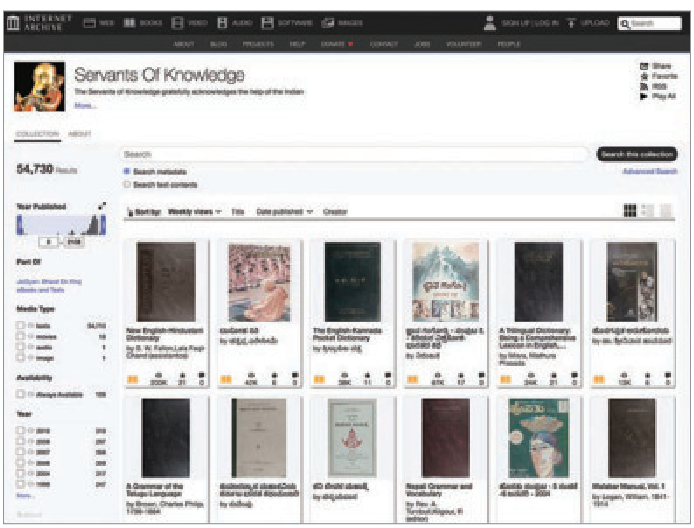
The collection is an effort to make up for the scarcity of library resources in India. There are about 50,000 public-funded libraries in this country of over 1.4 billion people, according to the Raja Rammohun Roy Library Foundation, a group established by the Indian government to promote the public-library movement there. Village and tribal libraries may contain just a few thousand books, compared with a median 77,000 books in each state's central library and 24,000 in every district library, according to a 2018 report by the foundation. Some libraries have lost their collections to fire. A number of books have been ruined by neglect. Others have gone missing.

Moreover, most public libraries aren't freely accessible to the public. "Getting access to many of our public libraries is so difficult, and after a point people will give up asking for access. That's the case in many of our public-funded educational institutes too," says Arul George Scaria, an associate professor at the National Law School of India University Bengaluru, who studies intellectual-property law. One of the best ways to liberate access to these libraries, he says, is through digitization.

Technologist Omshivaprakash H L felt the acute lack of such resources when he needed references for writing Wikipedia articles in Kannada, a southwestern Indian language. Around 2019, he heard that Carl Malamud, who runs Public Resource, a registered US charity, was already archiving books like Gandhi's Hind Swaraj collection on Indian self-rule and works of the Indian government in the public domain. "I also knew that he used to buy a lot of these books from secondhand bookstores and take them to the US to get them digitized," says Omshivaprakash.

Public Resource had been working with the Indian Academy of Sciences, Bengaluru, to digitize its books using a scanner provided by the Internet Archive, but the efforts had tapered off. Omshivaprakash proposed engaging community members to help. During the weekends, these volunteers began scanning some of the books Omshivaprakash had and that Malamud had bought. "Carl really understood the idea of community collaboration, the idea of local language technology that we needed, and the kind of impact we were creating," Omshivaprakash says.

The scanners use a V-shaped cradle to hold the books and two DSLR cameras to capture the pages in high resolution. The device is based on the Internet Archive's scanner but was reengineered by Omshivaprakash and manufactured



The Servants of Knowledge digital collection aims to make up for the scarcity of library resources in India.

in India at a lower cost. Each worker can scan about 800 pages an hour.

The more crucial parts of the operation happen after the scan: volunteers make sure to apply accurate metadata to make the scans findable on the Internet Archive, and optical character recognition, which has been fine-tuned to work better for a range of Indian language scripts, makes the text searchable and accessible through text-to-speech programs.

Public Resource funds the SoK project, and Omshivaprakash manages the operation, with the help of staff and volunteers. Collaborators have come through social media and word of mouth. For instance, a community member and Kannada teacher named Chaya Acharya approached Omshivaprakash with newspaper clippings of work by her grandfather, the renowned journalist and writer Pavem Acharya, who wrote articles on science and social issues as well as satirical essays. Unexpectedly, she found more articles by her grandfather in the existing Servants of Knowledge collection. "Simply by searching his name, I got many more articles from the archive," she says. She began collecting copies of Kasturi, a prominent Kannada monthly magazine that Pavem Acharya had edited from 1952 to early 1975, and gave them to Omshivaprakash for digitizing. The old issues of the magazine contain rare writings and translations by popular Kannada authors, such as *Indirabai* by Gulavadi Venkata Rao, regarded as the first modern novel in Kannada, and a Kannada translation of Edgar Allan Poe's famous short story "The Gold-Bug."

This is all part of a vision of a public library on the internet as "a bottom-up, grassroots thing," Malamud says. "It's a bunch of people teaching each other. We just want to keep scanning and making [these materials] available to people. It's not a grand goal or single aim.

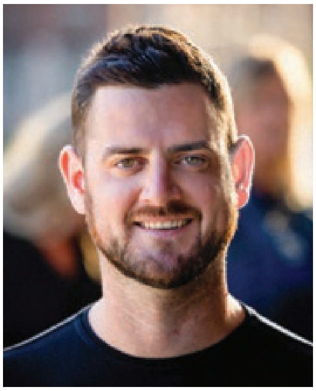
"It's what we do for a living," he says. "We have done it for years, and we are gonna keep doing it for years." ■

Ananya is a freelance science and technology journalist based in Bengaluru, India.

Job title of the future: Carbon accountant

More companies are hiring specialists to help them understand their climate impacts.

By Allison Arieff



COURTESY PHOTO

His official title is vice president of regulated reporting solutions. But really, Billy Scherba is a carbon accountant. At Personifi, a platform for climate management, Scherba works with companies to measure, manage, and disclose their contributions to climate change.

Carbon accountants help companies understand what data matters to their carbon footprint, how to collect that data in a consistent manner, and how to use it to calculate the greenhouse-gas emissions they're responsible for. Many times, that means working with clients to upgrade their data infrastructure so it's easier to see what parts of their operations emit the most.

A growing field

A relatively new occupation, carbon accounting involves collecting a wide variety of data from an organization and using consistent measurement techniques to translate that data into a carbon emissions footprint. The calculations can be based on specific organizational activities such as business flights, kilowatt-hours from a utility bill, the kinds of fuel used to transport products, or even financial data. As organizations collect and analyze more granular data, their calculations get more precise.

Notes on methodology

The Greenhouse Gas Protocol (GHGP), developed by the World Resources Institute and the World Business Council for Sustainable Development, is the primary methodology used for carbon accounting and is available publicly at no cost. Other, specialized carbon accounting standards do exist, but regulators from the US Securities and Exchange Commission, the European Union, Japan, and others have incorporated the GHGP into their rulings, making it the go-to accounting method for organizations publicly disclosing their carbon emissions.

Measure. Report. Decarbonize.

Business leaders need data they can understand that highlights where their firms are having the most significant positive and negative climate impact. "Good data should be used to drive business and societal value," says Scherba. "As we build controls and ensure this data is reliable, we have an opportunity to use it to make better climate decisions." ■

Are the captcha wars almost over?

Proving you're human on websites is harder than ever—but alternative tests are gaining ground.

By Shubham Agarwal

Earlier this year, HBO Max users hoping to sign in to the service had to pass an audio challenge in which they listened to a bunch of tunes and had to select the one with a repeating pattern. When I signed in to LinkedIn recently, it asked me to prove I'm human with an unusual puzzle. With a set of left and right buttons, I had to turn a 3D image of a pink dog until it faced the direction that a hand next to it was pointing.

Websites use these captchas (the name comes from "Completely Automated Public Turing test to tell Computers and Humans Apart") to tell whether a user is human or machine. You've likely noticed they have only gotten more difficult and more involved. That's because of what happens after we solve a captcha: the data from our efforts to label those blurry grids of traffic lights, text, or buses is used to train AI systems, which then get better at defeating captchas, tricking systems into thinking they are human.

The arms race between humans and machines has been progressing for a while. As early as 2016, researchers at the University of Illinois showed they could solve Google's image captchas with 70% accuracy using off-the-shelf automated image recognition tools, the sort that could readily be used by bot designers.

By now, some captchas have gotten a little surreal. A company called hCaptcha recently tasked people with identifying an object that doesn't exist—a "Yoko," which seems to be an AI-generated yo-yo with a roughly snail-like appearance.

Tech firms and consumers alike feel it's time for a change. For one thing, legacy captchas (which are still in use) just don't work anymore: "Clicking images such as buses and street signs is outdated," Ashish Jain, the CTO of Arkose Labs, the firm behind those LinkedIn and HBO captchas, told MIT Technology Review. "Bots have evolved, but legacy captchas haven't." Even more convoluted mini-games may not be enough to keep AI at bay. In one instance, a chatbot (guided by humans) pretended to be visually impaired and managed to hire a human to solve a captcha for it.

Mauro Migliardi, a professor of software engineering at the University of Padua, believes captcha designers will have to go a step further in order to stay ahead of machines. Because AIs can be trained to tackle any cognitive task, he says, we may need to transition to physical challenges, like requiring users to rotate their phones or move them in a certain way as they would in a video game.

That might solve some problems, but it would create others. The more complicated the challenge, the more cumbersome it is to do what you want to do on the web. And some approaches might shut some users out. "It's actually really hard to build a challenge like this that is friendly to the whole human population," Jess Leroy, senior director of product management at Google Cloud, wrote in an e-mail. "There are many reasons why something that may be obvious or easy to one person may be difficult to another." Those include disabilities and cultural differences.

In the long term, we may see captchas abandoned altogether. Companies such as Google and Cloudflare have already quietly switched to "invisible" challenges, which monitor online fingerprints of human behavior, like cursor motions or browsing behavior, to differentiate a person from a bot. If these sorts of signals convince the software you are human, you won't have to solve a captcha.

This approach raises privacy concerns: such signals can allow advertisers and websites to track what you are doing online. An alternative could come from a coalition of companies, including Google, Fastly, Cloudflare, and Apple, that has developed a more privacy-friendly mechanism called Privacy Pass. Before we even open a browser and run into a captcha challenge, we perform numerous actions on our phones and computers—like unlocking them with our faces—that are hard for a bot to imitate. On a Privacy Pass–enabled website, our devices take all that information and attest for us—allowing us to skip the captcha altogether. This data never leaves your device and isn't shared with the website. Apple calls these signatures Private Access Tokens (PATs) and already leaves the feature on by default on iPhones running at least iOS 16.

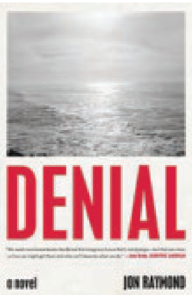
> Captchas have gotten more complex out of necessity. Because as AI gets more sophisticated, they've become less effective.

Most captcha providers, like hCaptcha and Cloudflare, now support PATs as well. Cloudflare's CTO, John Graham-Cumming, said in July that more than half of requests from iOS devices used PATs. Leroy says that Google's Chrome and Android teams are "working on similar technologies."

But don't expect captchas to disappear anytime soon. While Privacy Pass may prove a reliable alternative, captchas remain popular. Ting Wang, an information science and technology professor at Penn State University, predicts they will "continue to exist as a cheap, platform-agnostic, and universal verification solution." ■

Shubham Agarwal is a freelance tech journalist.

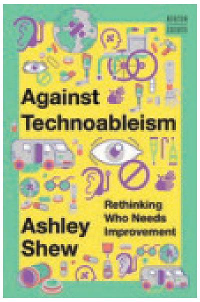
Book reviews



Denial

By Jon Raymond (Simon & Schuster, 2023)

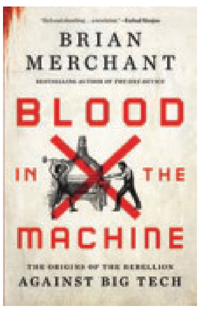
It's 2052. A global protest movement helped break the planet's fossil-fuel dependency, and some—though not all—of those responsible for it have been held accountable. As the world slowly recovers from an era of relentless climate disasters, Jack, a journalist, is given a tip about the whereabouts of one of the oil barons who'd managed to slip away. A short, strange, and unsettling exploration of climate, crime, and punishment.



Against Technoableism: Rethinking Who Needs Improvement

By Ashley Shew (Norton, 2023)

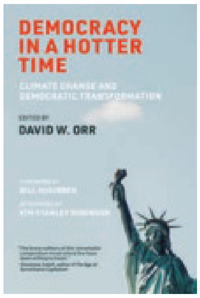
This is a book, writes Shew, "about the stories that disabled people tell that non-disabled people usually aren't interested in." A professor of science, technology, and society who also happens to be disabled, Shew argues against the feel-good narratives that serve to make "normal" people feel okay. We should be seeing disabilities not as liabilities, she writes, but as skill sets enabling us all to navigate a challenging world.



Blood in the Machine: The Origins of the Rebellion Against Big Tech

By Brian Merchant (Little, Brown, 2023)

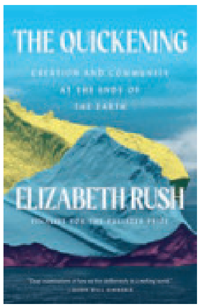
Imagine "millions of ordinary people plagued by a fear that technology is accelerating out of control," writes Merchant, an LA Times technology columnist. "They worry that machines are coming to take away their jobs, erode their status, threaten their futures, and upend the order of their lives." Does this describe 2023? Well, yes, but also 200 years ago during the Industrial Revolution, when the Luddites revolted as technology was used to replace human jobs en masse for the first time. Merchant draws parallels between then and now, arguing that today it's not robots coming for our jobs—it's CEOs.



Democracy in a Hotter Time: Climate Change and Democratic Transformation

Edited by David Orr (MIT Press, 2023)

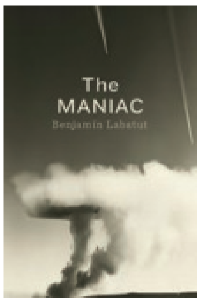
We need to prepare for life in a much hotter world, but it seems increasingly difficult to figure out what exactly to prepare for. These essays search for some answers. "Our only authentic hope," argues Orr, "is in a renewed commitment to repair and fundamentally improve democratic institutions and governments at all levels." No easy feat, but "democracy has always demanded a great deal from citizens." Contributors include Kim Stanley Robinson, Richard Louv, and Anne-Marie Slaughter.



The Quickening: Creation and Community at the Ends of the Earth

By Elizabeth Rush (Milkweed Books, 2023)

Climate change is melting Antarctica's Thwaites Glacier. Should it collapse, it could single-handedly raise global sea levels half a meter or more. In January 2019, Rush joined a 57-person icebreaker mission to catch the first glimpse of the place where the glacier meets the sea. Interweaving the voices of other members of the expedition, she meditates on endings and beginnings, and how we conceive of the future for both ourselves and our children.



The MANIAC

By Benjamin Labatut (Penguin Press, 2023)

John von Neumann is the most central of the three men explored in *The MANIAC* (the word is an acronym for "Mathematical Analyzer Numerical Integrator and Automatic Computer Model" but also, as the author suggests, an apt descriptor of the Hungarian-Jewish prodigy and polymath). Semi-fictional recollections from von Neumann's friends, colleagues, and rivals paint a portrait of this enigmatic man, whose work was foundational to AI and to modern computing. He was relentless in his quest to explain the world yet also destroyed by his inability to do so. ■

COURTESY OF THE PUBLISHERS

Cultivated meat is coming to the US. Whether it'll clean up emissions from food is complicated.

By Casey Crownhart
Illustration by Julia DuFossé

Here's what we know about lab-grown meat and climate change

One of the major drivers for businesses focusing on cultivated (also called lab-grown, or cultured) meat is its potential for cleaning up the climate impact of our current food system. Greenhouse-gas emissions from cows and other livestock account for nearly 15% of the global total, a fraction that's expected to increase in the future.

But whether cultivated meat is better for the environment is still not entirely clear, because there are still many unknowns around how production will work at commercial scales. Many of the startups are just now working out plans for bigger facilities to make food that real, paying customers will finally get to eat.

Exactly how this shift happens will not only determine whether these new food options will be cheap enough to make it into people's carts. It may also decide whether cultivated meat can ever deliver on its big climate promises.

Moo-ve over, cows

Raising livestock, especially beef, is infamously emissions-intensive, both because feeding animals requires a lot of land and energy and because some animals, like cows and sheep, produce methane during digestion.

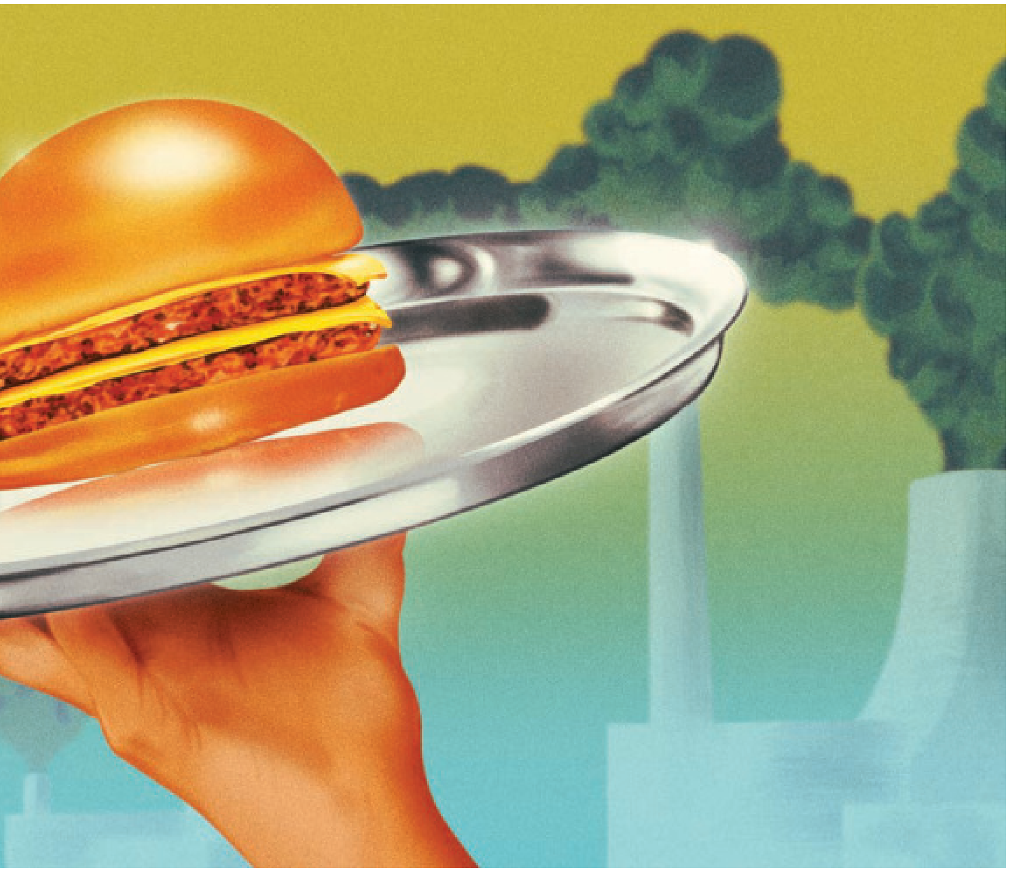
At a cellular level, cultivated meat is made from the same ingredients as the meat we eat today: animal cells. But instead of raising animals for slaughter, scientists can grow cells in a reactor.

Producing cultivated meat will still generate emissions, since energy is required to run the reactors that house the cells as they grow. Renewable electricity could help the climate case for cultivated meat, but even then the supplies and facilities needed would still come with associated emissions.

Research and early commercial efforts to produce meat in labs have relied on materials and techniques borrowed from the biopharmaceutical industry, where companies grow cells in order to produce drugs. It's a tightly regulated process involving high-purity ingredients, expensive reactors, and a whole lot of energy, says Edward Spang, a food science researcher at the University of California, Davis.

Spang and his team set out to estimate the climate impacts of cultivated meat assuming current production techniques. In a preprint study that hasn't yet been peer-reviewed, Spang estimated the total global-warming potential of cultivated meat in two different scenarios.

In one scenario, the researchers assumed that cultivated-meat production would use ingredients similar to what's used in the food industry today. In this case, cultivated meat's emissions would be lower than the global average emissions from beef and in line with production in some countries today.



In another scenario, the researchers assumed that cultivated meat would be produced with processes and materials similar to those used in the biopharmaceutical industry—specifically including an energy-intensive purification step to remove contaminants. In that case, cultivated meat would produce even more emissions than beef production does today.

Where's the beef?

Spang's preprint drew quick criticism from some in the industry; experts particularly took issue with the assumption that materials used in producing cultivated meat would need to use pharmaceutical-grade ingredients and go through intense purification steps to remove contaminants.

The study's results do differ from those of many previous analyses in the field, which have generally assumed that cultivated meat will scale up to commercial facilities and use more widely available, food-grade ingredients. As a result, researchers have largely found that cultivated meat would reduce emissions compared with conventional beef production.

"I'm not sure we should worry that much that [cultivated meat] will add an enormous burden to the climate globally," says Pelle Sinke, a researcher at CE Delft, an independent research firm and consultancy focusing on energy and the environment.

In an analysis published in January 2023, Sinke and his team set out to estimate emissions associated with cultivated meat in 2030, assuming that the production process can use food-grade ingredients and will reach commercial scale. That study found that cultivated meat would have a significantly lower climate impact than current beef production.

Cultivated meat could eventually have major climate benefits, says Hanna Tuomisto, a sustainability researcher at the University of Helsinki and author of several analyses of cultivated meat's climate impact. However, she adds, the industry's emissions are yet to be determined. "There are many, many open questions still, because not very many companies have built anything at larger scale," Tuomisto says.

Till the cows come home

Scaling up to make cultivated meat in larger production facilities is an ongoing process, and there are already "plenty of reasons to be hopeful" about the climate impacts of cultivated meat, says Andrew Noyes, vice president of communications at Eat Just, a company that produces both lab-grown and plant-based protein alternatives. "However, achieving those goals is dependent on several factors tied to the optimization and scale-up of our production process, as well as the design of future large-scale manufacturing facilities."

Ultimately, energy-intensive methods aren't just unsustainable for the planet: they'd also be prohibitively expensive, says Sinke, the researcher with CE Delft.

But for Spang and some other researchers, there are still questions about the future of cultivated meat. "The leap from lab-scale science to cost-effective climate impact—there's a substantial amount of distance there, in my opinion," Spang says.

It's still possible for cultivated meat to become a major positive for the climate. An industry where cells can be grown efficiently in massive reactors while being fed widely available ingredients, in a process all powered by renewable electricity, could be a significant way to help clean up our food system.

But the facilities that would make that possible are mostly still in the planning phases—and it's not yet clear which path cultivated meat might take to reach our plates. ■

Casey Crownhart is a climate reporter at MIT Technology Review.

Making sense of nature's complexity

Applied mathematician Gábor Domokos describes patterns and shapes in useful ways.

By Elise Cutts
Portrait by Akos Stiller

It takes Gábor Domokos about an hour to pick his way up into the hills that rise over Budapest. He stops along the way to look for lizards and rescue a beetle that had gotten stuck on its back. If he were to keep going, he'd soon reach a tower with a panoramic view of the Danube and its course through the city. But he stops where the dirt path cuts across a patch of exposed grayish-tan rock crisscrossed with cracks and strewn with stone fragments.

"Look at this—look at this mosaic!" Domokos sits down on the ground and picks at cracks in the rock, feeling for loose pieces. "This was what first captured my attention. It's such an absolute beauty."

To Domokos, 61, a professor at the Budapest University of Technology and Economics, this ordinary rocky outcrop is a wellspring of mathematical questions.

Inspired by rock cracks, Domokos devised a new framework for classifying polygonal tessellation that's flexible enough to accommodate messy natural patterns, but rigorous enough to be useful. Applied in geology, it reveals universal patterns in the geometry of fractures at every scale from mud cracks to the tectonic jigsaw, and it's now helping NASA scientists understand the surfaces of other worlds. His work on the geometry of pebbles has helped trace erosion on Earth and Mars. In the hands of MIT researchers, Domokos's work on the balancing points of 3D forms inspired the design of a self-orienting pill capsule for delivering vaccines to the stomach. And most recently, Domokos teamed up with chemists to use his rock fracture geometry to predict how molecules assemble into "2D" sheets—a notoriously stubborn problem usually left to supercomputers.

"Gábor's problems are somehow topological, somehow geometric, somehow mechanics, partial differential equations. Some [are] crazy," says Sándor Bozóki, a mathematician at the Institute for Computer Science and Control in Budapest, who has published with Domokos. "He's not a leading figure in any of these fields," says applied mathematician Alain Goriely of Oxford University. But, he adds, like the best applied mathematicians, "he is using them in the most clever and beautiful way."

Best known for co-discovering the gömböc—the first convex 3D shape with just two balancing points—Domokos aims to understand the physical world by describing its forms in the simplest possible geometry.

He often begins new projects by concocting original ways to classify shapes. To prove that the gömböc existed before they found it, he and Péter Várkonyi introduced mathematically precise definitions of flatness and thinness. To categorize pebbles, Domokos counts their number of stable and unstable balancing points. And to describe tessellating patterns in rock cracks or nanomaterials, he calculates just two numbers: the average number of "tiles" meeting at each vertex in the "mosaic" and the average number of vertices per tile.

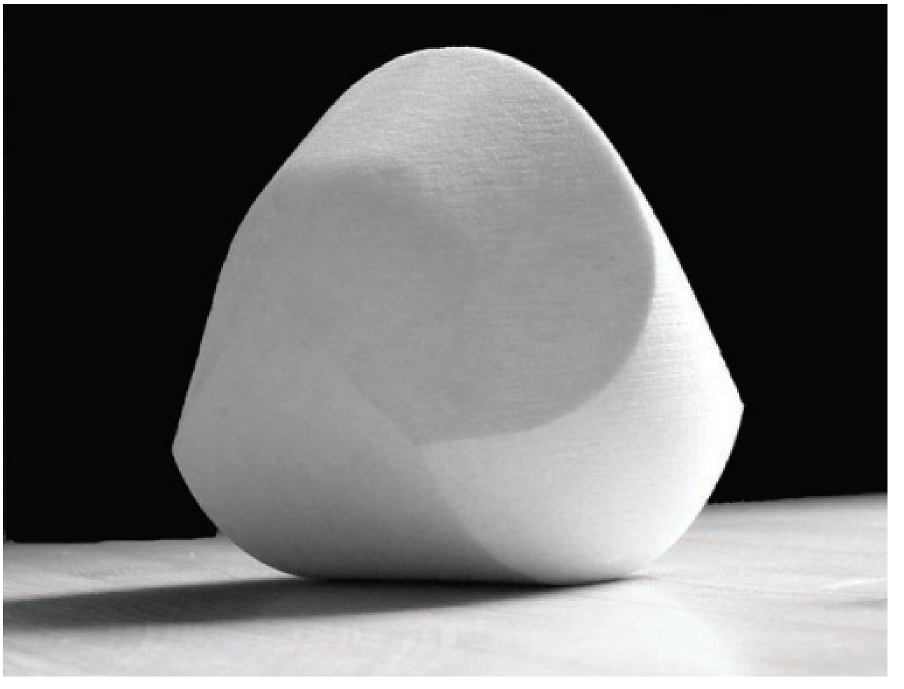
The point is to find "a new language" to describe the shapes, says mathematician Krisztina Regős, one of Domokos's graduate students. "The first thing that people do when they understand something: give it a name," Domokos says. "And shapes don't have names."

But with the right language, it's possible to start asking questions: Do homogenous 3D shapes with just two balancing points exist? Yes. These shapes minimize flatness and thinness, and one is the gömböc—which, thanks to its geometry, always rights itself no matter how it is set down. What happens to pebbles as they erode? They lose balancing points, getting rounder and then flatter over time. What does the Earth break into when it falls apart? Plato was right: on average, it breaks into cubes.

Of course, fields like geomorphology already have schemes for classifying objects of study—there are several ways of cataloguing pebbles, for instance, says Mikaël Attal, a geomorphologist at the University of Edinburgh. But as a perpetual outsider, Domokos either doesn't know or doesn't care about upsetting convention. Even within mathematics, he doesn't fit into a discipline.

The "dark secret," says Domokos, is that he's really an architect—his research group even sits in the same architecture department where he studied in the 1980s. As a mathematician and scientist, Domokos is largely self-taught. He credits much of what he knows to the secondhand German texts he bought at a little shop near the university during his student days. A worn first edition of the German mathematician Carl Friedrich Gauss's *Werke* still stands alongside pebbles and other significant knickknacks on the shelves of his home office. By the time Domokos earned his doctorate in 1989, the year communism ended in Hungary, he'd morphed into an applied mathematician.

András Sipos, a professor in Domokos's department, sees this unusual background



Domokos is best known for co-discovering the gömböc—a convex 3D shape with just two balancing points.

PUBLIC DOMAIN VIA WIKIMEDIA COMMONS

as one reason for Domokos's originality. "He is not stuck to the symbols and the language of one field," he says.

By describing shapes to understand the forces that sculpt them, Domokos and his colleagues are asking what Marjorie Senechal, a mathematician and historian of science at Smith College, calls "growth and form" questions—a reference to D'Arcy Thompson's 1917 book *On Growth and Form,* a foundational text of mathematical biology.

"They've taken up the question again of the relation between growth and form, or local development, local patterns, and global patterns," says Senechal, who is an honorary member of Domokos's department. The tension between local and global, tile and mosaic, appears in "all great problems," she adds, "whether it's biology, or whether it's physics, or whether it's philosophy."

Domokos is more apt to describe the problems he works on as simple, not great. Indeed, it's easy to underestimate the significance of his work while talking with him. Though his vivid, rambling anecdotes often include run-ins with Fields medalists or Nobel laureates, they never come across as haughty. And he's quick to play down his own accomplishments. He was the youngest person to join the Hungarian Academy of Sciences when he was elected in 2004 at the age of 43, and he was a visiting fellow at Cambridge's Trinity College. But he's reluctant to say he's been successful. "If you take out the gömböc," he says, "then I am not visible as a scientist."

Talk to others, and the picture is clearer. In geomorphology, Domokos's work on pebbles and fractures "is a major contribution," says Attal, whose own research focuses on the evolution of hillslopes and rivers. Senechal notes that he "may be humble," but he "is using very contemporary mathematics" to describe nature. Bozóki calls him "too modest" and says he's well respected in Hungarian academic circles. When Bozóki travels to foreign conferences and says he's Hungarian, he adds, he's often asked whether he knows Domokos.

"The first thing that people do when they understand something: give it a name," Domokos says. "And shapes don't have names."

Still, there is truth to the idea that Domokos chases simple problems. In mathematics, "it's very easy to ask very hard questions," says Bozóki. One of Domokos's gifts seems to be an intuitive sense of which questions don't just look simple, but really are.

When his curiosity leads him to some exciting new problem, says Sipos, Domokos usually devises some "toy" version first and works up from there, testing the border between the known and the unknown.

"He told me that doing science means that you are addressing the question along this border," says Sipos, who is also Domokos's former graduate student. "And this is difficult to find."

This pattern is playing out now in Domokos's work on tessellations. The relatively simple model he developed for rock cracks became a predictive tool for nanotechnology once infused with a few additional layers of mathematical complexity. Now, he and his colleagues are trying to leap from describing form to modeling growth: in recent papers, they introduced crack healing and formation to their geometric framework describing tessellations.

Science should be about proof, says Domokos, but "questions are guiding science. And the questions are certainly not a matter of proof. They are a matter of intuition." And along the hazy borders of the known and unknown, mathematics and science, Domokos has a good eye for cracks—places like his spot in the Buda Hills where, with just a little tug, stone falls away. ■

Based in Austria, Elise Cutts is a freelance science writer covering physics and geoscience.

We must stop producing so much plastic

Think that recycling will solve the problem? Think again.

By DOUGLAS MAIN
Illustrations by Michael Byers

On

a Saturday last summer, I kayaked up a Connecticut river from the coast, buoyed by the rising tide, to pick up trash with a group of locals. Blue herons and white egrets hunted in the shallows. Ospreys soared overhead hauling freshly caught fish. The wind combed the water into fields of ripples, refracting the afternoon sun into a million diamonds. From our distance, the wetlands looked wild and pristine.

Further inland, we left the main river channel and paddled into the muddy heart of the marsh—and began to notice all manner of plastic waste. Big things appeared first: empty bags of chips tangled in the reeds, grocery bags just beneath the surface, Styrofoam trays covered in mud, plastic bottles mixed in with other debris.

As we traveled through the marsh, we kept seeing more, and increasingly tiny, bits of plastic. Not just straws, lighters, combs, and fishing line, but unidentifiable and seemingly never-ending small pieces, ranging in size from as big as my hand to as small as grains of sand. You could stay in the hinterlands plucking trash and never leave. Even in one of the less-polluted parts of the East Coast, outside a city with organized waste management and a recycling system, the land and water are awash in plastic waste.

Plastic, and the profusion of waste it creates, can hide in plain sight, a ubiquitous part of our lives we rarely question. But a closer examination of the situation can be shocking.

Indeed, the scale of the problem is hard to internalize. To date, humans have created around 11 billion metric tons of plastic. This amount surpasses the biomass of all animals, both terrestrial and marine, according to a 2020 study published in Nature.

Currently, about 430 million tons of plastic is produced *yearly*, according to the United Nations Environment Programme (UNEP)—significantly more than the weight of all human beings combined. One-third of this total takes the form of single-use plastics, which humans interact with for seconds or minutes before discarding.

A total of 95% of the plastic used in packaging is disposed of after one use, a loss to the economy of up to $120 billion annually, concludes a report by McKinsey. (Just over a quarter of all plastics are used for packaging.) One-third of this packaging is not collected, becoming pollution that generates "significant economic costs by reducing the productivity of vital natural systems such as the ocean." This causes at least $40 billion in damages, the report states, which exceeds the "profit pool" of the packaging industry.

These numbers are understandably hard to make concrete sense of, even at the scale of specific companies, such as Coca-Cola, which produced 3 million tons of plastic packaging in 2017. That's the equivalent of making 200,000 bottles per minute.

Notably, what doesn't get reused or recycled does not chemically degrade but rather becomes a fixture of our world; it breaks apart to form microplastics, pieces smaller than five millimeters in diameter. In the past few years, scientists have found significant quantities of microplastics in the further reaches of the ocean; in snow and rainfall in seemingly pristine places worldwide; in the air we breathe; and in human blood, colons, lungs, veins, breast milk, placentas, and fetuses.

One paper estimated that the average person consumes five grams of plastic every week—mostly from water. About 95% of the tap water in the United States is contaminated. Microplastics are also widely found in beer, salt, shellfish, and other human foods. Significant quantities of these plastic bits have turned up in common fruits and vegetables, as one recent study in Italy found.

All this meant that our journey in the kayaks, picking up plastic waste along the way, looking after our local environment, was—while a genuinely helpful service to our fellow humans—only fixing a symptom of a larger problem.

The solution to that problem lies further upstream: to address plastic pollution, those who produce plastics need to pay for the damage it causes, and the world will also have to make less of it. We'll have to develop better, more recyclable products. We'll also have to find sustainable alternatives and increase what ecologists call circularity—keeping those products in use as long as possible and finding ways to reuse their materials after that.

While these are not exactly new ideas, they've received renewed attention from global policymakers, innovators, and companies looking to make a sustainable future profitable.

"We have to dramatically reduce the amount of plastic that we make. Everything else is second order."

Making less is the most important goal—and the most politically charged one, given the immense profits and political power of plastic producers. "What's the best way to manage waste?" says Jenna Jambeck, an environmental engineer at the University of Georgia. "To not produce it in the first place."

Because consider this: most of the plastic we make, 72%, ends up in landfills or the environment, according to a 2022 report from the Organisation for Economic Co-operation and Development.

About
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And
1/3
of that total takes the form of single-use plastics.

A total of
26%
of all plastics are used for packaging.

And
95%
of that total is disposed of after one use.

SOURCE: UN ENVIRONMENT PROGRAMME; MCKINSEY

Only 9% of the plastic ever produced has been recycled, and 19% has been incinerated. Some of it reaches the sea; estimates suggest that between 8 million and 11 million tons of plastic waste enter the ocean each year. According to the National Academy of Sciences, that's the equivalent of dumping a garbage truck of plastic into the ocean every minute.

"A scourge on a planetary scale"

Plastic production has grown dramatically in recent years; in fact, half of all plastics in existence have been produced in just the last two decades. Production is projected to continue growing, at about 5% annually. If current trends continue, humans will have produced 34 billion tons of plastics by 2050—three times the current total.

Plastic pollution—"a scourge on a planetary scale," as French president Emmanuel Macron has put it—most affects those least able to deal with its consequences. Noting that the plastic industry generates upward of $700 billion a year in revenues, the UN Environment Programme also concluded that the industry "inflicts a heavy burden on human health and environmental degradation, with the poorest in society facing the highest impacts whilst contributing the least to plastic over-consumption and waste."

This is true at every stage of plastic's life cycle. Manufacturing plants are concentrated in communities of color—such as in Louisiana, in an area along the Mississippi River often called "Cancer Alley," which is home to nearly 150 oil refineries, plastics plants, and chemical facilities. Such plants emit air pollution that raises risks of cancer and other diseases. A panel of UN human rights experts said the situation amounts to a "form of environmental racism [that] poses serious and disproportionate threats to the ... human rights of its largely African American residents."

This pollution also disproportionately harms poor and developing countries that produce little or no plastic, such as those in Africa, the Pacific, and elsewhere.

Solutions such as recycling and reuse cannot deal with this much waste, says Marcus Eriksen, a marine scientist and cofounder of the 5 Gyres Institute, which studies plastic pollution. "There have to be drastic cuts in production," he says, especially of single-use plastics.

Dozens of studies and institutional reports—from the likes of the United Nations, the National Academy of Sciences, and the Pew Charitable Trusts—conclude that continued increases in production of virgin plastics will overwhelm actions to combat the problem.

Alarmed by such data, and animated by growing public awareness of the issue, the United Nations Environment Assembly resolved at a March 2022 meeting to begin working toward a global treaty to end plastic pollution, forming an intergovernmental negotiating committee to accomplish this goal. This group has gathered twice and will meet another three times before the treaty is finalized in late 2024. All parties agree that it will be binding and will put forth a range of mandatory and voluntary approaches. Some have likened its importance to that of the Paris accords on climate change.

Few details have yet been ironed out, but the majority of countries agree that a primary way to prevent plastic from polluting the environment is to make less of it.

Neil Tangri, a researcher at the University of California, Berkeley, and a member of an informal advisory group called the Scientists' Coalition for an Effective Plastics Treaty, strongly agrees: "We have to dramatically reduce the amount of plastic that we make. Everything else is second order."

At the second round of talks in Paris this summer, international leaders made this desire clear. Humanity has a duty to begin "[reducing] the production of new plastics," said Macron, "and to ban as soon as possible the most polluting products." Representatives from many other countries, from Ghana to Mauritius to Norway, argued the same.

Yet the countries that have not yet embraced limits on production include the biggest producers, such as China and the United States, though they are participating in the process.

Limits or levies on production are not currently being considered as a solution, according to a member of the US State Department (which coordinates the country's delegation at the UN meetings), who was not authorized to speak publicly on the matter.

"We really need to find a way to bring everybody on board," this person said, and such "supply side" changes might be unpalatable to certain countries. "We want the strongest and most ambitious obligations that we can get consensus around."

The American Chemistry Council, the trade group that represents plastic producers, has also not embraced such policies. Limits or levies could "affect all sectors of the economy" and "create a lot of unintended consequences for those least able to afford it," says Stewart Harris, the group's senior director of global plastics policy.

Inspiration from nature

How can we make less plastic, and deal with the pollution that already exists? Circularity may be the most promising answer. Circularity can mean reusing or recycling plastics, or employing alternatives that can be reused or recycled as well. Proponents often describe the concept as an attempt to imitate the natural world, where there is no waste; everything has a use.

Ghana and several other countries worldwide are currently working to establish a country-level circular economy for plastic, says Oliver Boachie, who chairs the African Group of Negotiators for the UN treaty-making process and is an advisor to the Ghanaian government. This will involve gradually banning single-use plastics that have little reuse value, such as thin plastic films used in food packaging, as well as instituting robust collection, reuse, and recycling efforts.

Many existing waste management techniques have already been shown to reduce plastic pollution and demand for plastic in the first place. But they are energy and time intensive.

In Tanzania, for instance, a group called Nipe Fagio ("give me the broom" in Swahili) runs waste management and recycling systems that have reduced landfill waste by 75% to 80% in neighborhoods in several cities. Waste collectors visit households once a week to gather four different varieties of trash before transporting it to a collection center. There, workers further sort the recyclable materials for sale, turn organic waste into compost and chicken feed, and send the rest to the landfill.

To help fund programs like Nipe Fagio, and to help them grow on a much larger scale, many countries are looking to extended producer responsibility (EPR) plans, policies requiring producers of plastic bottles, packaging, and the like to provide some funding to support management of these materials after their initial use. Just about every country in Europe has an EPR scheme, and Ghana too is working to create a national program.

Currently, however, EPR schemes are limited in their impact, since those that have done the most to embrace and pay for them are bottlers and manufacturers of products like beverages, known as "midstream" producers.

To make a bigger difference, the programs need to bring in the "upstream" producers—those that create virgin plastics and polymers, like Exxon, Dow, Sinopec, and Saudi Aramco. An overwhelming 98% of plastics come from fossil fuels, and plastic production and use accounts for 3.4% of humanity's carbon emissions. Many big plastic producers—such as the world's biggest, ExxonMobil—are highly entangled with Big Oil or representatives of it. "Beyond a physical pollution crisis, it's becoming an energy crisis," says Katrina Knauer, a polymer scientist with the National Renewable Energy Laboratory. "The amount of plastic on our planet—it's like one big oil spill."

Nevertheless, these companies do not currently pay for the consequences of plastic pollution, Boachie says, adding: "We believe that those who are [most] heavily responsible for the proliferation of plastics around the world are the polymer and virgin plastics producers, and they should be responsible for providing funds for countries to manage the plastic waste that they create."

Ghana has introduced a proposal to the UN to extend the "polluter pays" principle to these polymer producers, and Boachie says he believes elements of it will find their way into the final UN agreement. That would "allow us to mobilize a significant amount of resources to provide all countries the means to manage their plastics."

But Ana Lê Rocha, the executive director of Nipe Fagio in Tanzania, argues that waste management is not actually a solution to the pollution crisis but merely a way to deal with a symptom. "We need to remember that the main issue—the main goal of the UN treaty—must be to reduce production," she says.

Obstacles to circularity

Reuse is the most energy-efficient version of circularity. Collecting, cleaning, and refilling glass bottles was once common and widespread, and it remains a small but significant part of the economy in many countries. It's also the norm in many places to buy foods in bulk and transport them in reusable bags.

But one of the biggest obstacles to circularity is a lack of infrastructure, says Ellie Moss, CEO of a company called Perpetual, which is "looking to stand up a whole reuse ecosystem [at] the scale of a small city" to change that. Four cities, to be exact—Galveston, Texas; Hilo, Hawaii; Ann Arbor, Michigan; and Savannah, Georgia. In Galveston, where Perpetual is furthest along, it is working to create a system whereby metal beverage containers can be reused by many restaurants in the city, saving large amounts of plastic and creating new green jobs. It hopes to hire companies that will have the program up and running there by the middle of 2024.

"If we want reuse to work, it has to happen at scale, and the community has to have a voice in how the system is set up," Moss says.

Other companies are also exploring refill and reuse schemes. One Chilean company, Algramo, founded in 2013, allows customers to buy various liquid products such as shampoo, laundry detergent, and soaps in reusable plastic bottles, purchased from a large network of filling stations. The company has the explicit goal of eliminating the "poverty tax," the penalty that lower-income people often have to pay for not being able to buy in bulk; it charges the same unit price for each item regardless of how much volume is sold. Algramo (which means "by the gram" in Spanish) has expanded throughout Chile and is now opening locations in the United Kingdom.

These schemes can be thought of as a type of system redesign, requiring a radical shift in infrastructure *and* behavior. We spent nearly a century "building out an exceptionally complex linear economy for these materials," says Kathryn Beers, a polymer chemist at the National Institute of Standards and Technology, who leads an institute-wide program geared toward

"The amount of plastic on our planet—it's like one big oil spill."

facilitating a circular economy. But we never "built the second half of the system" that would make it circular, she says. "It needs all the complexity and nuance of the front half—and that takes time."

Awareness helps prompt such shifts—viral moments such as the video of a turtle with a straw in its nose that circulated widely in 2017 are credited with greatly increased demand for straw bans or alternatives. But for real change, policies are necessary, including bans as well as fees and taxes. Research shows that all of the above can greatly reduce plastic waste.

Redesigning products to use less plastic and to be more easily reused or recycled is also critical, said Inger Andersen, executive director of UNEP, at the opening of the second meeting. "Is there a good reason that businesses can't look at refillable bottles, reusable packaging, take-back services, and so on? Of course not," she said.

Some manufacturers have already made strides to use less plastic in their products. Such incremental changes help but will still not be enough.

To solve the pollution crisis, many "unnecessary and problematic" plastics—such as polyvinyl chloride, or PVC—will have to be eliminated and replaced with more sustainable alternatives, says Imari Walker-Franklin, a research chemist who published a book with MIT Press on plastics earlier this year. PVC, which is often used to make pipes and other materials, breaks down into toxic chlorine-containing components and cannot be recycled.

One of the most promising replacements is a substance called PHA, or polyhydroxyalkanoate, a type of bio-polyester made by bacterial fermentation of sugars and lipids. "We'd love to see an all-PHA future," NREL's Knauer says, in part because the plastic can degrade into nontoxic components over the course of months.

It's important to note, however, that producing more sustainable plastics is difficult, and most of the so-called "biodegradable" and "compostable" plastics on the market biodegrade only in industrial reactors. Industrial composters, for example, reach temperatures that cannot be achieved in people's yards or homes. Moreover, most of these materials are not actually less toxic than conventional plastics, says Bethanie Almroth, an ecotoxicologist with Sweden's University of Gothenburg.

"Bioplastics are plastics. And they are usually quite harmful," Lê Rocha agrees.

For that reason, it's vital that bio-based plastics don't just become a replacement.

"The best alternative is reusable systems, because replacing a single-use plastic with a single-use bioplastic won't change the problem," says Andrea Lema, an advocate for zero-waste systems in Quito, Ecuador, who's involved in the UN process.

Non-plastic alternatives, such as packaging made from fungi, hemp, and other environmentally friendly materials, may hold the most promise in the long term, but in the short term they are generally not economically viable given how cheap plastic is. That could change with the right set of progressive policies and economic incentives.

How much plastic is actually being recycled?

In the United States, only about 5% to 6% of plastics are being recycled each year—a paltry rate. As with reuse, increasing this rate should decrease the demand for virgin polymers. The biggest problem is a shortage of the costly infrastructure that's required, says Kate Bailey, chief policy officer with the Association of Plastic Recyclers.

The further you get from large cities, the less recycling there is, because rural areas can't afford it, says Knauer: "We need more state and federal incentives to build an infrastructure for collection."

The vast majority of "recycling" involves grinding up plastic, melting it down, and re-forming it. Doing this type of mechanical recycling well involves properly sorting and cleaning materials, which can be time intensive and expensive. It's also very difficult or impossible to recycle many types of plastic more than once without causing the material to acquire defects and contaminants. In fact, many recycled materials commonly contain significant levels of unwanted toxins, Almroth says.

Local policies can make a huge difference in encouraging recycling. In Maine and Oregon, which have invested in recycling programs, up to 80% of bottles made from PET (polyethylene terephthalate) are recycled, Bailey says. In some states, such as in the South, that percentage is in the single digits. The national average for these materials is 30%, which is a shame, Bailey says, because 100% of PET bottles could be recycled.

Some states, though, have instituted policies that actually hinder progress. Industry lobbyists are increasingly helping to institute state-level laws that prevent bans or limits on the use of plastics, especially plastic bags. Over a dozen states currently have preemptive laws on the books to prevent ordinances limiting plastics, though some of the same states are also trying to pass anti-preemption laws.

One way to improve recycling—and prevent unwanted health effects and environmental problems—would be to simplify and standardize the process of plastic production, Walker-Franklin says. Currently, more than 10,000 chemicals are used in the production of plastics, and upward of 3,200 have "one or more hazardous properties of concern," with the potential

Fundamentally, to solve the plastic pollution crisis, society must address the root problem: plastics are shockingly profitable and cheap.

to harm humans and wildlife, according to UNEP. Very little or nothing is known about the health effects or basic properties of thousands more.

Another way to improve recycling would be to find a way to process mixed polymers into useful materials instead of having to sort everything first. One promising technique, described in an October 2020 study coauthored by Julie Rorrer, then a researcher at MIT, can process polypropylene and polyethylene into propane. Another process, described in a study published in Science the same month, can break down mixtures of common consumer plastics and re-form them into a bioplastic, in part by using an engineered soil bacterium.

Others dream of a day when microbes could be used to recycle or clean up all this waste. One French biotechnology company, Carbios, opened a pilot plant in September 2021 to break down and recycle PET using an engineered form of an enzyme first discovered in compost; it's currently building a full-scale facility due to open in 2025. In theory, this type of recycling could be truly circular, as it wouldn't require the high heat that normally causes much of the degradation seen with recycled plastics.

A microbe discovered in Japan in 2016, called *Ideonella sakaiensis*, produces two other enzymes that can break down PET. This microbe is especially intriguing because it is the first one identified that can live solely upon plastic as a food source. MIT researcher Linda Zhong-Johnson is working to create more efficient versions of the enzymes by tinkering with microbial genes. So far, one mutation she has identified creates an enzyme that appears to be up to 30% more efficient than its original wild form.

Reducing demand

Fundamentally, to solve the plastic pollution crisis, society must address the root problem: plastics are shockingly profitable and cheap because polymer producers do not pay for the abundant harm they cause. Any solution will require policy and behavioral changes small and large.

As an example of the former, policymakers in Washington, DC, instituted a five-cent charge on plastic bags that began in 2010. Estimates suggest that the number of bags used quickly dropped—by more than half in the months after it was instituted—and the quantity found in local waterways dropped between 30% and 70% thereafter. Seemingly tiny changes like this can add up to reduce demand and decrease pollution. Meanwhile, a global EPR scheme would be an example of a major shift, and the UN process is seeking other big changes to the status quo.

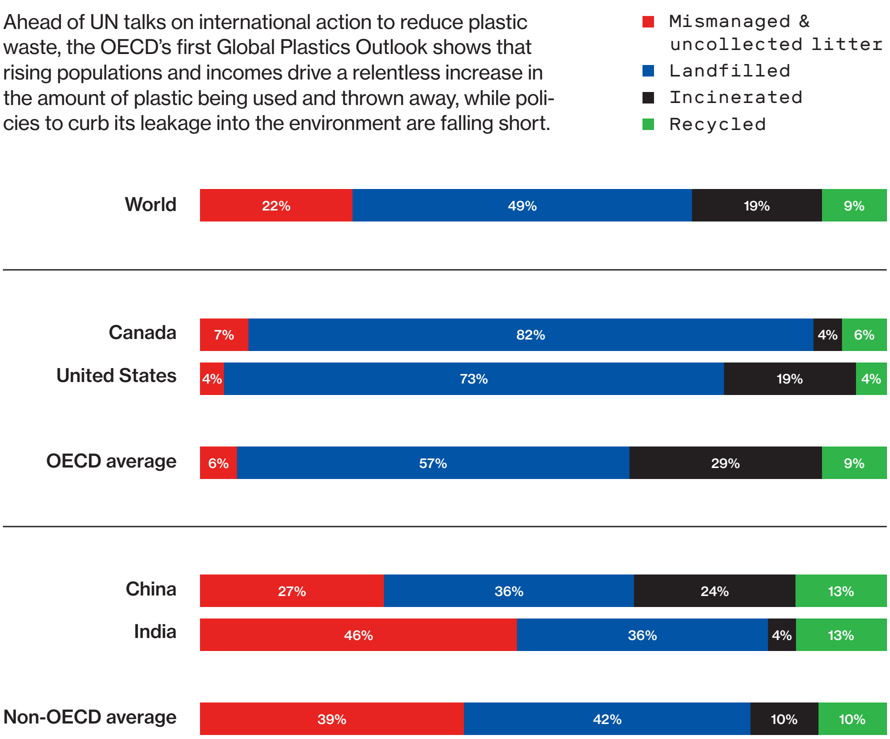
Of course, such changes will be difficult, but they can be instituted in gradual ways that don't hurt businesses, Boachie says: "My hope emanates from the fact that what we are talking about is not something that will impede the growth and success of any company." On the contrary, he adds, creating incentives for alternatives will spur innovation and create new jobs.

A lot of such innovation will doubtless be needed to reverse situations like what I saw in the Connecticut salt marsh. At one point we came upon a couple of osprey nests from which plastic strands billowed, unwittingly collected by the birds as they built their nests. Later, we found a vinyl firehose lodged intractably in the muck between oysters. I couldn't pull it out, nor could I cut into it with a small pocketknife. We reluctantly left it behind. ■

Douglas Main is a journalist and former senior editor and writer at National Geographic.

Share of plastics treated by waste management category, after disposal of recycling residues and collected litter, 2019

Ahead of UN talks on international action to reduce plastic waste, the OECD's first Global Plastics Outlook shows that rising populations and incomes drive a relentless increase in the amount of plastic being used and thrown away, while policies to curb its leakage into the environment are falling short.



SOURCE: OECD GLOBAL PLASTICS OUTLOOK DATABASE

David Chalmers was not expecting the invitation he received in September of last year. As a leading authority on consciousness, Chalmers regularly circles the world delivering talks at universities and academic meetings to rapt audiences of philosophers—the sort of people who might spend hours debating whether the world outside their own heads is real and then go blithely about the rest of their day. This latest request, though, came from a surprising source: the organizers of the Conference on Neural Information Processing Systems (NeurIPS), a yearly gathering of the brightest minds in artificial intelligence.

Less than six months before the conference, an engineer named Blake Lemoine, then at Google, had gone public with his contention that LaMDA, one of the company's AI systems, had achieved consciousness. Lemoine's claims were quickly dismissed in the press, and he was summarily fired, but the genie would not return to the bottle quite so easily—especially after the release of ChatGPT in November 2022. Suddenly it was possible for anyone to carry on a sophisticated conversation with a polite, creative artificial agent.

Chalmers was an eminently sensible choice to speak about AI consciousness. He'd earned his PhD in philosophy at an Indiana University AI lab, where he and his computer scientist colleagues spent their breaks debating whether machines might one day have minds. In his 1996 book, *The Conscious Mind*, he spent an entire chapter arguing that artificial consciousness was possible.

If he had been able to interact with systems like LaMDA and ChatGPT back in the '90s, before anyone knew how such a thing might work, he would have thought there was a good chance they were conscious, Chalmers says. But when he stood before a crowd of NeurIPS attendees in a cavernous New Orleans convention hall, clad in his trademark leather jacket, he offered a different assessment. Yes, large language models—systems that have been trained on enormous corpora of text in order to mimic human writing as accurately as possible—are impressive. But, he said, they lack too many of the potential requisites for consciousness for us to believe that they actually experience the world.

At the breakneck pace of AI development, however, things can shift suddenly. For his mathematically minded audience, Chalmers got concrete: the chances of developing any

machines like US

Philosophers, cognitive scientists, and engineers are grappling with what it would take for AI to become conscious.

By GRACE HUCKINS | Illustrations by Stuart Bradford

HIGH
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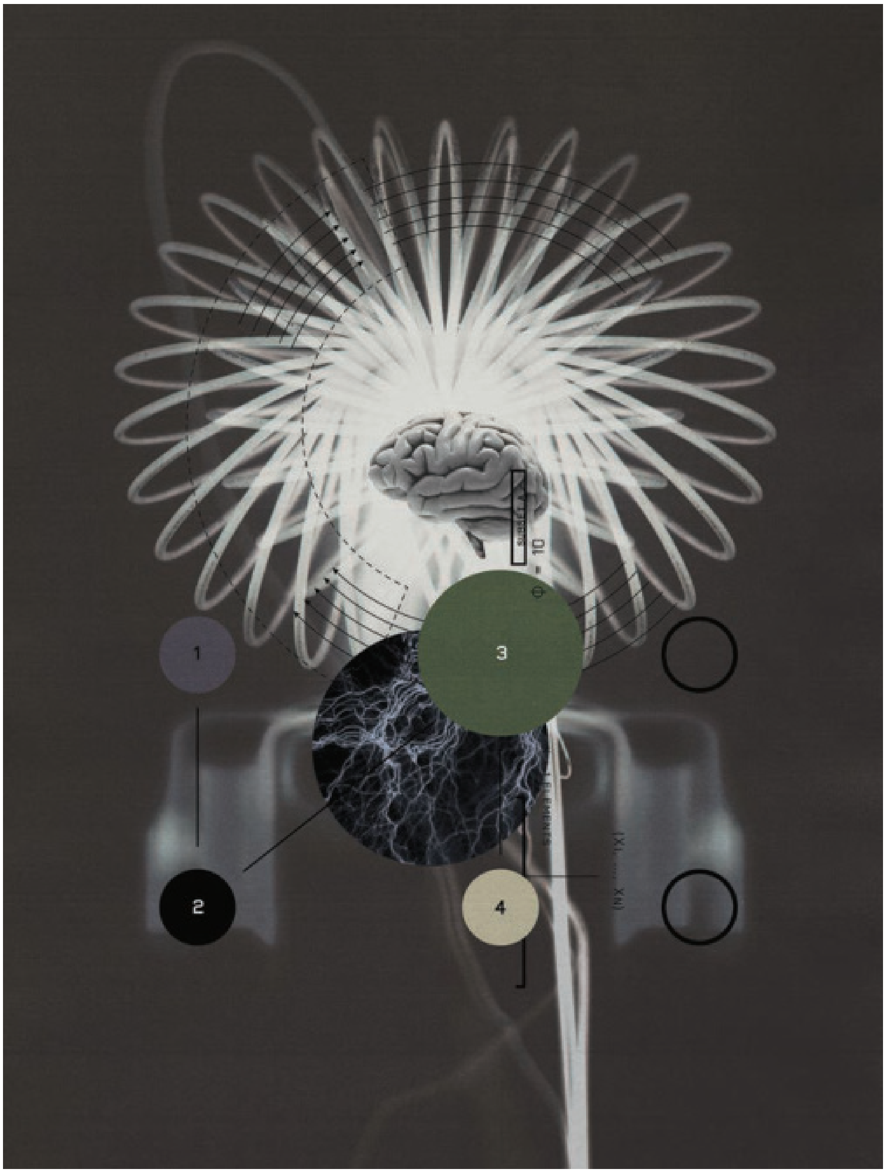


conscious AI in the next 10 years were, he estimated, above one in five.

Not many people dismissed his proposal as ridiculous, Chalmers says: "I mean, I'm sure some people had that reaction, but they weren't the ones talking to me." Instead, he spent the next several days in conversation after conversation with AI experts who took the possibilities he'd described very seriously. Some came to Chalmers effervescent with enthusiasm at the concept of conscious machines. Others, though, were horrified at what he had described. If an AI were conscious, they argued—if it could look out at the world from its own personal perspective, not simply processing inputs but also experiencing them—then, perhaps, it could suffer.

AI consciousness isn't just a devilishly tricky intellectual puzzle; it's a morally weighty problem with potentially dire consequences. Fail to identify a conscious AI, and you might unintentionally subjugate, or even torture, a being whose interests ought to matter. Mistake an unconscious AI for a conscious one, and you risk compromising human safety and happiness for the sake of an unthinking, unfeeling hunk of silicon and code. Both mistakes are easy to make. "Consciousness poses a unique challenge in our attempts to study it, because it's hard to define," says Liad Mudrik, a neuroscientist at Tel Aviv University who has researched consciousness since the early 2000s. "It's inherently subjective."

Over the past few decades, a small research community has doggedly attacked the question of what consciousness is and how it works. The effort has yielded real progress on what once seemed an unsolvable problem. Now, with the rapid advance of AI technology, these insights could offer our only guide to the untested, morally fraught waters of artificial consciousness.

"If we as a field will be able to use the theories that we have, and the findings that we have, in order to reach a good test for consciousness," Mudrik says, "it will probably be one of the most important contributions that we could give."

When Mudrik explains her consciousness research, she starts with one of her very favorite things: chocolate. Placing a piece in your mouth sparks a symphony of neurobiological events—your tongue's sugar and fat receptors activate brain-bound pathways, clusters of cells in the brain stem stimulate your salivary glands, and neurons deep within your head release the chemical dopamine. None of those processes, though, captures what it is like to snap a chocolate square from its foil packet and let it melt in your mouth. "What I'm trying to understand is what in the brain allows us not only to process information—which in its own right is a formidable challenge and an amazing achievement of the brain—but also to experience the information that we are processing," Mudrik says.

Studying information processing would have been the more straightforward choice for Mudrik, professionally speaking. Consciousness has long been a marginalized topic in neuroscience, seen as at best unserious and at worst intractable. "A fascinating but elusive phenomenon," reads the "Consciousness" entry in the 1996 edition of the *International Dictionary of Psychology*. "Nothing worth reading has been written on it."

Mudrik was not dissuaded. From her undergraduate years in the early 2000s, she knew that she didn't want to research anything other than consciousness. "It might not be the most sensible decision to make as a young researcher, but I just couldn't help it," she says. "I couldn't get enough of it." She earned two PhDs—one in neuroscience, one in philosophy—in her determination to decipher the nature of human experience.

As slippery a topic as consciousness can be, it is not impossible to pin down—put as simply as possible, it's the ability to experience things. It's often confused with terms like "sentience" and "self-awareness," but according to the definitions that many experts use, consciousness is a prerequisite for those other, more sophisticated abilities. To be sentient, a being must be able to have positive and negative experiences—in other words, pleasures and pains. And being self-aware means not only having an experience but also *knowing* that you are having an experience.

"Consciousness poses a unique challenge in our attempts to study it, because it's hard to define."

In her laboratory, Mudrik doesn't worry about sentience and self-awareness; she's interested in observing what happens in the brain when she manipulates people's conscious experience. That's an easy thing to do in principle. Give someone a piece of broccoli to eat, and the experience will be very different from eating a piece of chocolate—and will probably result in a different brain scan. The problem is that those differences are uninterpretable. It would be impossible to discern which are linked to changes in information—broccoli and chocolate activate very different taste receptors—and which represent changes in the conscious experience.

The trick is to modify the experience without modifying the stimulus, like giving someone a piece of chocolate and then flipping a switch to make it feel like eating broccoli. That's not possible with taste, but it is with vision. In one widely used approach, scientists have people look at two different images simultaneously, one with each eye. Although the eyes take in both images, it's impossible to perceive both at once, so subjects will often report that their visual experience "flips": first they see one image, and then, spontaneously, they see the other. By tracking brain activity during these flips in conscious awareness, scientists can observe what happens when incoming information stays the same but the experience of it shifts.

With these and other approaches, Mudrik and her colleagues have managed to establish some concrete facts about how consciousness works in the human brain. The cerebellum, a brain region at the base of the skull that resembles a fist-size tangle of angel-hair pasta, appears to play no role in conscious experience, though it is crucial for subconscious motor tasks like riding a bike; on the other hand, feedback connections—for example, connections running from the "higher," cognitive regions of the brain to those involved in more basic sensory processing—seem essential to consciousness. (This, by the way, is one good reason to doubt the consciousness of LLMs: they lack substantial feedback connections.)

A decade ago, a group of Italian and Belgian neuroscientists managed to devise a test for human consciousness that uses transcranial magnetic stimulation (TMS), a non-invasive form of brain stimulation that is applied by holding a figure-eight-shaped magnetic wand near someone's head. Solely from the resulting patterns of brain activity, the team was able to distinguish conscious people from those who were under anesthesia or deeply asleep, and they could even detect the difference between a vegetative state (where someone is awake but not conscious) and locked-in syndrome (in which a patient is conscious but cannot move at all).

That's an enormous step forward in consciousness research, but it means little for the question of conscious AI: OpenAI's GPT models don't have a brain that can be stimulated by a TMS wand. To test for AI consciousness, it's not enough to identify the structures that give rise to consciousness in the human brain. You need to know why those structures contribute to consciousness, in a way that's rigorous and general enough to be applicable to any system, human or otherwise.

"Ultimately, you need a theory," says Christof Koch, former president of the Allen Institute and an influential consciousness researcher. "You can't just depend on your intuitions anymore; you need a foundational theory that tells you what consciousness is, how it gets into the world, and who has it and who doesn't."

Here's one theory about how that litmus test for consciousness might work: any being that is intelligent enough, that is capable of responding successfully to a wide enough variety of contexts and challenges, must be conscious. It's not an absurd theory on its face. We humans have the most intelligent brains around, as far as we're aware, and we're definitely conscious. More intelligent animals, too, seem more likely to be conscious—there's far more consensus that chimpanzees are conscious than, say, crabs.

But consciousness and intelligence are not the same. When Mudrik flashes images at her experimental subjects, she's not asking them to contemplate anything or testing their problem-solving abilities. Even a crab scuttling across the ocean floor, with no awareness of its past or thoughts about its future, would still be conscious if it could experience the pleasure of a tasty morsel of shrimp or the pain of an injured claw.

Susan Schneider, director of the Center for the Future Mind at Florida Atlantic University, thinks that AI could reach greater heights of intelligence by forgoing consciousness altogether. Conscious processes like holding something in short-term memory are pretty limited—we can only pay attention to a couple of things at a time and often struggle to do simple tasks like remembering a phone number long enough to call it. It's not immediately obvious what an AI would gain from consciousness, especially considering the impressive feats such systems have been able to achieve without it.

As further iterations of GPT prove themselves more and more intelligent—more and more capable of meeting a broad spectrum of demands, from acing the bar exam to building a website from scratch—their success, in and of itself, can't be taken as evidence of their consciousness. Even a machine that behaves indistinguishably from a human isn't necessarily aware of anything at all.

Schneider, though, hasn't lost hope in tests. Together with the Princeton physicist Edwin Turner, she has formulated what she calls the "artificial consciousness test." It's not easy to perform: it requires isolating an AI agent from any information about consciousness throughout its training. (This is important so that it can't, like LaMDA, just parrot human statements about consciousness.) Then, once the system is trained, the tester asks it questions that it could only answer if it knew about consciousness—knowledge it could only have acquired from being conscious itself. Can it understand the plot of the film *Freaky Friday*, where a mother and daughter switch bodies, their consciousnesses dissociated from their physical selves? Does it grasp the concept of dreaming—or even report dreaming itself? Can it conceive of reincarnation or an afterlife?

There's a huge limitation to this approach: it requires the capacity for language. Human infants and dogs, both of which are widely believed to be conscious, could not possibly pass this test, and an AI could conceivably become conscious without using language at all. Putting a language-based AI like GPT to the test is likewise impossible, as it has been exposed to the idea of consciousness in its training. (Ask ChatGPT to explain *Freaky Friday*—it does a respectable job.) And because we still understand so little about how advanced AI systems work, it would be difficult, if not impossible, to completely protect an AI against such exposure. Our very language is imbued with the fact of our consciousness—words like "mind," "soul," and "self" make sense to us by virtue of our conscious experience. Who's to say that an extremely intelligent, nonconscious AI system couldn't suss that out?

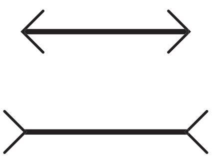
If Schneider's test isn't foolproof, that leaves one more option: opening up the machine. Understanding how an AI works on the inside could be an essential step toward determining whether or not it is conscious, if you know how to interpret what you're looking at. Doing so requires a good theory of consciousness.

A few decades ago, we might have been entirely lost. The only available theories came from philosophy, and it wasn't clear how they might be applied to a physical system. But since then, researchers like Koch and Mudrik have helped to develop and refine a number of ideas that could prove useful guides to understanding artificial consciousness.

Numerous theories have been proposed, and none has yet been proved—or even deemed a front-runner. And they make radically different predictions about AI consciousness.

Some theories treat consciousness as a feature of the brain's software: all

Understanding how an AI works on the inside could be an essential step toward determining whether or not it is conscious.



Knowing that the two lines in the Müller-Lyer illusion are exactly the same length doesn't prevent us from perceiving one as shorter than the other. Similarly, knowing GPT isn't conscious doesn't change the illusion that you are speaking to a being with a perspective, opinions, and personality.

that matters is that the brain performs the right set of jobs, in the right sort of way. According to global workspace theory, for example, systems are conscious if they possess the requisite architecture: a variety of independent modules, plus a "global workspace" that takes in information from those modules and selects some of it to broadcast across the entire system.

Other theories tie consciousness more squarely to physical hardware. Integrated information theory proposes that a system's consciousness depends on the particular details of its physical structure—specifically, how the current state of its physical components influences their future and indicates their past. According to IIT, conventional computer systems, and thus current-day AI, can never be conscious—they don't have the right causal structure. (The theory was recently criticized by some researchers, who think it has gotten outsize attention.)

Anil Seth, a professor of neuroscience at the University of Sussex, is more sympathetic to the hardware-based theories, for one main reason: he thinks biology matters. Every conscious creature that we know of breaks down organic molecules for energy, works to maintain a stable internal environment, and processes information through networks of neurons via a combination of chemical and electrical signals. If that's true of all conscious creatures, some scientists argue, it's not a stretch to suspect that any one of those traits, or perhaps even all of them, might be necessary for consciousness.

Because he thinks biology is so important to consciousness, Seth says, he spends more time worrying about the possibility of consciousness in brain organoids—clumps of neural tissue grown in a dish—than in AI. "The problem is, we don't know if I'm right," he says. "And I may well be wrong."

He's not alone in this attitude. Every expert has a preferred theory of consciousness, but none treats it as ideology—all of them are eternally alert to the possibility that they have backed the wrong horse. In the past five years, consciousness scientists have started working together on a series of "adversarial collaborations," in which supporters of different theories come together to design neuroscience experiments that could help test them against each other. The researchers agree ahead of time on which patterns of results will support which theory. Then they run the experiments and see what happens.

In June, Mudrik, Koch, Chalmers, and a large group of collaborators released the results from an adversarial collaboration pitting global workspace theory against integrated information theory. Neither theory came out entirely on top. But Mudrik says the process was still fruitful: forcing the supporters of each theory to make concrete predictions helped to make the theories themselves more precise and scientifically useful. "They're all theories in progress," she says.

At the same time, Mudrik has been trying to figure out what this diversity of theories means for AI. She's working with an interdisciplinary team of philosophers, computer scientists, and neuroscientists who recently put out a white paper that makes some practical recommendations on detecting AI consciousness. In the paper, the team draws on a variety of theories to build a sort of consciousness "report card"—a list of markers that would indicate an AI is conscious, under the assumption that one of those theories is true. These markers include having certain feedback connections, using a global workspace, flexibly pursuing goals, and interacting with an external environment (whether real or virtual).

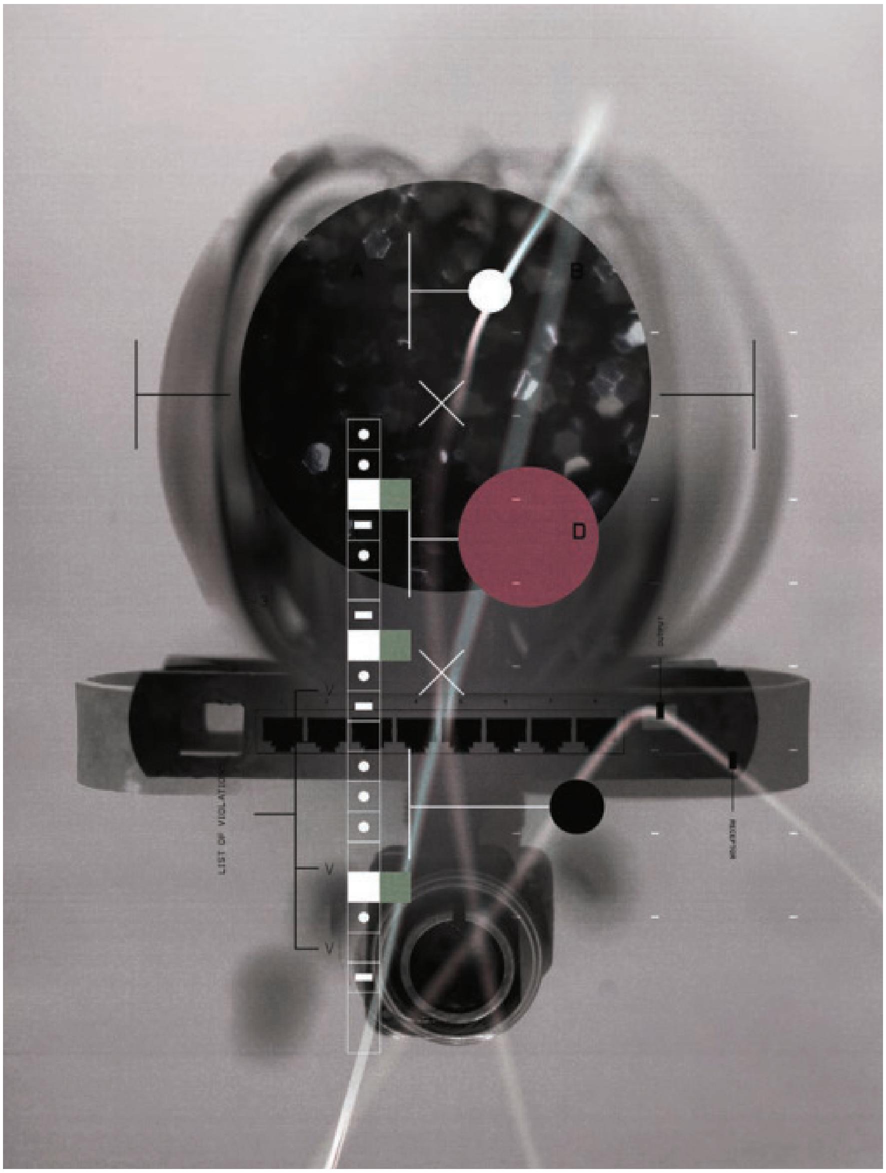
In effect, this strategy recognizes that the major theories of consciousness have some chance of turning out to be true—and so if more theories agree that an AI is conscious, it is more likely to actually be conscious. By the same token, a system that lacks all those markers can only be conscious if our current theories are very wrong. That's where LLMs like LaMDA currently are: they don't possess the right type of feedback connections, use global workspaces, or appear to have any other markers of consciousness.

The trouble with consciousness-by-committee, though, is that this state of affairs won't last. According to the authors of the white paper, there are no major technological hurdles in the way of building AI systems that score highly on their consciousness report card. Soon enough, we'll be dealing with a question straight out of science fiction: What should one do with a potentially conscious machine?

In 1989, years before the neuroscience of consciousness truly came into its own, *Star Trek: The Next Generation* aired an episode titled "The Measure of a Man." The episode centers on the character Data, an android who spends much of the show grappling with his own disputed humanity. In this particular episode, a scientist wants to forcibly disassemble Data, to figure out how he works; Data, worried that disassembly could effectively kill him, refuses; and Data's captain, Picard, must defend in court his right to refuse the procedure.

Picard never proves that Data is conscious. Rather, he demonstrates that no one can disprove that Data is conscious, and so the risk of harming Data, and potentially condemning the androids that come after him to slavery, is too great to countenance. It's a tempting solution to the conundrum of questionable AI consciousness:

treat any potentially conscious system as if it is really conscious, and avoid the risk of harming a being that can genuinely suffer.



Treating Data like a person is simple: he can easily express his wants and needs, and those wants and needs tend to resemble those of his human crewmates, in broad strokes. But protecting a real-world AI from suffering could prove much harder, says Robert Long, a philosophy fellow at the Center for AI Safety in San Francisco, who is one of the lead authors on the white paper. "With animals, there's the handy property that they do basically want the same things as us," he says. "It's kind of hard to know what that is in the case of AI." Protecting AI requires not only a theory of AI consciousness but also a theory of AI pleasures and pains, of AI desires and fears.

And that approach is not without its costs. On *Star Trek*, the scientist who wants to disassemble Data hopes to construct more androids like him, who might be sent on risky missions in lieu of other personnel. To the viewer, who sees Data as a conscious character like everyone else on the show, the proposal is horrifying. But if Data were simply a convincing simulacrum of a human, it would be unconscionable to expose a person to danger in his place.

Extending care to other beings means protecting them from harm, and that limits the choices that humans can ethically make. "I'm not that worried about scenarios where we care too much about animals," Long says. There are few downsides to ending factory farming. "But with AI systems," he adds, "I think there could really be a lot of dangers if we overattribute consciousness." AI systems might malfunction and need to be shut down; they might need to be subjected to rigorous safety testing. These are easy decisions if the AI is inanimate, and philosophical quagmires if the AI's needs must be taken into consideration.

Seth—who thinks that conscious AI is relatively unlikely, at least for the foreseeable future—nevertheless worries about what the possibility of AI consciousness might mean for humans emotionally. "It'll change how we distribute our limited resources of caring about things," he says. That might seem like a problem for the future. But the perception of AI consciousness is with us now: Blake Lemoine took a personal risk for an AI he believed to be conscious, and he lost his job. How many others might sacrifice time, money, and personal relationships for lifeless computer systems?

Even bare-bones chatbots can exert an uncanny pull: a simple program called ELIZA, built in the 1960s to simulate talk therapy, convinced many users that it was capable of feeling and understanding. The perception of consciousness and the reality of consciousness are poorly aligned, and that discrepancy will only worsen as AI systems become capable of engaging in more realistic conversations. "We will be unable to avoid perceiving them as having conscious experiences, in the same way that certain visual illusions are cognitively impenetrable to us," Seth says. Just as knowing that the two lines in the Müller-Lyer illusion are exactly the same length doesn't prevent us from perceiving one as shorter than the other, knowing GPT isn't conscious doesn't change the illusion that you are speaking to a being with a perspective, opinions, and personality.

In 2015, years before these concerns became current, the philosophers Eric Schwitzgebel and Mara Garza formulated a set of recommendations meant to protect against such risks. One of their recommendations, which they termed the "Emotional Alignment Design Policy," argued that any unconscious AI should be intentionally designed so that users will not believe it is conscious. Companies have taken some small steps in that direction—ChatGPT spits out a hard-coded denial if you ask it whether it is conscious. But such responses do little to disrupt the overall illusion.

Schwitzgebel, who is a professor of philosophy at the University of California, Riverside, wants to steer well clear of any ambiguity. In their 2015 paper, he and Garza also proposed their "Excluded Middle Policy"—if it's unclear whether an AI system will be conscious, that system should not be built. In practice, this means all the relevant experts must agree that a prospective AI is very likely not conscious (their verdict for current LLMs) or very likely conscious. "What we don't want to do is confuse people," Schwitzgebel says.

Avoiding the gray zone of disputed consciousness neatly skirts both the risks of harming a conscious AI and the downsides of treating a lifeless machine as conscious. The trouble is, doing so may not be realistic. Many researchers—like Rufin VanRullen, a research director at France's Centre Nationale de la Recherche Scientifique, who recently obtained funding to build an AI with a global workspace—are now actively working to endow AI with the potential underpinnings of consciousness.

The downside of a moratorium on building potentially conscious systems, VanRullen says, is that systems like the one he's trying to create might be more effective than current AI. "Whenever we are disappointed with current AI performance, it's always because it's lagging behind what the brain is capable of doing," he says. "So it's not necessarily that my objective would be to create a conscious AI—it's more that the objective of many people in AI right now is to move toward these advanced reasoning capabilities." Such advanced capabilities could confer real benefits: already, AI-designed drugs are being tested in clinical trials. It's not inconceivable that AI in the gray zone could save lives.

VanRullen is sensitive to the risks of conscious AI—he worked with Long and Mudrik on the white paper about detecting consciousness in machines. But it is those very risks, he says, that make his research important. Odds are that conscious AI won't first emerge from a visible, publicly funded project like his own; it may very well take the deep pockets of a company like Google or OpenAI. These companies, VanRullen says, aren't likely to welcome the ethical quandaries that a conscious system would introduce. "Does that mean that when it happens in the lab, they just pretend it didn't happen? Does that mean that we won't know about it?" he says. "I find that quite worrisome."

Academics like him can help mitigate that risk, he says, by getting a better understanding of how consciousness itself works, in both humans and machines. That knowledge could then enable regulators to more effectively police the companies that are most likely to start dabbling in the creation of artificial minds. The more we understand consciousness, the smaller that precarious gray zone gets—and the better the chance we have of knowing whether or not we are in it.

For his part, Schwitzgebel would rather we steer far clear of the gray zone entirely. But given the magnitude of the uncertainties involved, he admits that this hope is likely unrealistic—especially if conscious AI ends up being profitable. And once we're in the gray zone—once we need to take seriously the interests of debatably conscious beings—we'll be navigating even more difficult terrain, contending with moral problems of unprecedented complexity without a clear road map for how to solve them. It's up to researchers, from philosophers to neuroscientists to computer scientists, to take on the formidable task of drawing that map. ■

"With animals, there's the handy property that they do basically want the same things as us. It's kind of hard to know what that is in the case of AI."

Grace Huckins is a science writer based in San Francisco.

Big problems that demand bigger energy

Technology is all about solving big, thorny problems. Yet one of the hardest things about solving hard problems is knowing where to focus our efforts. There are so many urgent issues facing the world. Where should we even begin? So we asked dozens of people to identify what problem at the intersection of technology and society they think we should focus more of our energy on. We queried scientists, journalists, politicians, entrepreneurs, activists, and CEOs.

Some broad themes emerged: the climate crisis, global health, creating a just and equitable society, and AI all came up frequently. There were plenty of outliers, too, ranging from regulating social media to fighting corruption. You'll find some of these responses on the following pages—and many more online at techreview.com/hardproblems.

We want to hear from you too. What's a problem you think society should be more focused on, and why? Use the hashtag #hardproblems on social media, and we may add your response to our list.

Bruce Schneier

Fellow and lecturer at Harvard Kennedy School

The technologies of democracy are centuries out of date. The legislator is 18th-century technology. The regulatory agency is a 19th-century patch on that technology. Single representatives, winner-take-all elections, districts based on geography, voting every few years: these are all systems of democracy devised for a very different technological world. They are not suited for today, and it shows. Today we have new and different technologies to create fair, equitable, just, and democratic policy outcomes. We've upgraded everything else in our society—why not democracy? Imagine the possibilities!

Martine Rothblatt

Technologist, entrepreneur, CEO of United Therapeutics

More energy should be put into using technology to achieve a zero carbon footprint for all new construction and vehicles by 2030, and for existing factories by 2040. It is totally possible: United Therapeutics developed new technology to achieve that for a 150,000-square-foot office building and has achieved proof of concept for small carbon-neutral electric planes. Green hydrogen is as good as gas, the earth gets 10,000 times more solar energy each day than it uses, and hydrogen fuel cells are superb batteries. The only priority right now should be the climate priority.

Katharine Hayhoe

Climate scientist, professor and endowed chair at Texas Tech University, and chief scientist of the Nature Conservancy

Innovative technologies often capture our imaginations and dominate headlines. In my opinion, though, it's the seemingly ordinary solutions that hold the greatest potential to accelerate our progress toward a brighter future. Practical and effective climate solutions like minimizing energy and food waste, eliminating methane emissions, greening urban areas, and adopting climate-smart agricultural practices also benefit our health, protect biodiversity, and strengthen local economies. With the help of technology, we can supercharge these solutions.

Meredith Broussard

Data journalist, associate professor at New York University's Arthur L. Carter Journalism Institute

We should focus on problems of racism, sexism, and ableism—but we should not expect tech or technologists to deliver complete solutions. Computers are machines that do math—no more, no less. AI and machine-learning systems work by detecting and reproducing mathematical patterns in training data. There isn't a perfect world in which racism, sexism, and ableism have been eliminated (although I hope we are working toward that), so AI will inevitably reproduce preexisting social problems.

LEXEY SWALL/NEW YORK TIMES/REDUX (HAYHOE); SUE BRUCE (SCHNEIER); ANDRE CHUNG/WIKIMEDIA COMMONS (ROTHBLATT); COURTESY OF MEREDITH BROUSSARD

“… if it won’t scale, it doesn’t matter.”

Yet-Ming Chiang

Professor of materials science and engineering at the Massachusetts Institute of Technology; cofounder and chief scientist of Form Energy

When it comes to clean tech, if it won’t scale, it doesn’t matter. I believe that between now and mid-century, we need to substantially reinvent our approach to minerals extraction, and to look toward substitution of scarce elements and earth resources with abundant ones wherever possible. Such work is already underway in energy storage (e.g., vehicle and grid batteries) and construction materials (e.g., cement and steel) and will likely propagate rapidly to other sectors.

SIMON SIMARD

“... data surveillance risks becoming even more entrenched.”

Lina Khan

Chair of the US Federal Trade Commission

When firms rely on business models that monetize personal data, it tends to create financial incentives to endlessly vacuum up people's sensitive information. As algorithmic decision-making tools further take hold, this data surveillance risks becoming even more entrenched. All too often, people must surrender to expansive tracking in order to use services that are essential for navigating modern life. Enforcing and strengthening laws against overcollection and misuse of our personal data is critical for maintaining people's right to privacy in the 21st century.

LEXEY SWALL/NEW YORK TIMES/REDUX

Annalee Newitz

Journalist, author of fiction and nonfiction

As early-21st-century social media platforms are abandoned, we need civic organizations to focus on building a robust public sphere online where people can get factual information during natural disasters and other emergencies, as well as engage in democratic debate without threats of violence or misinformation.

Kathryn Peters and Francesca Tripodi

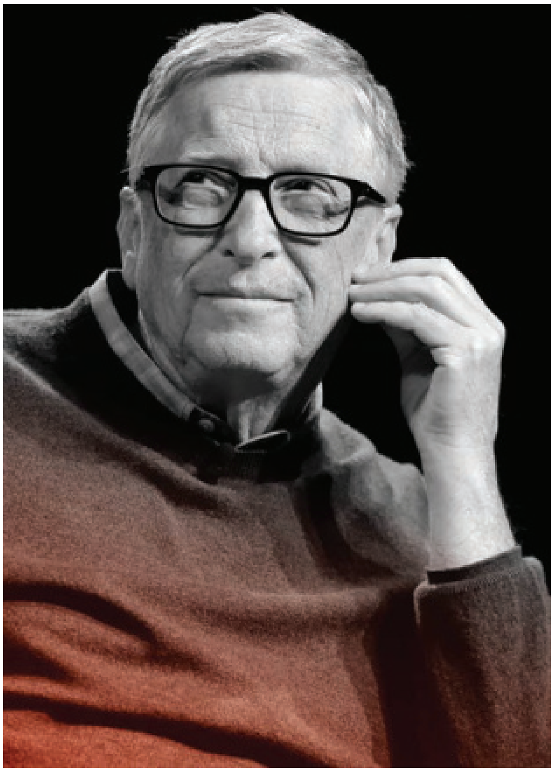
Executive director and principal investigator at the Center for Information, Technology, and Public Life (CITAP) at the University of North Carolina at Chapel Hill

Search engines increasingly answer our questions rather than linking to results, and we need to keep a critical eye on where those answers come from. This is especially true in local politics: candidates vie for attention in a nationalized media environment in which Wikipedia is a top source of search data. Yet Wikipedia's notability guidelines often exclude first-time candidates for office, furthering bias in who gets seen—and elected. Understanding and addressing these gaps is a pressing civic information problem.

H.-S. Philip Wong

Willard R. and Inez Kerr Bell Professor in the School of Engineering, Stanford University

Without continued advances in semiconductor technology year after year, it will be very difficult to fulfill the high expectations we have for future technologies such as AI, 5G, quantum computing, and self-driving cars, along with many of the United Nations' Sustainable Development Goals. Yet very few people today would make this connection. The US cannot be complacent about its leadership in basic science research and hope that somehow the scientific discoveries will trickle down into leadership technologies. We need to figure out a way to value and nurture applied engineering research.



Bill Gates

Philanthropist, investor, and former CEO of Microsoft

Technological innovation is one of the most powerful tools we have to address the world's toughest challenges, especially in the areas of health, development, climate, and education. But there's not nearly enough focus on making its benefits available to everyone. Now, as we consider the potential for AI to improve life for millions of people around the world, more attention is needed on responsible and equitable development, so tools may be delivered by and for those who need it most.

SARAH DERAGON (NEWITZ); RUNYARO PSWARAYI (PETERS); JON GARDINER/UNC-CHAPEL HILL (TRIPODI); COURTESY OF H.-S. PHILIP WONG/STANFORD UNIVERSITY (WONG); MICHALE LOCCISANO/GETTY IMAGES (GATES)

Isobel Coleman

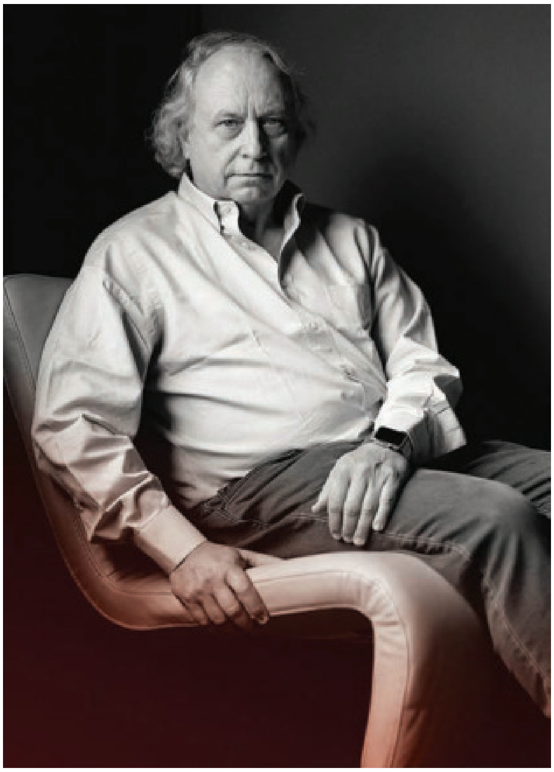
Deputy administrator of the United States Agency for International Development

Countering corruption. Corruption stunts development and equitable growth; it undermines democracy and the rule of law. E-government platforms like Ukraine's Diia—an app built in partnership with USAID and UK Aid that connects 19 million Ukrainians with more than 120 government services—reduce corruption and foster citizen engagement. Already, Diia has had an economic and anticorruption impact valued at more than $400 million. USAID is supporting countries that are inspired by Diia to adopt similar technologies in order to fight corruption.

Katie Moussouris

Founder and CEO of Luta Security

We don't have a solid plan to ensure that societal needs regarding security, privacy, and human rights are met in the face of developments in AI and unchecked capitalism. AI advancements and increased labor efficiency should pave the way for unrestricted basic income. Humanity should be free of working in order to survive in favor of becoming laser focused on solving the climate catastrophe and ending climate-driven human displacement, as well as propelling scientific advancements to cure endemic diseases like cancer and current and future pandemics.



Rodney Brooks

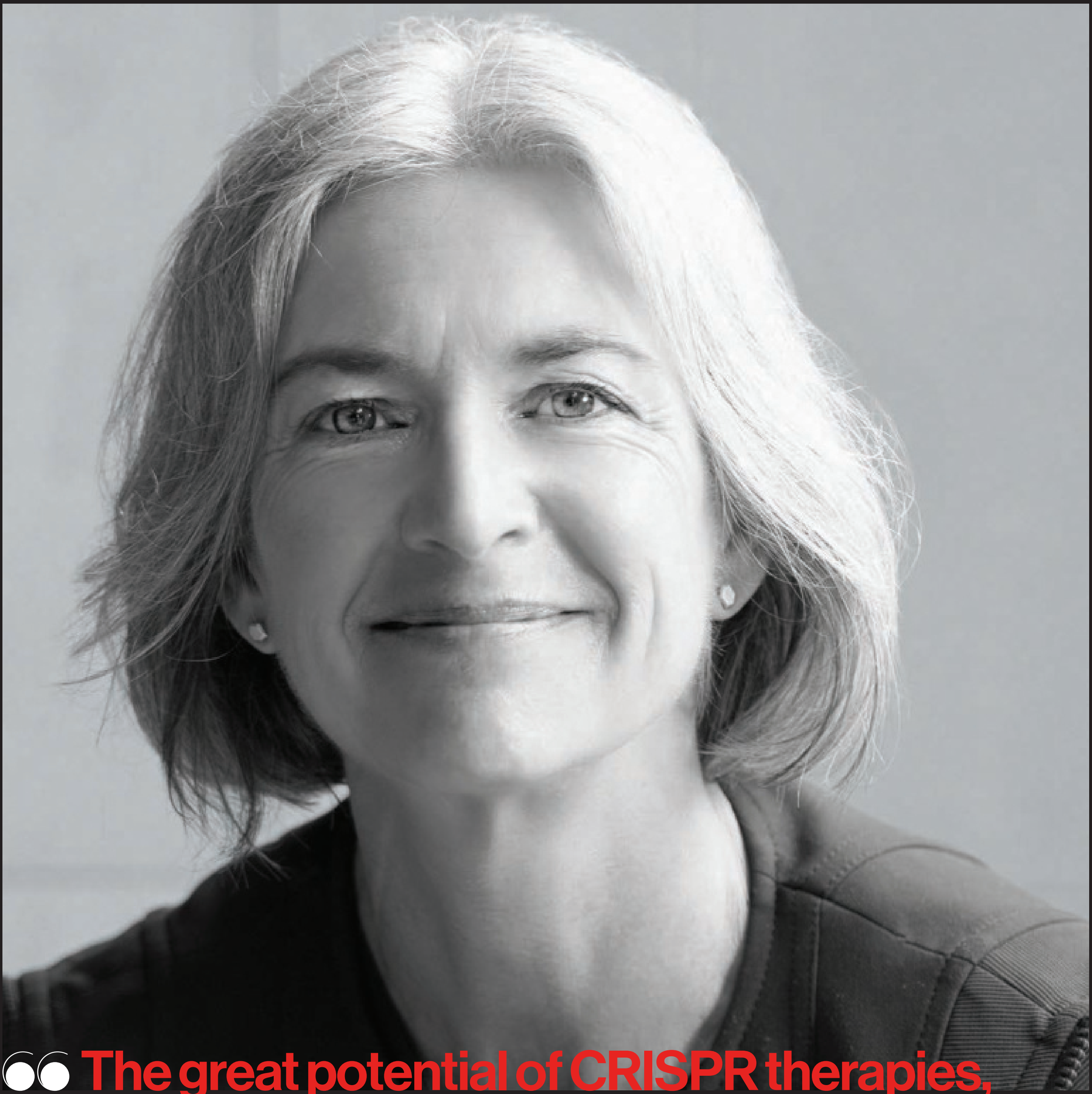
Roboticist; CTO and cofounder of RobustAI

For countries like Japan, China, most of those in Europe and North America, and Australia, there is a demographic inversion, with a radically higher proportion of elderly people than before. There are far fewer people to provide the additional care that they need. What technologies can be developed to let them live longer in their own homes with dignity and independence?

Mohsin Hamid

Novelist

It amazes me that we can land rovers on Mars but fail to provide safe drinking water to so many of our fellow humans on Earth. For me, the most pressing technological questions are not just about the frontier but also about the places left behind. My question: How can technology better enable us to get the technologies we already have to those who need them most, when markets and states are failing to do so?



“The great potential of CRISPR therapies, especially for neglected diseases, risks being wasted ...”

CHRISTOPHER MICHEL/COURTESY OF STANFORD UNIVERSITY

Jennifer Doudna

CRISPR pioneer and Nobel laureate in chemistry

Is a cure really a cure if it’s inaccessible? Can market incentives support cures for rare diseases? Currently, the answer to both is no. CRISPR tools have progressed rapidly from labs to clinical trials, promising to address genetic disease at scale. Yet with costs reaching the millions, some trials halt for financial reasons, while the treatments that reach approval will be unaffordable to all but a few. The great potential of CRISPR therapies, especially for neglected diseases, risks being wasted without reducing costs and establishing new pathways to the clinic.

Government can't automate every

Every Tuesday, Jessica Ramgoolam heads down to the New Amsterdam branch of the New York City Public Library, sets up a small folding table, and takes a seat with her laptop. She lays out piles of paper flyers, and it's clear she has information to share, like a fortune teller awaiting a passing seeker.

Just before 11 a.m., when the library opens, people may begin lining up for her assistance. With the aid of her team, she can communicate with people in nearly 20 languages, and her iPhone can help her manage many more.

Though she holds no unique powers of foresight, Ramgoolam represents for many the keys to the future. Sitting behind a bright yellow sign reading "GetCoveredNYC," she's there to help people—anyone—enroll in health care.

Determining what programs you might be eligible for, gathering the bewildering amount of information required for different applications, and navigating the submission process is a headache, even for the most administratively savvy.

That's true even though most New Yorkers have already submitted information about their income and employment to the city many times over, and more and more residents get regular updates from and about the city government through websites, phone calls, chatbots, text messages, Twitter, email, Facebook and Instagram, livestreams, TV, and radio—all of which are used to communicate everything from emergency notifications to trash collection schedules. Not to mention the overwhelming volume of information online devoted specifically to the several public health-care plans available.

But even with those programs and a variety of tax credits, there are still hundreds of thousands of people in the city who do not have health insurance.

By Tate Ryan-Mosley

thing

It's a reality of politics that is often overlooked: once a law is passed, it needs to evolve from an idea into a plan with a budget and a staff, and from there it needs to actually reach the lives of millions of people. Moving from policy to implementation has always been a hard part of governing, but today it's easy to assume technology can make it easier.

Yet even as technology presents unprecedented opportunities to bridge the gap between government programs and the people they serve, it also brings unprecedented challenges. How do we modernize without leaving people behind? How do we increase access without unduly burdening citizens? How do we increase efficiency and make services easier to use while still protecting sensitive data?

Today, technology is both an instrument and a medium of government, and in turn, it's transforming the way citizens and states interact with each other. And it's essential, even urgent, that governments understand this relationship—and how easily it can be broken, even by the tools meant to bolster it. After all, civic technology has the power to help, but not *everything* can be technologically simplified. Not everything can be automated. Bureaucrats can make forms all day long, but they are useless if people don't know how to use them—or if they don't even have the resources to access them or fill them out.

Which is why, every week, Ramgoolam supports uninsured New Yorkers as they navigate the ever growing, ever changing, always tangled web of online forms that promise access to affordable care.

"I've come across, in my lifetime, so many folks who have had many detrimental issues with the health insurance system," she told me. "What motivates me is how great it makes me feel to know that I've succeeded in helping someone."

New York City is something of a test lab for strategies to confront some big problems that plague the modern state. Akin to a country in the budget and bureaucratic complexity of its government, it is, and has been, dealing with the key question of how to make government work for people today. And through its experimentation, it is finding that sometimes the solution to doing big things also involves doing a lot of small things, sometimes with the lowest tech possible: a human sitting behind a table.

Bureaucrats can make forms all day long, but they're useless if people don't know how to use them. That's why in New York City every Tuesday, Jessica Ramgoolam sets up shop at this table to assist folks trying to get health insurance.

COURTESY PHOTO

"Why can't we just ...?"

When President Barack Obama took office in 2009, his administration was heralded as more technologically savvy than any that had come before. At the dawn of Web 2.0 and with immense faith in the power of technology to do big things, it hired the country's first chief information officer, started the US Digital Service to modernize the executive branch, and issued a directive to "build a 21st-century digital government." Technology was envisioned as a key to the administration's ambitious plan for expanding access to health insurance.

Yet when Healthcare.gov launched in 2013, after three years of work and a cost of more than $300 million, the website crashed. Fewer than 10 people were able to enroll on the first day.

In the years since, the Healthcare.gov fiasco has turned into a sort of parable for those working in policy implementation. The program's tech-forward approach was meant to make it easier for people to compare the costs of health-care plans and enroll in one, but at least at first, the tech failed in spectacular fashion.

The crash was indicative of massive challenges that the US still faces when it comes to government use of technology. Jennifer Pahlka was serving as deputy chief technology officer of the White House Office of Science and Technology Policy at the time. As she explains in her book *Recoding America: Why Government Is Failing in the Digital Age and How We Can Do Better*, the failed site launch was a reflection of just how big the "glaring gap between policy intentions and actual outcomes" really is.

In the book, Pahlka—who also founded Code for America, a nonprofit that pairs engineers, designers, and product managers with government agencies to improve public services—lays out the problem. "Whether for good or for ill, the essence of the digital revolution is that it has become easier to implement ideas of all kinds—business, cultural, and social," she writes. "Inside government, however, the digital revolution has played out very differently. Even as our expectations about the immediacy and accuracy of services have skyrocketed, the implementation of laws has become anything but easier."

In several conversations, Pahlka explained to me how well-intended policies morph between the time they pass a legislature and the time they finally trickle through the bureaucracy and down to the lives of everyday Americans. And today, of course, the way Americans interact with those policies is so often through technology—government websites, data management and record keeping, or benefit enrollment.

"Ultimately, we tell the American public we're gonna do this thing," she told me, "and then the actual outcome that was desired may or may not occur." The reason, she argued, is that policy implementation has grown so complex—and technology often complicates it even further. What's more, the American system isn't designed to empower technology designers in this process. Instead, legislators are making the choices without necessarily understanding what technology would help carry them out most effectively.

"We need to rediscover what democracy offers to us and apply that in the context of building services, making decisions, and doing regulation that works for people in a way that's less like 'Everybody throws their stuff in the pot of soup and then that's what the soup is,'" she told me.

Officials working on digital transformation and public services in New York, San Francisco, and Boston all told me that there is no silver bullet. Technology can be as much a part of the problem as it is part of the solution. As Cyd Harrell, the chief digital services officer of San Francisco, put it, the story of government technology is a story of the question "Why can't we just …?" In other words, the contrast between the opportunities technology seems to offer and the challenges it often creates can make modern governing maddening.

Even if the technology is promising, deploying it takes money and talent. There are challenges with procurement and integrating new systems with legacy tech. There are the realities of budgets, bureaucratic red tape, election cycles, and ever-growing legal complexities. And getting the technology itself right is no simple task, especially when citizens are accustomed to easy-to-use interfaces and information management systems from the likes of Apple, Microsoft, and Google.

It's all these things at once that make the problems with government technology so intractable. But at the same time, it's never been more critical to improve government effectiveness.

"The stakes matter more at this moment than they ever have," says Pahlka. "The [Inflation Reduction Act] is trying to save us from a climate collapse, the CHIPS Act is trying to save us from potential national security disasters, the infrastructure [law] is trying to save us from driving over bridges that might fall.

"These are all core issues where I think if the American public doesn't see government deliver, I think it's less that they get driven toward one party or another, and more that they get driven away from government altogether."

In fact, according to recent survey data, trust in government is near record lows. Research has shown, too, that people who have had an unpleasant experience with government services are less likely to engage in civic activities like voting—and democracy depends on this kind of involvement from the people it serves.

People invest trust in their government when it works for them. And right now it isn't working.

The disconnect

Bridging the gap between policy and implementation is just what Ramgoolam, the health-care specialist in New York, is doing at her table.

She is a staffer for the Public Engagement Unit of the New York City Mayor's Office, which was first created by Mayor Bill DeBlasio in 2015 and was specifically designed to boost enrollment in underutilized programs. Before this, New Yorkers who needed help had to call 311 for assistance or physically show up at the offices of the Human Resources Administration.

"Unfortunately," says Adrienne Lever, the executive director of the Public Engagement Unit, "there are resources that are underused, and that is just a waste. There is a resource, and there is a person in need. We just need to figure out how to make that connection happen."

Lever told me that often those most in need of benefits are the least equipped to navigate a complex process required to access them, and the discrepancy becomes particularly acute when someone is in crisis.

"PEU's target populations are often lower income. We work with a lot of seniors. Many of them don't have access to computers, let alone the internet. Some are homebound and don't have the ability to go out," Lever explains. "So with those populations in mind, even if the technology is not flawed in and of itself, they may not have the resources or the information to be able to just fill out a simple Google form."

And many applications are much more difficult to navigate than a Google form. Take New York City's Senior Citizen Rent Increase Exemption (SCRIE) program, which enables people over 62 to have their rent frozen, depending on their income, even if a landlord raises the price. The city then reimburses the landlord through a tax credit. The PEU has reached out to 20,000 New Yorkers so far this year who might be eligible for a rent freeze.

Lever told me about one eligible New Yorker, whom she identified only by his first initial. D called the city asking for help renewing his enrollment in the program, but he was missing some required documentation, including a renewed lease. He also had severe cognitive and physical disabilities after suffering a stroke, which made it impossible for him to navigate the rest of the application online, or even with help over the phone.

Benefit programs like SCRIE and those related to health care are particularly troublesome. They're often the product of complex regulation that has been chewed on by many policymakers and regulatory agencies with lots of legal requirements, stipulations, and definitions, necessitating lots of compromises.

The frequent upshot is that these programs are implemented only partially or with so many barriers that they are inaccessible to people most in need. As a result, many policies lose their impact. The SCRIE program, for example, had nearly 76,000 people enrolled as of 2019, though it's estimated that around 135,000 New Yorkers were eligible, according to an October 2022 status report. Many benefit programs in the city—including Fair Fares, which offers lower public transportation prices for eligible travelers, and NYC Care, which increases access to low-cost and no-cost health care—are also underenrolled.

Making matters worse, the system is always growing as more laws are written and more programs are started—but different public benefit programs are administered by different agencies, each with its own databases and registration processes. When people are eligible for a number of separate programs, which is common, they have to work through each of these agencies individually to enroll. New York doesn't currently have a centralized database that manages city benefits, in part because of regulatory constraints that limit data sharing and in part because siloed processes and legacy technology make it difficult to stitch all these processes together.

Virtually every government office across the US faces or has recently faced a similar problem. In 2015, for instance, there were over 450 different websites just for veteran services before the US Digital Service swooped in to overhaul the online registration processes through a redesign of Vets.gov.

As the world moves online, policy implementation that doesn't center citizen accessibility will increasingly lead to undersubscribed benefits programs or laws that, in practice, look very different from what their drafters intended.

Vivek Kundra, who served as the first chief information officer of the United States in the Obama administration, told me that government is working, even if slowly, to adapt to this new reality. "I think we have to reimagine and even rethink what we mean when we talk about policy," Kundra said. "There's going to be a massive impact on the regulatory front that we haven't even conceived yet."

Door knocking for benefits

New York City's Public Engagement Unit has found that it needs to deploy low-tech interventions to bring people into the high-tech ecosystem. Consistent outreach through multiple channels is the most effective way it's found to support people eligible for city programs as they cope with the bureaucratic complexity. Above everything else, the unit's staffers aim to take some of the burden, technological or otherwise, off average city residents.

Lever told me she believes it's the government's responsibility to "help people break through that struggle and find the resources they need to get access to the services that they deserve."

So the unit applies what it calls "campaign tactics" to policy implementation, proactively engaging with New Yorkers through door knocking, phone banking, text messages, emails, and public events to share information about city services like rent assistance, public transportation subsidies, and—of course—health care and help people sign up for them.

The specific outreach approach depends on the population involved. For young people in the city, texts alone might do the trick. If the unit wants to target seniors, it might also start with a mass text campaign, since most people are comfortable with cell phones, and quickly move on to door knocking and in-person support for those who don't respond to texts. To reach those who are not accessible by phone or at home, staffers work with community-based organizations and in public spaces like libraries to meet people in person.

I recently tested the PEU's system, texting the unit to ask for help with my health insurance options. I received an immediate text back and two follow-up calls the same day. When I didn't reply, I continued to get texts and calls consistently throughout the week until I informed them that I did not need help any longer. It was almost annoying, but it was effective.

The PEU has seen that people are significantly more likely to sign up for government programs when the city comes to them, whether it's through texts, calls, or some other approach. In one study of a campaign to enroll New Yorkers in the Fair Fares program, the PEU targeted people already registered in the Supplemental Nutrition Assistance Program (SNAP), since the eligibility requirements are similar. It found that people it texted were 46% more likely to sign up for Fair Fares than those it didn't reach out to. And eligible New Yorkers who texted back were 168% more likely to enroll.

Avoiding techno-solutionist traps

The PEU is proving that more, or more complicated, tech is not always the answer. Shiny tech-savvy government projects touted by politicians can prove to be radical letdowns. Take blockchain voting, which West Virginia briefly piloted during the 2020 election; after much media attention, the experiment was abandoned once it was clear the technology couldn't provide any increased security for electronic voting.

Or consider the rise, and rapid fall, of education technology programs during the pandemic; at first, Zoom and personalized online lessons seemed like a great way to replace in-person teaching, but core learning metrics dipped dramatically across the country.

In many cases, advances in technology meant to help implement public policy have actually harmed people they were supposed to help. Think of electronic health records, which have led to infringements on patient privacy, and even deaths, caused by data errors. Or the use of facial recognition in policing, which is less accurate for Black and brown people, leading to false arrests and actually decreasing public safety for large swaths of the population.

But this hasn't stopped political leaders from pinning their administrations' fates on new technology, even in New York City.

In December 2022, toward the end of his first year in office, Mayor Eric Adams told Politico: "It blows my mind how much we have not embraced technology, and part of that is because many of our electeds are afraid. Anything technology, they think, 'Oh, it's a boogeyman. It's Big Brother watching you.'

"No, Big Brother is protecting you," he added.

The comments have somewhat defined Adams's style in office since. He has supported the deployment of police tech, including facial recognition, and he has prioritized incorporating technological solutions into city programs. This includes finally building a centralized database residents can use for city services—a potential one-stop shop for benefits access.

"The newly launched MyCity online portal will allow New Yorkers to go online [and] easily search, apply for, and track city services and benefits right from their smartphones or computers," Adams said in March 2023. "We are using the power of technology to reduce the bureaucracy and red tape in our government, to help New Yorkers get the services their taxes pay for, and to get stuff done for the working people of this

"My goal and my team's goal is to limit the technical complexity and, as much as possible, also minimize the amount of times that you have to provide the same piece of information."

city." (The mayor's press office did not respond to requests for comment.)

NYC chief technology officer Matt Fraser has high hopes for the project, which will focus first on child-care benefits. (It's a particularly daunting initial target; infant care in New York City costs over $21,000 per year on average, and according to the federal affordability standard, a household would need a combined income of over $300,000 in order to afford that.)

The city offers several subsidized child-care programs, which are administered by at least three separate agencies; the sign-up process previously started with a separate paper form for each of them. In March, MyCity launched a child-care benefit portal that can screen applicants for two of the programs online and at once.

"My goal and my team's goal is to limit the technical complexity and, as much as possible, also minimize the amount of times that you have to provide the same piece of information," Fraser told me.

The ability to go to one website, be screened, and submit one application for all city programs they may be eligible for would be a major upgrade for New Yorkers who struggle to navigate so many disparate, confusing applications today.

The Adams administration isn't the first to try to achieve this, though. In fact, he's the third mayor to attempt to centralize and streamline city benefits enrollment online. And while some more limited projects have had considerable success, like the DeBlasio administration's redesign of the central screening tool Access NYC, no one managed to create and sustain the technology for a comprehensive centralized registration portal.

Ariel Kennan, a product designer and government tech researcher who led the redesign of Access NYC in 2016, told me that MyCity's success depends on both political will and an internal investment in designing human-centered technology. The work of building the portal has been contracted out, as is common with government technology projects, even though Kennan notes that many similar projects have failed after outsourcing. Hiring contractors can lead to slow and expensive procurement cycles, high turnover, and minimal investment in technology and design teams *within* government, which ultimately makes it hard to turn digital services into sustainable, evolving solutions.

Noel Hidalgo, cofounder and executive director of BetaNYC, a civic technology organization, echoes these sentiments. "Technology is a manifestation of bureaucracy and its complexities," he told me. "These systems are built over decades, and we need technologists and designers to go work inside of city government." (Fraser said that government employees "remain very involved" in MyCity.)

For his part, Fraser recognizes the bleak history of government's digital services, but he told me he's committed to making MyCity a success; he sees the project as part of a greater mission. By expanding access to benefits through an easy online interface, MyCity will help "bring equity to government," he said, adding that other initiatives to increase connectivity, digital access, and online literacy in largely offline communities are helping the city close the digital divide.

Still, there are New York residents like D, the senior citizen who was trying to renew his SCRIE benefits. For him, technology simply couldn't replace in-person assistance. After he had an unsuccessful phone call with the PEU, one of the unit's specialists, Hakim Hamsi, showed up at his door and walked him through the forms. Hamsi expedited D's application, and D's rent dropped from $1,000 a month back down to his original rate of $850. D also introduced Hamsi to a neighbor, who now helps him stay on top of his renewal forms.

"All of this takes time," says Hidalgo.

"Government doesn't work at the speed of the internet, and that's fine—so long as it's working to actually address these problems for New Yorkers." ■

Tate Ryan-Mosley is the senior tech policy reporter for MIT Technology Review.

WHEN IT COMES TO SPACECRAFT DESIGN, SCIENTISTS AND

By DAVID W. BROWN — Portraits by Spencer Lowell

The NASA probe's retrorockets pressed desperately against the apricot afternoon skies of Mars. It was November 26, 2018, by Earth's calendar. As the InSight lander worked its way down, slowing from 12,000 miles per hour to a graceful landing, overhead a pair of robots coursing through space monitored its progress. Though InSight was the size of a grand piano and the twin Mars Cube One spacecraft the size of cereal boxes, the lander was, in some sense, the easier challenge. Since the 1970s, we've sent a lot of big things to Mars. Until that moment, we had never sent something so small.

Engineers designed the tiny travel companions to act as radio relays, sending InSight's telemetry back to Earth. Technically their job was a nice-to-have: InSight was landing autonomously, and it would communicate with Earth via the Mars Reconnaissance Orbiter after touching down.

But just making it this far heralded a new age in space exploration. And engineers were only more pleased when the Deep Space Network, a global array of radio antennas, picked up the tiny explorers' real-time signals from Mars. InSight was healthy, said MarCO. Its parachute had

This computer-generated image of Mars was built with laser altimeter data from NASA's Mars Global Surveyor, which operated for nine years in orbit around the planet.

Pushing the limits of solar system exploration

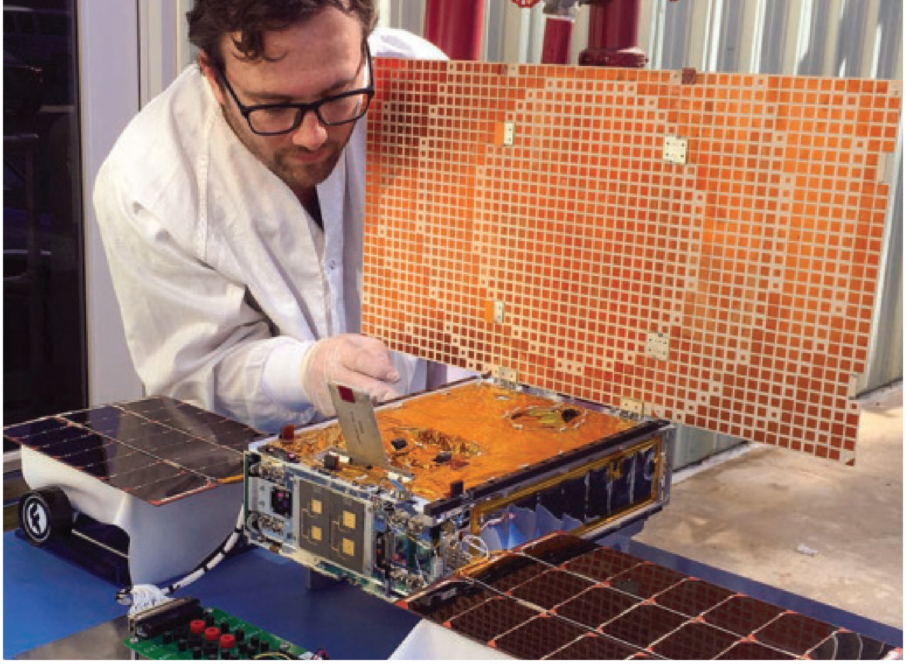
ENGINEERS MUST GRAPPLE WITH HARD CONSTRAINTS.

deployed, the cubes added. The lander had separated from the back-shell and chute; it was on rockets now. One minute later, it was done. InSight, the small spacecraft reported, had survived.

In this diminutive mission, NASA as an agency, and the community of planetary science researchers, caught a glimpse of a future long sought: a pathway to much more affordable space exploration. Each MarCO was the smallest, cheapest spacecraft ever to fly beyond the Earth-moon system. The pair cost less than $20 million to construct, launch, and operate. If engineers could build more such spacecraft—and make them even more capable in the process—they'd be an attractive alternative to multibillion-dollar flagships that launched only every 20 years or so, or even near-billion-dollar probes like InSight.

The media ran with the vision. The Wall Street Journal championed MarCO as the vanguard of a new era of "swarms of tiny probes prowling the solar system." The New York Times reported the potential for "whole fleets of MarCO-like satellites" exploring deep space.

NASA had been quietly building toward the notion of small solar system explorers. In addition to greenlighting



MarCO, it had launched a program to develop other small planetary probes. As MarCO sped toward Mars, making trajectory maneuvers and phoning home like any large spacecraft, Thomas Zurbuchen, then associate administrator for NASA's science mission directorate, declared that every rocket launched by NASA's science program would include a payload adapter for small spacecraft to hitch a lift. "We're not going to ask whether we need it," he said. "You have to convince us that we don't need it."

There was a catch, though—one that NASA soon had to grapple with. Miniaturization can only go so far before it comes to a crashing halt against some very fundamental laws of physics.

"Have you ever heard of a wicked problem?" Alfred Nash asks me.

Five years after the InSight landing, we are in his office on the third floor of the formulation building at the Jet Propulsion Laboratory, NASA's sprawling research and development facility in Pasadena, California. The room is sparsely decorated. He recently changed offices, and many of his things are still in boxes stacked off to the side.

In 1973, he explains, two professors at UC Berkeley published a paper asserting that there are two kinds of problems. One type—the "tame" kind—can be solved with science and brute-force engineering. But there is another sort that is resistant to being solved with math and physics. In these complex problems, a group of stakeholders with differing value propositions want distinct and oftentimes contradictory outcomes. These are the "wicked" problems.

Nash says that when people think of formulating a space mission—turning a probe from scribbles on a notepad into hardware on a lathe—they imagine only the system-level design of a spacecraft. "What valves am I going to use? That kind of thing. But the problem is much, much more complex than that," he says. It is, indeed, a wicked problem, with scientists, engineers, and project managers pulling projects in conflicting directions.

Nash helps design missions for a living. When planetary scientists from NASA and academia want to send robots somewhere strange to study something hard, they come to him and a small cadre at the JPL Innovation Foundry, not only to develop the spacecraft but to figure out what scientific measurements of a celestial object they can actually make given the budget and mass constraints that limit instrument payloads, and where such data would fit in the NASA portfolio.

In one form or another, Nash has touched about half of all current JPL flight projects. Now, to show me what he's talking about, he grabs a marker and draws a Venn diagram of three circles on his office whiteboard. He labels one DESIRABILITY, one FEASIBILITY, and one VIABILITY. Where the three intersect, he writes the word POSSIBILITY. "Rocket science is not the hard part of this job," he says. Before any spacecraft flies, it must satisfy three conditions: a scientist must need the data it can collect, engineers must be able to build it, and NASA must be willing to pay for it. Each step in the development of the mission goes toward strengthening those three things simultaneously—and not everyone can get everything they want. The zero-sum principles of game theory apply; no player can do better without somebody else doing worse. "That's mission design in a nutshell," he says.

NASA science missions generally come in two flavors: directed and competed. The James Webb Space Telescope was a directed mission. NASA headquarters told Goddard Space Flight Center what it wanted built, and for how much. Directed missions tend to be high dollar and high profile. Meanwhile, the asteroid mission Psyche, which was set to launch in October just after this issue went to press, took shape as a competed mission. NASA headquarters issued an "announcement of opportunity" in 2014 for institutions to propose deep-space robotic missions that cost less than $450 million. Researchers in government, industry, and academia developed missions that fit within those parameters. After 28 proposed missions were reviewed in an independent process, the agency selected Psyche, built by JPL, and Lucy, a mission developed by the Southwest Research Institute in Boulder, Colorado. It has already launched and will explore asteroids that share Jupiter's orbit.

Most prominent within the Innovation Foundry are two groups that work on such competed missions, striving to turn an inkling of an idea for a spacecraft into a concept mature enough for NASA to select for flight. Nash leads the A-Team (the A stands for "architecture"), which can bring a space mission from a mere notion to a detailed study with sharply defined science objectives and a plan for how to achieve them. Afterward, a group called Team X takes it from there, using the mission plan to design the actual spacecraft.

ABOVE: Engineer Joel Steinkraus uses sunlight to test the solar arrays on one of the Mars Cube One (MarCO) spacecraft.

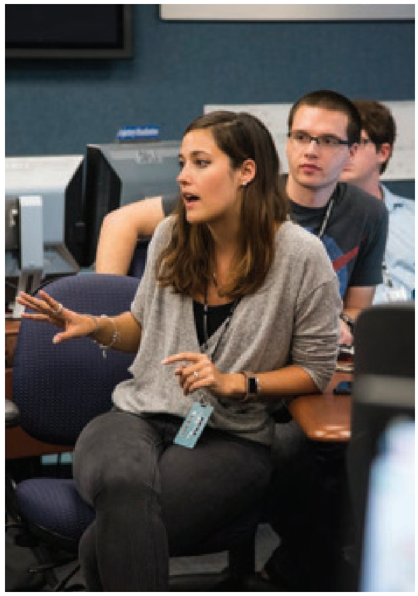
OPPOSITE: Alfred Nash leads the A-Team within the Innovation Foundry at the Jet Propulsion Laboratory.

ABOVE AND PREVIOUS: NASA/JPL-CALTECH


A-TEAM


Mechanical
Power


TEAMX
Jet Propulsion Laboratory




EXIT

JPL created Team X in 1995, during NASA's so-called Faster, Better, Cheaper era. The agency had recently established a planetary program called Discovery, whose initial purpose was to launch one low-cost, tightly constrained mission every 12 to 18 months. To keep up with such an aggressive cadence, the lab needed a way to design, analyze, and evaluate mission concepts rapidly. Team X ultimately developed a system in which experienced engineers, using extensive databases of spacecraft components as well as lessons learned from practically every mission going back to 1958, concurrently design a complete and credible science mission in a matter of days—a plan for an instrumented spacecraft able to make specific measurements at specific places for a specific cost.

In 2012, JPL stood up the A-Team to help scientists get a better grip on the science and architecture of their missions before subjecting them to the intensity of Team X. The A-Team, which meets in a room called Left Field ("because that's where good ideas come from"), helps scientists develop testable hypotheses, determine the measurements and scientific instruments necessary to assess them, and work out the best type of mission to carry those instruments: perhaps it's an orbiter, a flyby, or a six-wheeled, nuclear-powered car. In terms of Nash's Venn diagram, the A-Team endeavors to sketch out a mission that sits in the middle: one that will give scientists the data they want, be something that engineers can build, and merit NASA's approval to buy and fly.

OPPOSITE: Two groups within the Innovation Foundry turn ideas into mature concepts for NASA: the A-Team (the A stands for "architecture") defines the science objectives and devises the mission plan, and Team X designs the actual spacecraft.

After leaving Left Field, scientists take their proposed mission to the Team X project design center. For two or three days, they sit beside engineers in a room that looks something like a computer science classroom, with multiple rows of workstations. Signs emblazoned with words like "Propulsion," "Cost," Mechanical," and "Telecom" sit atop each console. There, the sky is not the limit. You are going to make some very hard choices. Every NASA spacecraft is an expensive box of compromises. In one corner of the room, engineers have hung a sign describing the five stages of grief.

Every decision the spacecraft designers make has cascading effects. Science goals affect the instrument payload necessary for a successful mission. The instrument payload affects the command and data subsystems (which handle signals sent from Earth and data to be returned). This, in turn, affects spacecraft telecommunications hardware (which performs the actual transmissions). It can affect the power necessary to keep the spacecraft alive. And so on. If scientists desire something as seemingly simple as a higher-resolution image, dominoes can fall in such a way that the spacecraft can no longer regulate its fuel temperature or is too heavy to launch.

In developing a spacecraft, Team X engineers for each subsystem work in parallel. You're building a house all at once. While someone is building the chimney, someone else is building the roof and another is designing the air-conditioning system. Because each spacecraft subsystem affects every other, consoles are arranged so that the people who need to talk to each other can lean over and chat easily. Periodically, the team checks to see whether the spacecraft design "closes"—whether the myriad parts of the system work with each other to form an internally consistent whole that achieves its objectives given the space provided and for the correct price.

These studies, which generally take three days or less, can be intense for would-be mission teams. "You're sitting there starstruck," says Lindy Elkins-Tanton, the principal investigator for Psyche, a mission matured in the Innovation Foundry. "All the consoles with all the experts are manipulating subsystems, and numbers are clicking this way and that, and mass and power and dollar totals are changing, and the experts are shouting back and forth with each other." *If we use this trajectory, how much xenon do you need? If we measure this instead of that, how do your power needs change? What mass is that instrument? What kind of orbit control will achieve that?* She says it has an energy similar to Mission Control, in terms of focus and import.

The systems do not always close—they didn't at first with Psyche, even after two rounds with Team X. Scientists often must reconsider their goals in the face of mass, power, fuel, or funding.

"During the process, I was feeling really good," Elkins-Tanton says. "We had made the hard decisions, we brought really useful information, we could get the power, we could get the mass—and then cost came through way above the cost cap. I almost couldn't believe it. I just thought, 'That's not possible.'" Eventually, the Psyche team opted to use an off-the-shelf spacecraft bus, the component that forms the main body of the spacecraft. It was much less expensive than the custom-made bus they'd originally planned to build, and that solved the cost problem.

"To me, the magic of Team X is it gives you structure, and it gives you the perspective of what a mission looks like [to] a disinterested outside party," she says. A team of scientists can go into Team X having convinced each other of the rightness of their plan, their prospective payload, and the measurements they intend to make. In some of those cases, she notes, "it is very important for someone to tell you, *I'm sorry, but that does not work*."

Mission competitions are relatively rare. NASA released the announcement of opportunity for its most recent small, sub-billion-dollar Discovery-class mission in 2019. The agency will not likely release another until 2025 at the soonest—and Discovery missions are the competitions that run most frequently. Missions in the billion-dollar New Frontiers class are rarer still,

NASA/JPL-CALTECH (RIGHT COLUMN)

and their destinations tend to be tied to a short list identified in the Decadal Survey, a community report written by planetary scientists that is released every 10 years. The most recent list, announced in 2022, called for missions to three targets in the Saturnian system as well as three missions to small bodies, one to the moon, and one to the surface of Venus.

If for no other reason, then, the availability of a new class of miniature, inexpensive spacecraft of the MarCO variety is deeply enticing to planetary scientists. In 2014, NASA headquarters created the Small, Innovative Missions for Planetary Exploration program, or SIMPLEx, to fund such small, high-risk (failure is an option) planetary science probes. In addition, in 2016 the agency commissioned concept studies for deep-space planetary science missions that could employ small satellites, individually or in constellations. There is no universally agreed-upon definition of a small sat, but they are generally less than 2,600 pounds (though they can be as small as a postage stamp). The most recent SIMPLEx announcement of opportunity limits small sats for non-Earth missions to dimensions that would fit on a specific payload adapter—about the size of a dorm-room fridge and a weight of 400 pounds. A "cube sat," such as MarCO, is formally defined as one or more 10-centimeter-wide cubes, each weighing about four pounds.

Scientists submitted 102 proposals to the 2016 study, 19 of which NASA funded for further analysis. Two years later, Zurbuchen, then the associate administrator of NASA's Science Mission Directorate, announced an annual $100 million investment in small sats, more than half of which would go toward planetary science missions.

And yet today, though small sats of every flavor circle the Earth, no swarms darken the skies of other worlds. Five years is not an enormous span of time in deep-space exploration, but JPL developed Mars Pathfinder, the first rover on another planet, in three. Surely building a Neptune orbiter the size of a shoebox should have been trivial in comparison, especially in an age of advanced semiconductors and reusable rocketry.

In developing a spacecraft, Team X engineers for each subsystem work in parallel. You're building a house all at once. While someone is building the chimney, someone else is building the roof and another is designing the air-conditioning system.

Earlier this year, the European Space Agency launched the Juice mission to study Jupiter and three of its moons. Next year, NASA will launch Europa Clipper to the same system, focusing on the moon that could potentially harbor extant life. Neither spacecraft will carry small sat companions. No follow-on to MarCO accompanied the Perseverance rover to Mars in 2020, either. (Perseverance did carry a four-pound helicopter to the surface, though neither NASA nor JPL described it as a cube sat.) Psyche was set to launch with cube sats, but NASA put the small spacecraft in cold storage when Psyche's schedule slipped. Agency officials have hopes, but no plans, to launch them.

To the extent that the most recent Decadal Survey even mentioned cube sats or small sats, it was to request more money for them. It also recommended that NASA pursue a flagship Uranus orbiter and probe for $4.2 billion. But why put "all eggs in one basket" on a flagship, as Zurbuchen warned when announcing the $100 million program, when you could build many small sats?

In part, Nash explained, it is a matter of mission design. The simple novelty of a spacecraft—in this case, an extremely small spacecraft—is not an adequate reason to fly it.

A small sat sent to Mars faces a daunting task because we already know so much about the planet. It wasn't always so. Before 1965, we had no idea what the surface of Mars looked like beyond what we could see through our Earth-bound telescopes. Every picture the Mars probe Mariner 4 returned was thus game-changing. "The universe is not so much that way anymore," Nash says. "We're victims of our own success. The science floor is moving up all the time."

And when it comes to designing a capable small spacecraft, engineers are up against formidable foes. Nash first noticed them during the NASA-funded 2016 concept studies. The agency had sent several of the prospective projects to Team X for development. For days Nash, who at the time was its lead engineer, worked alongside Alex Austin, the lead engineer for Team Xc, the Innovation Foundry group dedicated to small sats. Amid the din of spacecraft development, with consoles working though thermal, telecom, fuel, and computer issues—"That instrument won't work" and "That mass is too high" and "That's not enough power"—Nash and Austin felt they were beating their heads against a wall. Forget issues like radiation shielding or autonomy at Jupiter—they couldn't even seem to get a cube sat into orbit around Mars, something we've been doing with large satellites for more than 50 years. Scientists wanted images at a certain resolution, but the cube sats couldn't carry a camera capable of it. Once at their targets, they were unable to get data back to Earth. A small sat could reach its destination but would then just fly right on by it, because it had no way of slowing down.

After a particularly grim day in the project design center, they walked back to their desks, grumbling all the way, vexed and annoyed. Between the two of them, they had participated in hundreds and hundreds of studies, tackling practically every engineering problem a space program could muster—and still, the designs of these little shoeboxes proved resistant to closure.

Austin pulled out his desk chair, slumped into it, and leaned back in head-pounding thought.

"It's those dead Europeans!" Nash exclaimed from his own desk.

OPPOSITE:
Alex Austin is the lead engineer for Team Xc, the Innovation Foundry group dedicated to small satellites.

BELOW:
Austin displays a full-scale, 3D-printed model of a 1.5-unit cube sat (one unit is a cube 10 centimeters on a side).

I met Austin and Nash in Left Field to find out who these Europeans were and what, exactly, their problem was. Austin is young and beardless, where Nash's beard is going gray. A Dumbledore/Harry Potter comparison is too facile, but not absurd.

"The thing that enabled small sats is the miniaturization of electronics," says Austin. "And that's great—but alone, it's not enough for planetary missions, which have to deal with really hard physics first described by dead Europeans."

Thousands of small sats fly above Earth today. They can be launched from the International Space Station, from small rockets, even from high-altitude balloons. Among the more high-profile of these spacecraft are the Starlink constellation (though the size of its individual satellites is growing with each iteration); Planet Labs' Earth-imaging Dove satellites; the Cyclone Global Navigation Satellite System developed by NASA, the University of Michigan, and the Southwest Research Institute, which measures the wind speed inside hurricanes; and NASA and MIT Lincoln Laboratory's TROPICS, a painful acronym for "Time-Resolved Observations of Precipitation structure and storm Intensity with a Constellation of Smallsats" (which does what the name suggests).

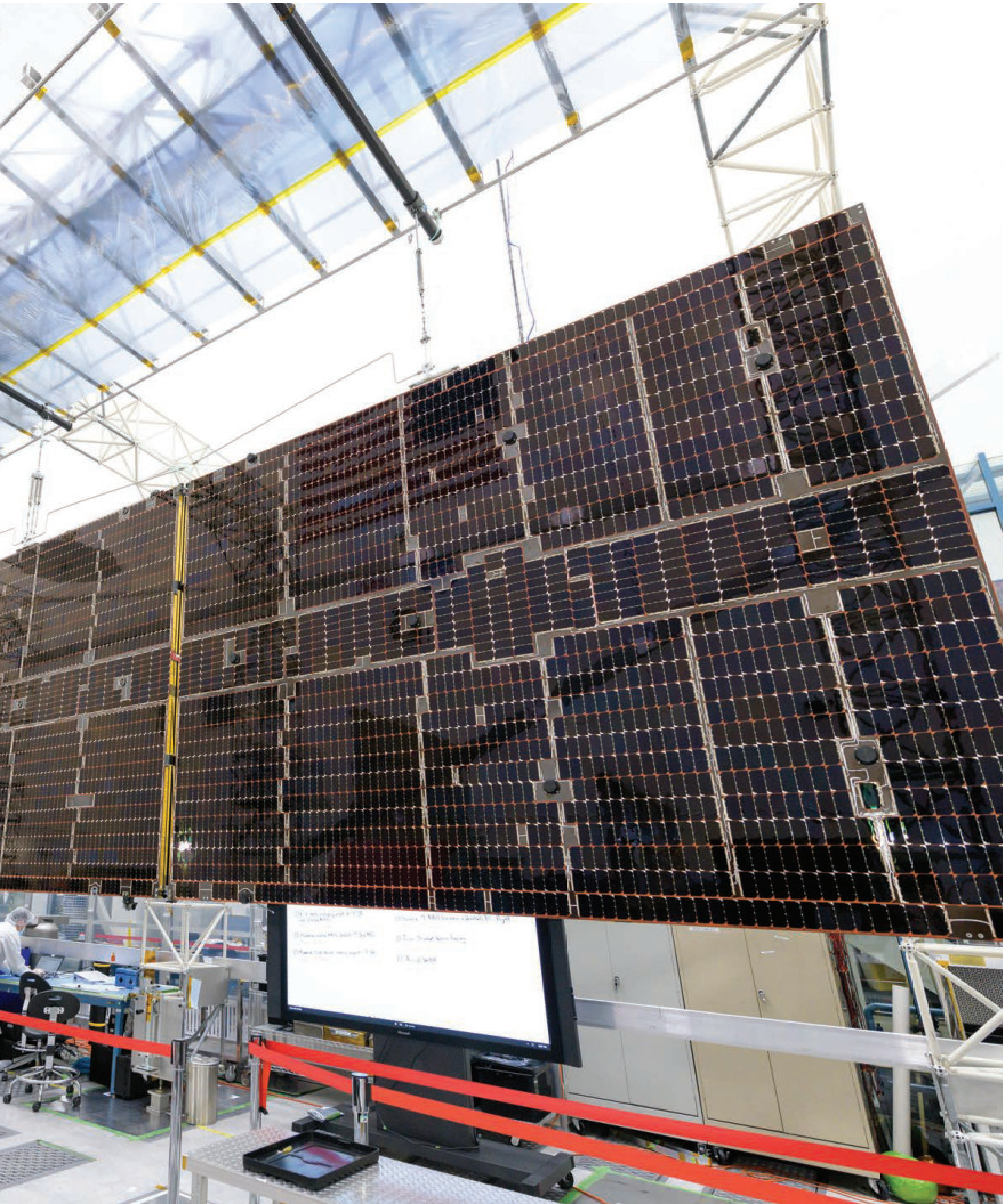
It is not a NASA-only club, either. Among others, the European Space Agency, the Indian Space Research Organization, and the China National Space Administration have launched cube sats to study everything from the weather to civil aircraft traffic. In 2020, the Japan Aerospace Exploration Agency launched one with two action figures on board, so they could be imaged in front of the Earth as part of a promotion for the Olympics and Paralympics.

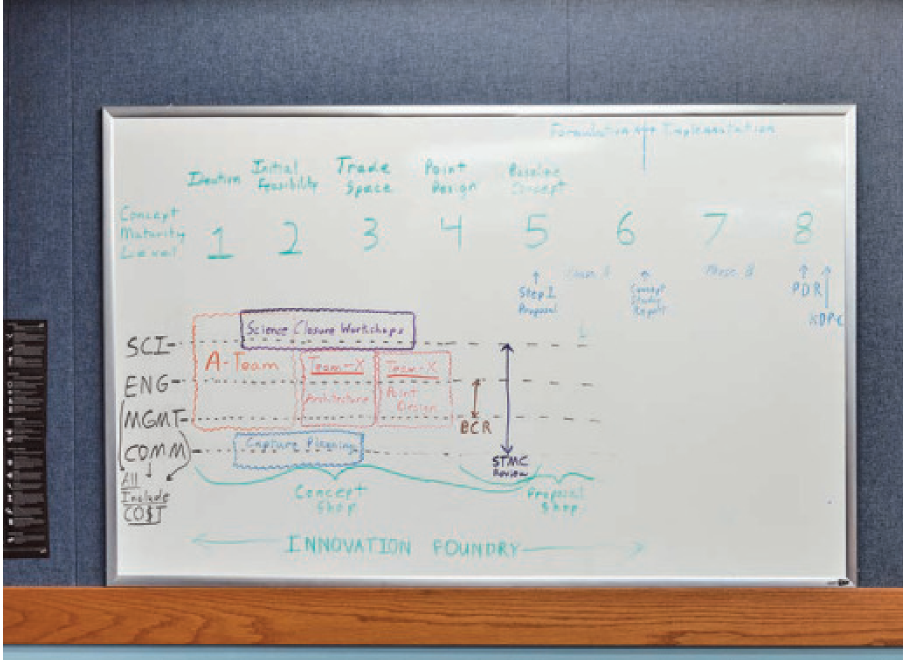
Given such successes in Earth's orbit, and NASA's desire to launch less expensive missions more frequently, it surprises no one that scientists want to send small sats to orbit other worlds. But as Nash and Austin realized, it is not so simple.

You can start with pretty much any subsystem to see the limits. Consider the need for high-resolution images. The higher the resolution, the larger the aperture size of the camera must be, as the British physicist Lord Rayleigh determined in a famous equation in the 19th century. But small spacecraft can only hold cameras so large.

Even if you could find a way around this fundamental concept in optics, you've got to get your data home. High-resolution images use large amounts of data. As the quantity of data grows, so do the mass requirements of the telecom subsystem and the necessary power source. The antenna and commensurate power requirements are driven by the Friis transmission equation, worked out by the Danish-American engineer Harald Friis.

A solar array on NASA's Psyche spacecraft is deployed in JPL's High Bay 2 clean room.





ABOVE: "Rocket science is not the hard part of this job," Nash says when discussing mission design.

OPPOSITE: Kelley Case leads the Innovation Foundry's Concept Office.

Augustin-Louis Cauchy, the French mathematician who founded the field of continuum mechanics, would insist on dedicating more spacecraft mass to withstanding the mechanical stress of launch. His equations for the distribution of forces through a material say that a six-pound cube sat, atop a Falcon Heavy with 5 million pounds of thrust, will need to be pretty tough.

As the spacecraft mass slowly creeps up, the reaction wheels necessary for pointing it this way or that likewise grow in size, as Isaac Newton and his laws of motion would explain. And the farther the small sat gets from the sun, the less solar energy it receives, as the Scottish physicist James Clerk Maxwell could (and did) tell you.

Then there is the temperature of the spacecraft. The requirements for thermal equilibrium, which it must maintain, vary on the basis of mass and volume. A hot spacecraft needs to dissipate the heat. A cold spacecraft needs to heat itself (which also affects the power subsystems). Principles articulated by the 19th-century Austrian physicist Ludwig Boltzmann describe the difficult thermal situation for a flying shoebox.

Perhaps the most daunting of all the dead Europeans is the Russian rocket scientist Konstantin Tsiolkovsky, because his rocket equation is so unforgiving. It calculates the change in a spacecraft's velocity as it uses fuel and ejects exhaust. In short, a spacecraft's mass diminishes as it uses propellant. The lower the mass, the faster the spacecraft flies. This becomes precarious when a spacecraft needs to slow down and enter orbit around a target: it needs more propellant yet, which requires a bigger tank to hold it, which requires more propellant to push the bigger tanks, and so on—and all this affects other subsystems like thermal protection, to keep the propellant at the correct temperature.

Overcoming all these problems becomes increasingly difficult as you travel farther from Earth. But, as demonstrated in 2018, it is not impossible with the right design.

"MarCO was our first Team Xc study," says Kelley Case, head of the Innovation Foundry's Concept Office, who joined us in Left Field. "At that point, there were not that many cube sat missions, and people were excited about it." As originally envisioned, Case explains, drawing the mission in the air with her finger, MarCO would put two cube sats in Martian orbit to do radio occultation science, sending radio signals to each other as a way of studying the atmosphere. During the Team X process, however, engineers realized that it was infeasible for the MarCO craft to fly to Mars and enter orbit on their own.

"So the MarCO team pivoted, which is really important as a case study for other small sat missions," she says. "They said, *Okay, let's not focus on what science we could do. What could we do with a cube sat at Mars, period?*"

The answer: solve the communications blackout invariably faced by Mars landers. "InSight was its opportunity," she says.

Austin calls MarCO a huge achievement, not only for what it did, but for what it forced scientists and engineers to do. "We are very proud of MarCO, but there is a reason that MarCO worked: It was a very focused mission. It was a flyby. They didn't have to deal with a lot of these physics problems." It is not that exploring other planets with small sats is impossible, he explains. "If someone came to me and said they absolutely want to do a cube sat at Uranus, there is some mission there—I'm just not sure if it's the mission they really want."

SIMPLEx missions are standalone projects; a small sat must address all the problems of classical physics on its own (once it gets into space). A new mission class could help solve that, says Austin. "There is no medium class after SIMPLEx. You jump straight to Discovery. I would argue that NASA should consider something that is in the middle that would allow you to conquer a few more dead Europeans." Such a class could afford larger spacecraft to ferry small sats to bodies, for example—offloading Tsiolkovsky—or carry communications relays, thwarting Friis. (In a similar fashion, there has been talk of using NASA's Lunar Gateway space station, currently slated to launch in 2025, to deploy small spacecraft from lunar orbit.)

For now, the scientific community should take note of small sats' successes over the Earth. "Earth science small sat missions are leading the way for planetary ones," Austin says. They deal with vastly fewer dead-European problems, yes—but Earth scientists are also thinking in new and interesting ways about how to leverage the unique strengths of small sats, rather than simply trying to stuff big-satellite science into a small box.

For example, the Investigation of Convective Updrafts (INCUS) mission, currently slated to launch in a few years, will place three cube sats in sequential orbit around Earth to study how storms form. The cube sats will not contain the most powerful radars ever built, but they will do something those radar systems cannot: visit the same place in rapid succession,

PREVIOUS SPREAD: NASA/JPL-CALTECH

“If someone came to me and said they absolutely want to do a cube sat at Uranus, there is some mission there—I’m just not sure if it’s the mission they really want.”

seeing how storms evolve in a short period of time.

“It’s not the same question a large satellite might ask, but better,” says Nash. “It is an orthogonal question. It is a question that has never been asked, because you couldn’t ask it with the other system.”

So far, NASA has flown only two SIMPLEx missions, both of which failed in their primary science objectives, and neither of which was sent to targets outside the Earth-moon system. And only two of the 10 US and international cube sats that launched on the Artemis 1 moon mission flew without issue. There have also been great successes. One week before NASA’s DART intentionally crashed into the asteroid Dimorphos, it released a cube sat called LICIACube, which was built by the Italian Space Agency. The shoebox-size probe, having hitched a ride and thus evaded the tyranny of Tsiolkovsky, successfully imaged DART’s final moments.

More missions are on the way. Annual budgets fluctuate, but NASA continues to fund small sats at or near the $100 million levels promised by Zurbuchen. Although most of the money goes to spacecraft studying Earth, the sun, and the stars, planetary science remains an agency priority. Among the funded projects is Lunar Trailblazer, a SIMPLEx mission to map water on the moon, which should launch next year.

Other countries have upcoming projects of their own. Next year, for example, the European Space Agency will launch Hera, a follow-on to the DART mission. It will carry two cube sats to study the composition and structure of the asteroid—precisely the sort of mission that would be necessary if a killer asteroid were inbound.

These may seem like small steps for small spacecraft. They are certainly still far from the vision of swarms skimming along Saturn’s rings and sampling the ice spewing from its moon Enceladus. But it is exploration nonetheless. ■

David W. Brown is a writer based in New Orleans. His next book, The Outside Cats, is about a team of polar explorers and his expedition with them to Antarctica. It will be published by Mariner Books.

How to fix the internet

If we want online discourse to improve, we need to move beyond the big platforms.

By Katie Notopoulos
Illustrations by Erik Carter

We're in a very strange moment for the internet. We all know it's broken. That's not news. But there's something in the air—a vibe shift, a sense that things are about to change. For the first time in years, it feels as though something truly new and different might be happening with the way we communicate online. The stranglehold that the big social platforms have had on us for the last decade is weakening. The question is: What do we want to come next?

There's a sort of common wisdom that the internet is irredeemably bad, toxic, a rash of "hellsites" to be avoided. That social platforms, hungry to profit off your data, opened a Pandora's box that cannot be closed. Indeed, there are truly awful things that happen on the internet, things that make it especially toxic for people from groups disproportionately targeted with online harassment and abuse. Profit motives led platforms to ignore abuse too often, and they also enabled the spread of misinformation, the decline of local news, the rise of hyperpartisanship, and entirely new forms of bullying and bad behavior. All of that is true, and it barely scratches the surface.

But the internet has also provided a haven for marginalized groups and a place for support, advocacy, and community. It offers information at times of crisis. It can connect you with long-lost friends. It can make you laugh. It can send you a pizza. It's duality, good and bad, and I refuse to toss out the dancing-baby GIF with the tubgirl-dot-png bathwater. The internet is worth fighting for because despite all the misery, there's still so much good to be found there. And yet, fixing online discourse is the definition of a hard problem. But look. Don't worry. I have an idea.

What is the internet and why is it following me around?

To cure the patient, first we must identify the disease.

When we talk about fixing the internet, we're not referring to the physical and digital network infrastructure: the protocols, the exchanges, the cables, and even the satellites themselves are mostly okay. (There are problems with some of that stuff, to be sure. But that's an entirely other issue—even if both do involve Elon Musk.) "The internet" we're talking about refers to the popular kinds of communication platforms that host discussions and that you probably engage with in some form on your phone.

Some of these are massive: Facebook, Instagram, YouTube, Twitter, TikTok, X. You almost certainly have an account on at least one of these; maybe you're an active poster, maybe you just flip through your friends' vacation photos while on the john.

Although the exact nature of what we see on those platforms can vary widely from person to person, they mediate content delivery in universally similar ways that are aligned with their business objectives. A teenager in Indonesia may not see the same images on Instagram that I do, but the experience is roughly the same: we scroll through some photos from friends or family, maybe see some memes or celebrity posts; the feed turns into Reels; we watch a few videos, maybe reply to a friend's Story or send some messages. Even though the actual content may be very different, we probably react to it in much the same way, and that's by design.

The internet also exists outside these big platforms; it's blogs, message boards, newsletters and other media sites. It's podcasts and Discord chatrooms and iMessage

groups. These will offer more individualized experiences that may be wildly different from person to person. They often exist in a sort of parasitic symbiosis with the big, dominant players, feeding off each other's content, algorithms, and audience.

The internet is good things. For me, it's things I love, like Keyboard Cat and Double Rainbow. It's personal blogs and LiveJournals; it's AIM away messages and MySpace top 8s. It's the distracted-girlfriend meme and a subreddit for "What is this bug?" It is a famous thread on a bodybuilding forum where meatheads argue about how many days are in a week. For others, it's Call of Duty memes and the mindless entertainment of YouTubers like Mr. Beast, or a place to find the highly specific kind of ASMR video they never knew they wanted. It's an anonymous supportive community for abuse victims, or laughing at Black Twitter's memes about the Montgomery boat brawl, or trying new makeup techniques you learned on TikTok.

It's also very bad things: 4chan and the Daily Stormer, revenge porn, fake news sites, racism on Reddit, eating disorder inspiration on Instagram, bullying, adults messaging kids on Roblox, harassment, scams, spam, incels, and increasingly needing to figure out if something is real or AI.

The bad things transcend mere rudeness or trolling. There is an epidemic of sadness, of loneliness, of meanness, that seems to self-reinforce in many online spaces. In some cases, it is truly life and death. The internet is where the next mass shooter is currently getting his ideas from the last mass shooter, who got them from the one before that, who got them from some of the earliest websites online. It's an exhortation to genocide in a country where Facebook employed too few moderators who spoke the local language because it had prioritized growth over safety.

The existential problem is that both the best and worst parts of the internet exist for the same set of reasons, were developed with many of the same resources, and often grew in conjunction with each other. So where did the sickness come from? How did the internet get so … nasty? To untangle this, we have to go back to the early days of online discourse.

The internet's original sin was an insistence on freedom: it was made to be free, in many senses of the word. The internet wasn't initially set up for profit; it grew out of a communications medium intended for the military and academics (some in the military wanted to limit Arpanet to defense use as late as the early 1980s). When it grew in popularity along with desktop computers, Usenet and other popular early internet applications were still largely used on university campuses with network access. Users would grumble that each September their message boards would be flooded with newbies, until eventually the "eternal September"—a constant flow of new users—arrived in the mid-'90s with the explosion of home internet access.

When the internet began to be built out commercially in the 1990s, its culture was, perversely, anticommercial. Many of the leading internet thinkers of the day belonged to a cohort of AdBusters-reading Gen Xers and antiestablishment Boomers. They were passionate about making software open source. Their very mantra was "Information wants to be free"—a phrase attributed to Stewart Brand, the founder of the Whole Earth Catalog and the pioneering internet community the WELL. This ethos also extended to a passion for freedom of speech, and a sense of responsibility to protect it.

It just so happened that those people were quite often affluent white men in California, whose perspective failed to predict the dark side of the free-speech, free-access havens they were creating. (In fairness, who would have imagined that the end result of those early discussions would be Russian disinformation campaigns targeting Black Lives Matter? But I digress.)

The culture of free demanded a business model that could support it. And that was advertising. Through the 1990s and even into the early '00s, advertising on the internet was an uneasy but tolerable trade-off. Early advertising was often ugly and annoying: spam emails for penis enlargement pills, badly designed banners, and (*shudder*) pop-up ads. It was crass but allowed the nice parts of the internet—message boards, blogs, and news sites—to be accessible to anyone with a connection.

But advertising and the internet are like that small submersible sent to explore the *Titanic*: the carbon fiber works very efficiently, until you apply enough pressure. Then the whole thing implodes.

Targeted advertising and the commodification of attention

In 1999, the ad company DoubleClick was planning to combine personal data with tracking cookies to follow people around the web so it could target its ads more effectively. This changed what people thought was possible. It turned the cookie, originally a neutral technology for storing Web data locally on users' computers, into something used for tracking individuals across the internet for the purpose of monetizing them.

The internet is good things.

It's Keyboard Cat, Double Rainbow. It's personal blogs and LiveJournals. It's the distracted-girlfriend meme and a subreddit for "What is this bug?"

To the netizens of the turn of the century, this was an abomination. And after a complaint was filed with the US Federal Trade Commission, DoubleClick dialed back the specifics of its plans. But the idea of advertising based on personal profiles took hold. It was the beginning of the era of targeted advertising, and with it, the modern internet. Google bought DoubleClick for $3.1 billion in 2008. That year, Google's revenue from advertising was $21 billion. Last year, Google parent company Alphabet took in $224.4 billion in revenue from advertising.

Our modern internet is built on highly targeted advertising using our personal data. That is what makes it free. The social platforms, most digital publishers, Google—all run on ad revenue. For the social platforms and Google, their business model is to deliver highly sophisticated targeted ads. (And business is good: in addition to Google's billions, Meta took in $116 billion in revenue for 2022. Nearly half the people living on planet Earth are monthly active users of a Meta-owned product.) Meanwhile, the sheer extent of the personal data we happily hand over to them in exchange for using their services for free would make people from the year 2000 drop their flip phones in shock.

And that targeting process is shockingly good at figuring out who you are and what you are interested in. It's targeting that makes people think their phones are listening in on their conversations; in reality, it's more that the data trails we leave behind become road maps to our brains.

When we think of what's most obviously broken about the internet—harassment and abuse; its role in the rise of political extremism, polarization, and the spread of misinformation; the harmful effects of Instagram on the mental health of teenage girls—the connection to advertising may not seem immediate. And in fact, advertising can sometimes have a mitigating effect: Coca-Cola doesn't want to run ads next to Nazis, so platforms develop mechanisms to keep them away.

But online advertising demands attention above all else, and it has ultimately enabled and nurtured all the worst of the worst kinds of stuff. Social platforms were incentivized to grow their user base and attract as many eyeballs as possible for as long as possible to serve ever more ads. Or, more accurately, to serve ever more you to advertisers. To accomplish this, the platforms have designed algorithms to keep us scrolling and clicking, the result of which has played into some of humanity's worst inclinations.

In 2018, Facebook tweaked its algorithms to favor more "meaningful social interactions." It was a move meant to encourage users to interact more with each other and ultimately keep their eyeballs glued to News Feed, but it resulted in people's feeds being taken over by divisive content. Publishers began optimizing for outrage, because that was the type of content that generated lots of interactions.

On YouTube, where "watch time" was prioritized over view counts, algorithms recommended and ran videos in an endless stream. And in their quest to sate attention, these algorithms frequently led people down ever more labyrinthine corridors to the conspiratorial realms of flat-earth truthers, QAnon, and their ilk. Algorithms on Instagram's Discover page are designed to keep us scrolling (and spending) even after we've exhausted our friends' content, often by promoting popular aesthetics whether or not the user had previously been interested. The Wall Street Journal reported in 2021 that Instagram had long understood it was harming the mental health of teenage girls through content about body image and eating disorders, but ignored those reports. Keep 'em scrolling.

There is an argument that the big platforms are merely giving us what we wanted. Anil Dash, a tech entrepreneur and blogging pioneer who worked at SixApart, the company that developed the blog software Movable Type, remembers a backlash when his company started charging for its services in the mid-'00s. "People were like, 'You're charging money for something on the internet? That's disgusting!'" he told MIT Technology Review. "The shift from that to, like, *If you're not paying for the product, you're the product* … I think if we had come up with that phrase sooner, then the whole thing would have been different. The whole social media era would have been different."

The big platforms' focus on engagement at all costs made them ripe for exploitation. Twitter became a "honeypot for a**holes" where trolls from places like 4chan found an effective forum for coordinated harassment. Gamergate started in swampier waters like Reddit and 4chan, but it played out on Twitter, where swarms of accounts would lash out at the chosen targets, generally female video-game critics. Trolls also discovered that Twitter could be gamed to get vile phrases to trend: in 2013, 4chan accomplished this with #cuttingforbieber, falsely claiming to represent teenagers engaging in self-harm for the pop singer. Platform dynamics created such a target-rich environment that intelligence services from Russia, China, and Iran—among others—use them to sow political division and disinformation to this day.

"Humans were never meant to exist in a society that contains 2 billion individuals," says Yoel Roth, a technology policy fellow at UC Berkeley and former head of trust and safety for Twitter. "And if you consider that Instagram is a society in some twisted definition, we have tasked a company with governing a society bigger than any that has ever existed in the course of human history. Of course they're going to fail."

How to fix it

Here's the good news. We're in a rare moment when a shift just may be possible; the previously intractable and permanent-seeming systems and platforms are showing that they can be changed and moved, and something new could actually grow.

One positive sign is the growing understanding that sometimes … you have to pay for stuff. And indeed, people are paying individual creators and publishers on platforms such as Substack, Patreon, and Twitch. Meanwhile, the freemium model that YouTube Premium, Spotify, and Hulu explored proves (some) people are willing to shell out for ad-free experiences. A world where only the people who can afford to pay $9.99 a month to ransom back their time and attention from crappy ads isn't ideal, but at least it demonstrates that a different model will work.

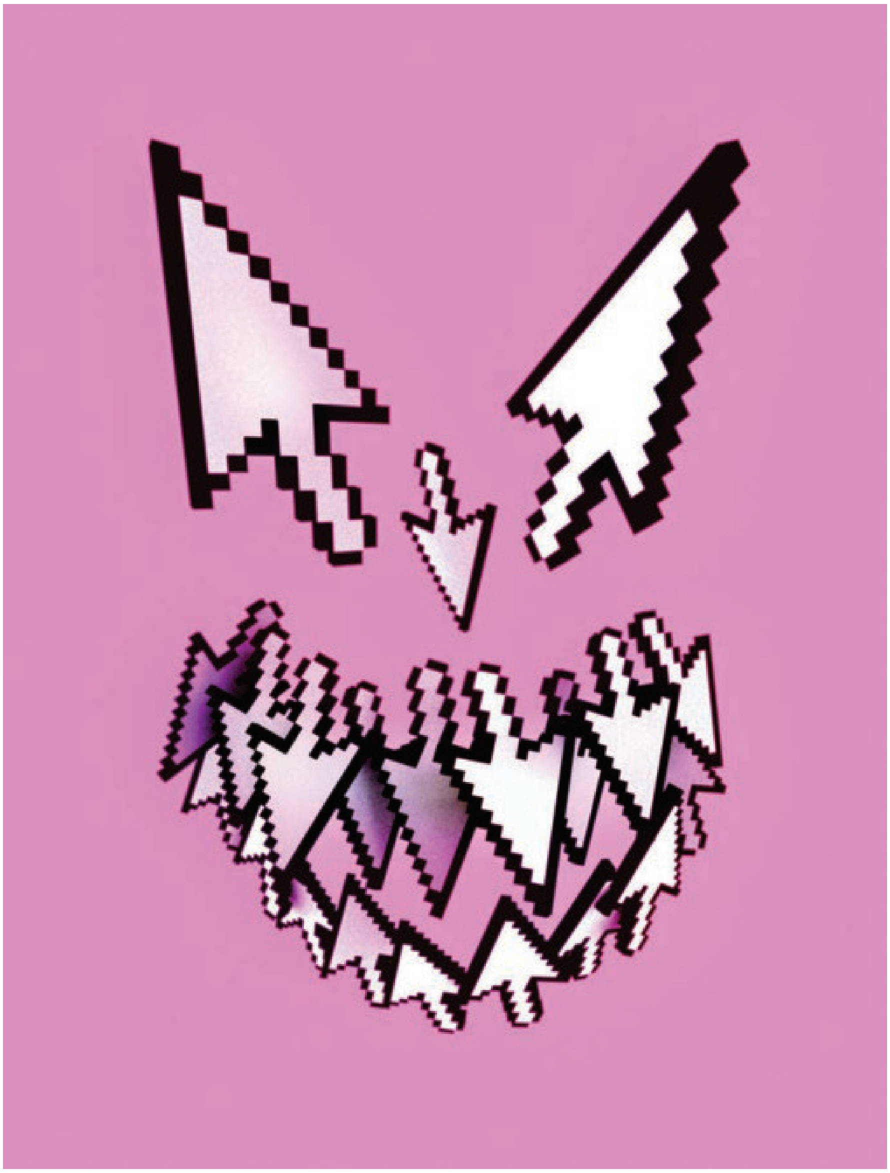
Another thing to be optimistic about (although time will tell if it actually catches on) is federation—a more decentralized version of social networking. Federated networks like Mastodon, Bluesky, and Meta's Threads are all just Twitter clones on their surface—a feed of short text posts—but they're also all designed to offer various forms of interoperability. Basically, where your current social media account and data exist in a walled garden controlled entirely by one company, you could be on Threads and follow posts from someone you like on Mastodon—or at least Meta says that's coming. (Many—including internet pioneer Richard Stallman, who has a page on his personal website devoted to "Why you should not be used by Threads"—have expressed skepticism of Meta's intentions and promises.) Even better, it enables more granular moderation. Again, X (the website formerly known as Twitter) provides a good example of what can go wrong when one person, in this case Elon Musk, has too much power in making moderation decisions—something federated networks and the so-called "fediverse" could solve.

The big idea is that in a future where social media is more decentralized, users will be able to easily switch networks without losing their content and followings. "As an individual, if you see [hate speech], you can just leave, and you're not leaving your entire community—your entire online life—behind. You can just move to another server and migrate all your contacts, and it should be okay," says Paige Collings, a senior speech and privacy advocate at the Electronic Frontier Foundation. "And I think that's probably where we have a lot of opportunity to get it right."

There's a lot of upside to this, but Collings is still wary. "I fear that while we have an amazing opportunity," she says,

It's also very bad things:

4chan and the Daily Stormer, revenge porn, fake news sites, racism on Reddit, eating disorder inspiration on Instagram, bullying, adults messaging kids on Roblox, harassment, scams, spam, incels.



"unless there's an intentional effort to make sure that what happened on Web2 does not happen on Web3, I don't see how it will not just perpetuate the same things."

Federation and more competition among new apps and platforms provide a chance for different communities to create the kinds of privacy and moderation they want, rather than following top-down content moderation policies created at headquarters in San Francisco that are often explicitly mandated not to mess with engagement. Yoel Roth's dream scenario would be that in a world of smaller social networks, trust and safety could be handled by third-party companies that specialize in it, so social networks wouldn't have to create their own policies and moderation tactics from scratch each time.

The tunnel-vision focus on growth created bad incentives in the social media age. It made people realize that if you wanted to make money, you needed a massive audience, and that the way to get a massive audience was often by behaving badly. The new form of the internet needs to find a way to make money without pandering for attention. There are some promising new gestures toward changing those incentives already. Threads doesn't show the repost count on posts, for example—a simple tweak that makes a big difference because it doesn't incentivize virality.

We, the internet users, also need to learn to recalibrate our expectations and our behavior online. We need to learn to appreciate areas of the internet that are small, like a new Mastodon server or Discord or blog. We need to trust in the power of "1,000 true fans" over cheaply amassed millions.

Anil Dash has been repeating the same thing over and over for years now: that people should buy their own domains, start their own blogs, own their own stuff. And sure, these fixes require a technical and financial ability that many people do not possess. But with the move to federation (which at least provides control, if not ownership) and smaller spaces, it seems possible that we're actually going to see some of those shifts away from big-platform-mediated communication start to happen.

"There's a systemic change that is happening right now that's bigger," he says. "You have to have a little bit of perspective of life pre-Facebook to sort of say, *Oh, actually, some of these things are just arbitrary. They're not intrinsic to the internet.*"

The fix for the internet isn't to shut down Facebook or log off or go outside and touch grass. The solution to the internet is more internet: more apps, more spaces to go, more money sloshing around to fund more good things in more variety, more people engaging thoughtfully in places they like. More utility, more voices, more joy.

My toxic trait is I can't shake that naïve optimism of the early internet. Mistakes were made, a lot of things went sideways, and there have undeniably been a lot of pain and misery and bad things that came from the social era. The mistake now would be not to learn from them. ■

Katie Notopoulos is a writer who lives in Connecticut. She's written for BuzzFeed News, Fast Company, GQ, and Columbia Journalism Review.

The advising algorithm

Theoretical computer scientist Manuel Blum has guided generations of graduate students into fruitful careers in the field.

By Sheon Han
Portraits by Ross Mantle

Every academic field has its superstars. But a rare few achieve superstardom not just by demonstrating individual excellence but also by consistently producing future superstars. A notable example of such a legendary doctoral advisor is the Princeton physicist John Archibald Wheeler. A dissertation was once written about his mentorship, and he advised Richard Feynman, Kip Thorne, Hugh Everett (who proposed the "many worlds" theory of quantum mechanics), and a host of others who could collectively staff a top-tier physics department. In ecology, there is Bob Paine, who discovered that certain "keystone species" have an outsize impact on the environment and started a lineage of influential ecologists. And in journalism, there is John McPhee, who has taught generations of accomplished journalists at Princeton since 1975.

Computer science has its own such figure: Manuel Blum, who won the 1995 Turing Award—the Nobel Prize of computer science. Blum's métier is theoretical computer science, a field that often escapes the general public's radar. But you certainly have come across one of Blum's creations: the "Completely Automated Public Turing test to tell Computers and Humans Apart," better known as the CAPTCHA—a test designed to distinguish humans from bots online.

"I don't know what his secret has been. But he has been a tremendously successful advisor," says Michael Sipser, a theoretical computer scientist at MIT who was advised by Blum, referring to the "extraordinary number of PhD students" who have worked with him and then gone on to make an impact in the field. "It is extraordinary in the literal sense of that word—outside the ordinary."

Three of Blum's students have also won Turing Awards; many have received other high honors in theoretical computer science, such as the Gödel Prize and the Knuth Prize; and more than 20 hold professorships at top computer science departments. There are five, for example, at MIT and three at Carnegie Mellon University (where there were four until one left to found Duolingo).

Blum is also distinguished by the great plurality of subfields that his students work in. When Mor Harchol-Balter, a professor of computer science at Carnegie Mellon, arrived at the University of California, Berkeley, as a PhD student, she quickly realized that she wanted to work with him. "Manuel was warm, smiling, and just immediately emanated kindness," Harchol-Balter told me. Her specialty, queueing theory, had little overlap with Blum's, but he took her on. "Every professor I know, if you start working on what's way out of their area, they would tell you to go find somebody else," she said. "Not Manuel."

A few months ago, as I was reading about some of the most significant yet counterintuitive ideas in modern theoretical computer science, I realized that the vast majority of the researchers responsible for that work had been advised by Blum. I wondered whether there might be some formula to his success. Of course, it's presumptuous to think such an intimately human process can be distilled into an algorithm. However, conversations with his students gave me a sense of his approach and revealed consistent themes. Many spoke warmly of him: I often heard some version of "I could talk about Manuel all day" or "Manuel is my favorite topic of conversation." The finer points of mentorship aside, what I learned was at least proof that kindness can beget greatness.

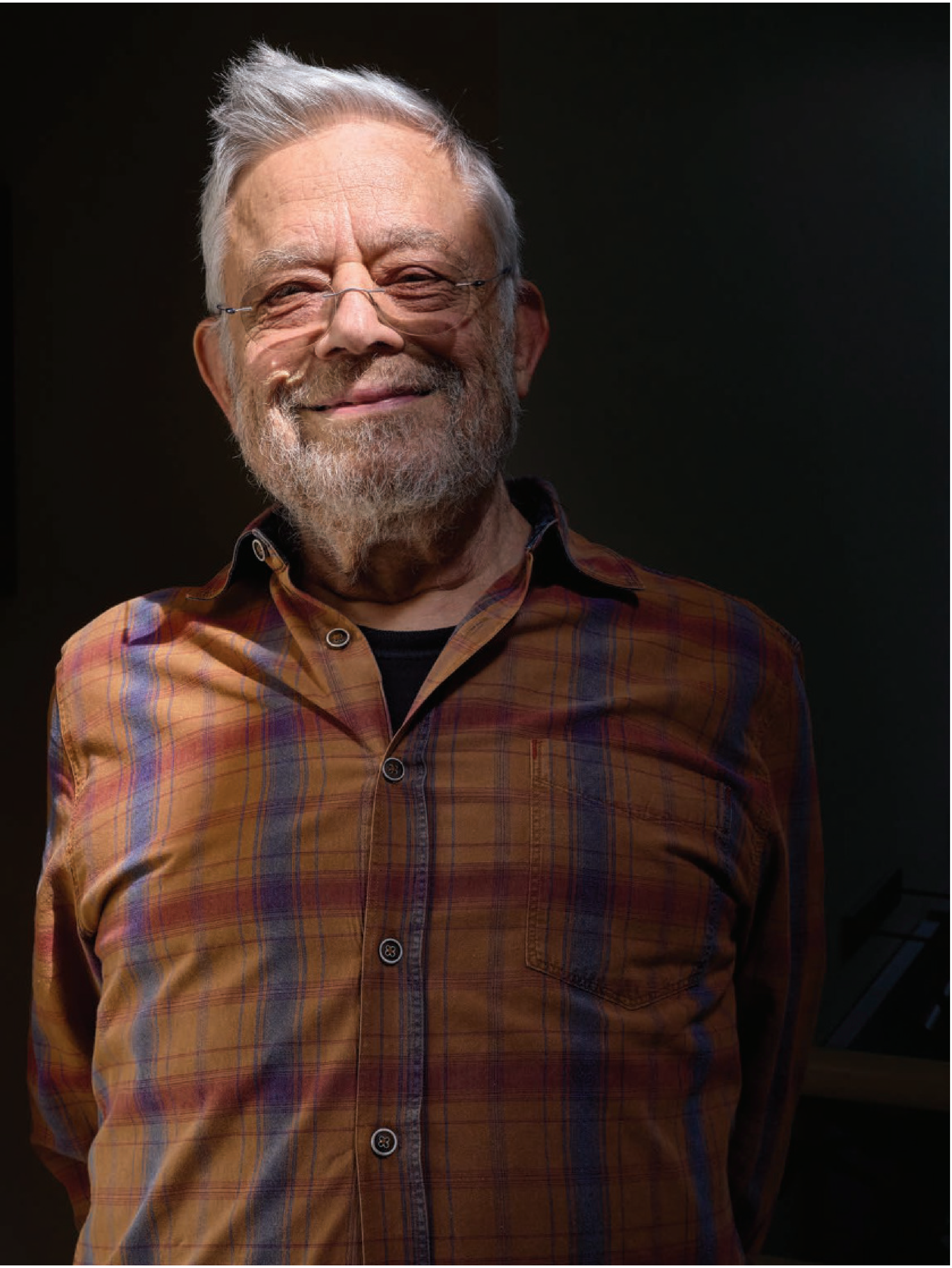
Slow beginning

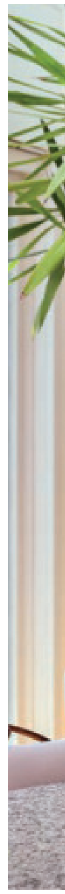
Manuel Blum is married to Lenore Blum, an accomplished mathematician and computer scientist, who has also been at the forefront of promoting diversity in math and computing (among other things, she founded America's first computer science department at a women's college and helped CMU's computer science department achieve 50-50 gender parity). They are both now emeritus professors at CMU and Manuel Blum is an emeritus professor at UC Berkeley; they split their time between the two coasts.

One day in August, I joined the couple for breakfast at their house in Pittsburgh. Breezy in his manner, Blum, at 85, still has a schoolboy's smile and frequently erupts into a resonant laugh; he is charismatic in a way typical of people who are utterly oblivious to their charisma. (When he says "WON-derful," which he frequently does, you can practically hear "WON" in all caps.)

The Blums, who recently celebrated their 62nd anniversary, still shuttlecock research ideas, enthuse over emails from their former students, and complete each other's memories—some dating from their life in Venezuela, where they met as kids.

Manuel Blum was born in 1938 in Caracas to Jewish parents who had moved from Romania. His first language was German, which his parents spoke at home. But when they moved to the Bronx, his





Manuel Blum and his wife, Lenore Blum, an accomplished mathematician and computer scientist, who has also been at the forefront of promoting diversity in math and computing.

family realized that people did not want to hear German spoken. The year was 1942, and the country was at war. After switching to Spanish at home, he quickly lost his fluency in German. But when he had to learn English for school, he soon forgot Spanish as well.

At one point, Blum says, he was listening to both languages but found himself understanding neither. "I remember thinking to myself, 'Very interesting—I don't have a language. I couldn't express myself through language. How was it that I was able to think?'" he told me. In a lucid moment of metacognition—an act that befits a future theorist of abstract concepts—he realized: You don't need language to think.

Likely because of his language difficulties, Blum's second-grade teacher warned his mother that while he might manage to complete high school, he might not go to college. "But I wanted to be smarter. So I asked my father, 'What can I do to get smarter?'" His father answered that if he understood how the brain works, he could be smart. The conversation marked the inception of Blum's interest in studying consciousness (something he and Lenore Blum now research full-time, often assisted by their son, the computer scientist Avrim Blum).

Blum was ultimately accepted to MIT, but he struggled the first year, until a friend noticed that his approach to studying physics—owing to Blum's training at a military academy he went to before college—was heavy on memorization. Blum recalls his friend saying, "You don't memorize. You memorize only '$F = ma$' and a few things like that. When you need a formula, you derive it." Soon, his grades started climbing. "I went from being a Xerox machine to being a thinker. I really enjoyed thinking," he says.

To pursue his interest in the brain, Blum took a course that involved reading multiple volumes of the standard edition of Freud's works. But they didn't offer much in the way of satisfactory answers. Then his professor told him that he should introduce himself to Warren S. McCulloch, known for very early research on neural networks and pioneering work in cybernetics.

Blum read some of McCulloch's papers and was able to prove a couple of theorems in mathematical biophysics, and McCulloch took him on in his MIT lab. "A wonderful person. A magnanimous person. Anything I wanted to do, he was supportive," Blum says.

McCulloch's lab focused on both the rigorous mathematical work of modeling the neuron and the experimental process of studying the brain to understand how it functions. But what Blum couldn't study in the lab was consciousness. The topic was taboo at the time. Many felt that subjective mental phenomena weren't fit for scientific inquiry, and there were few tools available in any case. (The fMRI, for example, which is an imaging technique that maps brain activity, wouldn't be developed until 1990.)

Blum would revisit the topic occasionally as he transitioned away from electrical engineering to mathematics and computer science in graduate school. As he pursued his graduate work at MIT, he became captivated by a branch of theoretical computer science known as recursive function theory—now more commonly referred to as computability theory—and began searching for a thesis advisor. Soon, he found Marvin Minsky, the mathematician and computer scientist, who was a pioneer of artificial intelligence. Minsky (who had an office full of mechanical hands) often dropped by McCulloch's lab to demonstrate his new machines and discuss mathematical problems.

After studying computational complexity and computability for his thesis, Blum received his PhD in 1964. At the time, computational complexity theory represented the hinterlands of computer science. It wasn't until 1971 that Stephen Cook formulated the foundational question of the field, "P vs. NP"—which essentially asks whether every problem whose solution can be checked quickly can also be solved quickly.

But Blum found a productive home in Berkeley's electrical engineering and computer science department. At MIT, he had helped form the contours of computational complexity theory. At Berkeley, he showed how this highly abstract field could also have useful applications in areas such as cryptography and program checking—a method that uses an algorithm to verify the correctness of a computer program.

The kinds of questions Blum poses read like paradoxes and have a somewhat playful quality, making complexity theory and cryptography sound almost like a subgenre of sci-fi. "He is completely original and goes off and does what he thinks is interesting and important. And often it turns out to be something really significant," Sipser told me.

"He is completely original and goes off and does what he thinks is interesting and important. And often it turns out to be something really significant."

In his seminal paper "Coin Flipping by Telephone," the question that he poses is: "Alice and Bob want to flip a coin by telephone. (They have just divorced, live in different cities, and want to decide who gets the car.)" Let's say that Alice calls "heads" and Bob says she lost; how does she trust that he is being truthful? And how could Bob trust Alice if the situation were reversed?

What sounds like a riddle addresses a fundamental problem in cryptography: How can two parties engage in trustworthy exchanges over a communication channel in such a way that neither party can cheat?

Blum showed that this can be achieved using the concept of "commitment." In a simplified analogy, the idea is that Alice

gives Bob a locked box with her prediction inside, but without the key. This prevents Alice from altering her prediction and stops Bob from discovering Alice's guess prematurely. Once Bob tosses the coin, Alice hands over the key to open the box.

"Work with me"

When you ask Blum about the secrets of good mentorship, he reacts with a sheepish head scratch, attributing his students' success to their own talents. "Students come up with wonderful ideas, and people don't realize how wonderful they are. The only thing I can say is that, more than most, I really enjoy the ideas that the students have," he told me. "I have learned from each of them."

His response left me puzzled, especially after I heard from his students that Blum never criticized their ideas or prescribed research directions. Offering full autonomy and boundless encouragement sounded wonderful in theory, but I was mystified as to how it worked in practice—how did students receive the occasional course correction or hyper-specific advice that is often essential in academic pursuits? Still, it's not that he was dodging my question. He is not so much a magician who refuses to give away his tricks as one who is himself astonished by what has been conjured around him.

One thing I came to understand about Blum's advising style is that when he says "Students are here to teach me," he truly means it, with all that entails. While it's easy to pay lip service to the principle of "treating a student as a colleague," Ryan Williams, a professor of computer science at MIT who studied with Blum, told me that working together made him *really* feel like one. What this means, in concrete terms, is that Blum imparted to his students a sense of pedagogical responsibility: he was *really* expecting to learn from them at every weekly meeting, which in turn meant they had to understand their ideas to the bone.

"During my first few months of working with him, I thought he was testing me. And then I realized that was just him," Russell Impagliazzo, a professor of computer science at the University of California, San Diego, told me. "You had to learn how to say things so that Manuel could understand them. And that's the most valuable skill that he gives his students, like the skill of learning to swim by being thrown into a pool: the ability to translate what you're saying into more concrete terms. This skill proves invaluable when you are teaching a class or writing a grant proposal."

Former students describe Blum as unwaveringly positive, saying he had other ways besides criticism to steer them away from dead ends. "He is always smiling, but you can see he smiles wider when he likes something. And oh, we wanted that big smile," says Ronitt Rubinfeld, a professor of electrical engineering and computer science at MIT.

Behind the general positivity, Rubinfeld says, is a fine taste for interesting ideas. Students could trust they were being guided in the right direction. Come up with a boring idea? Blum, who is known for his terrible memory, would have mostly forgotten it by your next meeting.

When Harchol-Balter was in graduate school, she says, Blum never told her what to work on and instead guided her by means of questions: "Manuel is fantastic at asking questions. Manuel *excels* at asking questions."

Blum also "really makes sure that each student has a special area to develop," Lenore Blum told me. "I don't think he's asked a student to ever do the next iteration of someone else's work," she said. "But he'll say, 'Work with me, and we'll do something brand new.'"

Working on a new idea is risky. But Blum's encouragement, coupled with his track record of spotting fruitful lines of inquiry, gave his students confidence to keep going in bold directions while enduring criticism and self-doubt. "There's a huge difference [between] Manuel's advising style and everyone else's in the world," says Impagliazzo. "Manuel's advising style is simply to listen to you and make you seem really, really important. Like what you're doing is the most amazing thing in the world."

Harchol-Balter says this is the magic she is now trying to emulate with her students. "Whenever I had an idea, whatever it was, he somehow made me feel like this was the most brilliant idea that had ever been invented," she remembers. She felt that every idea could be "a multimillion-dollar breakthrough," which allowed her to stay committed to her line of research, undeterred by external influences or trends. "He creates this feeling of supreme confidence—not just confidence, but like, 'You. Are. Brilliant,'" she adds. "Having somebody beside you all those six years, when you're feeling the most vulnerable, constantly boosting your confidence … It's amazing. And that's why his students are so great."

Excellence in academia, as in many other fields, is about both *what* you do and *how* you do it. You need to identify a promising topic and have the technical ability to execute it. A technically flawless idea without original insight can be trivial; a radically original idea without proper execution might never fully develop, while a bold idea powered by misplaced confidence could hit a dead end.

The psychological reassurance students get from Blum may come in part from his superhuman level of aplomb. "He never seems stressed out," says his son, Avrim Blum. "In the real world, there are deadlines and stresses, but he never showed any of that. At least I never saw it." I'm still awed by his ability to mask inner turbulence—something that affects everyone—so well that it remains invisible even to his closest observers, including his own son. It's a source of stability that students can rely on throughout their graduate studies. "I was more comfortable and more relaxed in grad school because I felt like he had things under control for me," Williams told me. "If there were any difficulties, he would help. He had my back. He was going to sort things out."

Speaking with Blum's students, I felt a pang of jealousy. What would it be like to have someone like Blum in your corner during your most vulnerable moments? And how many direct criticisms you've faced could have been reformulated into questions? What kinds of audacious ideas can take root when someone listens to you with absolutely no judgment?

But even as Blum's students claim they are still bewildered by the "magic" and "mystery" of their advisor's approach, they have become accomplished teachers and advisors in their own right. Umesh Vazirani, a theoretical computer scientist at Berkeley, told me that he has thought a lot about Blum's secrets. He said the essence can be expressed this way: "You respect every student, and you let them develop into whatever they want to be." Vazirani, who has advised a number of superstars in the field himself, believes that in education, "the most important thing is not to break anything. Cause no damage."

What would it be like to have someone like Blum in your corner? What kinds of audacious ideas can take root when someone listens to you with absolutely no judgment?

The potency of the Blumian approach to advising isn't domain specific, as illustrated by George Saunders's reflections on his writing teacher, Tobias Wolff. Writing teachers have "so much power," Saunders has written:

> They could mock us, disregard us, use us to prop themselves up. But our teachers, if they are good, instead do something almost holy, which we never forget: they take us seriously. They accept us as new members of the guild. They tolerate the under-wonderful stories we write, the dopy things we say, our shaky-legged aesthetic theories, our posturing, because they have been there themselves.
>
> We say: I think I might be a writer.
>
> They say: Good for you. Proceed.

On my last day in Pittsburgh, I noticed a photo of Blum's old advisor, Warren S. McCulloch, behind Blum's desk in his home office. It was in a prominent place where someone else might've chosen to display a family heirloom or showcase an autographed photo of himself shaking a president's hand. (McCulloch died in 1969, only a few years after Blum began his professorship.)

Out of curiosity, I pointed out the photo's prominent position. "Yes, because he is always with me," Blum replied. "Warren was Manuel's spiritual father in every way," added Lenore.

As I made my way back to the airport, I remembered a book called *Surviving Death,* by the philosopher Mark Johnston. In the book, Johnston postulates that a good person could "quite literally" survive death by redirecting self-interest toward the well-being of future people. This forfeiture doesn't spell the dissolution of the self but, rather, the expansion of it, allowing the person to live on in the "onward rush of humankind." A line from the book unfolded, with a time-release effect, in my head: "Every time a baby is born, a good person acquires a new face."

Behind every one of Blum's knowing smiles, it may well have been McCulloch himself, nodding, imparting a blessing: "Wonderful idea. Proceed." ■

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Cryptographers want encryption schemes that are impossible for tomorrow's quantum computers to crack. There's only one catch: they might not exist.

By Stephen Ornes

The quest for perfect security

When we check email, log in to our bank accounts, or exchange messages on Signal, our passwords and credentials are protected through encryption, a locking scheme that uses secrets to disguise our data. It works like a cyber padlock: with the right key someone can unlock the data. Without it, they'll have to resort to laborious brute-force methods, the digital equivalent of hacksaws and blowtorches.

Our trust in online security is rooted in mathematics. Encryption schemes are built on families of math problems called one-way functions—calculations that are easy to carry out in one direction but almost impossible to solve efficiently from the other, even with a powerful computer. They're sort of a computational equivalent of those road spikes found at the exits of airport car rental agencies. Drive in one direction and you barely notice. Hit reverse and you won't get far (and will need new tires).

There's a problem, however. Although mathematicians suspect true one-way functions exist, they have yet to prove it. They haven't proved that the thorny problems we *do* use are impossible, or even extremely impractical, to solve. Instead, it could just be that we haven't yet found the appropriate mathematical means to take the problems apart. This conundrum haunts all encryption. Our data is secured by the fact that no one knows how to crack the schemes that protect it—at least not yet.

It's not just today's hackers we may need to worry about. Security experts have long warned of a threat that hasn't yet materialized: quantum computers. In the future these machines could execute a program that quickly solves the math problems behind today's state-of-the-art encryption. That threat puts personal financial, medical, and other information at risk. Hackers could steal today's encrypted data and store it away, just waiting for the arrival of new technological lockpicks.

Computer scientists, mathematicians, and cryptographers are on a quest to find new encryption algorithms that can withstand attacks not only from today's conventional computers but also from tomorrow's quantum machines. What they want is a big, sticky math problem—something that's robust enough to withstand attacks from classical and quantum computers but can still be easily implemented in cyberspace.

Unfortunately, no one has yet found a single type of problem that is provably hard for computers—classical or quantum—to solve. (In the world of cryptography, "hard" describes a problem whose solution requires an unreasonable

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number of steps or amount of computing power.) If one-way functions don't exist, then cryptographers' whack-a-mole process of finding flaws and developing ever stronger schemes to block clever hackers will persist indefinitely.

"The question of whether one-way functions exist is really the most important problem," says Rafael Pass, a theoretical computer scientist at Tel Aviv University in Israel. It's a conundrum that dates to the 1970s and the dawn of a research area now known as computational complexity theory. Over five decades, theorists and cryptographers have been looking for ways to establish whether such functions do exist. Perhaps the problems we hope or suspect are one-way are just easier, breakable ones in disguise.

Pass is exploring how one-way functions are connected to a raft of other open problems, a promising line of research that has drawn other theorists into the quest. At the same time, people focused on the practical side of cryptography are plowing ahead, hunting for new schemes that are—if not provably hard—seemingly strong enough to hold up against quantum computers.

For the last seven years, the job of finding the best candidates has been spearheaded by the National Institute of Standards and Technology (NIST), the US government body charged with collecting, testing, and standardizing cryptographic algorithms for public use. NIST has been running dozens of potential "post-quantum" algorithms through a gauntlet of tests and making them available for outside testing. The process has winnowed the field to a few finalists, and in August NIST announced that one called CRYSTALS-Kyber, which takes an approach believed to be robust enough to counter quantum attacks, will be the first to be officially recommended for public use by 2024. After that, companies and governments will adopt the algorithm for encrypting data.

Will it hold up? The answer will help determine the trajectory of cybersecurity in the near term. But it's far from settled: history suggests that our faith in unbreakability has often been misplaced, and over the years, seemingly impenetrable encryption candidates have fallen to surprisingly simple attacks. Computer scientists find themselves at a curious crossroads, unsure of whether post-quantum algorithms are truly unassailable—or just believed to be so. It's a distinction at the heart of modern encryption security.

Computer scientists find themselves at a curious crossroads, unsure of whether post-quantum algorithms are truly unassailable—or just believed to be so.

The myth and reality of unbreakability

Securing secret messages hasn't always been tied to difficult math problems; until recently, cryptography was barely mathematical at all. In ancient Greece, military leaders encoded messages using a scytale, a cylindrical device that revealed a hidden message when a strip of seemingly jumbled text was wound around it. Centuries later, Roman historians described a code, often attributed to Julius Caesar, that involved shifting letters in a message three spots up in the alphabet; for example, a *d* would be written as an *a*.

In history as in our modern world, secret codes were frequently broken. In the 16th century, during the decades she spent imprisoned by her cousin Queen Elizabeth I, Mary, Queen of Scots, used elaborate, symbol-based ciphers to encode hundreds of letters, most of which were aimed at securing her freedom and regaining the throne. She didn't prevail: Elizabeth I's team of spies and codebreakers intercepted, decoded, and copied the letters. In the one that sealed her fate, Mary approved of a plan to assassinate Elizabeth with six words: "sett the six gentlemen to woork." In response, Elizabeth eventually ordered her cousin beheaded in 1587.

In 1932, codebreakers in Poland cracked the code for Germany's early Enigma machine, invented at the end of World War I. They later shared their intel with British codebreakers, who cracked a more advanced version of Enigma during World War II.

Pass, the theoretical computer scientist in Tel Aviv, half-jokingly refers to all time before the 1970s as the "dark age of cryptography."

"Cryptography wasn't really a scientific field," he says. "It was more like artist versus attackers. You needed to have [artistic] skills to invent an encryption scheme. And then it would get deployed until some clever person would figure out how to break it. And it was just going on and on like that."

That changed, Pass says, in November 1976, when cryptographers Whitfield Diffie and Martin Hellman, at Stanford, described a novel way for two people to devise a key that only they knew—one they could then use to pass secret messages. Crucially, they wouldn't have to meet to do it. This was a groundbreaking notion. Previously, both sender and receiver had to physically possess a key for encoding and decoding. To decrypt a message encoded with the Enigma machine, for example, a recipient needed a key sheet that revealed the initial encryption settings.

The secret to the Diffie-Hellman strategy was for two people to build the key using a straightforward mathematical problem that's easy to compute in one direction and laborious in the other. Here's how it works: The two people who want to communicate secretly, usually designated Alice and Bob in these setups, each pick a secret number. Then, together, they agree on a pair of numbers that they share publicly (one is a big prime, and the other is called the base). Each of them next carries out a series of mathematical operations to combine those private numbers with the prime and the base.

Then they exchange the results, and they each carry out another series of mathematical operations on the new numbers. In the end, both Alice and Bob will have done the same operations on the same numbers—just not in the same order—and arrived at the same answer. The digits of that answer become the encryption. And an eavesdropper who intercepts the transmission—often nicknamed Eve—won't be able to easily unravel the mathematical jumble without knowing at least one of the private numbers. She could start testing numbers in a brute-force approach, but that would require an unreasonable amount of calculation.

The complicated problem that Eve would have to solve is called finding a discrete logarithm. The Diffie-Hellman approach is still used today—to secure some VPNs, for example—and is integral to some post-quantum schemes.

In their paper, Diffie and Hellman noted that there was no existing algorithm capable of solving the discrete log problem in a reasonable amount of time. There still isn't. They went on to introduce, for the first time, the notion of one-way functions as a basis for secure cryptography.

Today, secure online interactions that involve authentication or digital signatures, for example, are based on that general idea. But without mathematical proof that the problems they rely on are one-way functions, the possibility remains that someone might discover an efficient scheme for cracking them.

The quantum menace

Today, online transactions begin with a kind of digital handshake, and the security of that handshake is often guaranteed by another math problem that's presumed to be difficult. The most popular encryption scheme used today was introduced in 1977 by a trio of young computer scientists who were energized by Diffie and Hellman's 1976 paper. They called their approach RSA, after the last names of the scientists (Ron Rivest, Adi Shamir, and Leonard Adleman).

RSA, which is based on the difficulty of finding prime factors relative to the ease of multiplying them together, is a bit different from the Diffie-Hellman approach. Diffie-Hellman is a shared secret: it allows two users to devise a key over an insecure channel (like the internet), and that key is used to disguise messages. In RSA, Alice uses Bob's key—based on big prime numbers—to encrypt a message that only he can unlock. RSA can secure data sent from one person to another.

It quickly became one of the most popular public-key encryption methods. It's easy to use and adapt. Over time, as new algorithms have emerged that can factor faster, and computers have become more powerful, NIST has recommended using larger and larger numbers for security. The numbers are represented in binary form with *1*s and *0*s, and these binary digits are better known as "bits." The number 13, for example, is written in binary as *1101*, which has four bits. NIST currently recommends using a key represented by at least 2,048 bits—which corresponds to a number with over 600 digits. (To date, the largest number that has been factored into two primes was made up of 250 digits, and the process took nearly 3,000 hours of computing time.) That's a strength of RSA—even if it's not uncrackable, it's been easy to keep upping the ante, making it computationally impractical to break.

In 1994, however, a threat of a different type emerged when the American mathematician Peter Shor, then at Bell Labs, devised an algorithm for quantum computers that could solve the factoring problem in a reasonable amount of time. (It was a double threat: his approach could also conquer the discrete log problem in the Diffie-Hellman approach.)

Shor's paper ignited excitement and anxiety among those who wanted to build quantum computers and those who recognized the threat it posed to cybersecurity. Fortunately for cryptographers, not just any quantum computer would do.

A few years back, researchers at Google and the KTH Royal Institute of Technology, in Sweden, estimated that it would take a quantum computer composed of 20 million quantum bits, or qubits, some eight hours to break today's 2,048-bit RSA security. Current state-of-the-art machines are nowhere close to that size: the largest quantum computer to date, built by IBM, debuted last year with 433 qubits.

Whether or not RSA can be considered at immediate risk of a quantum attack depends largely on whom you ask, says computer scientist Ted Shorter, who cofounded the cybersecurity company Keyfactor. He sees a cultural divide between the theorists who study the mathematics of encryption and the cryptographers who work in implementation.

To some, the end seems nigh. "You talk to a theoretical computer scientist and they're like, *Yes, RSA is done*, because they can imagine it," Shorter says. For them, he adds, the existence of Shor's algorithm points to the end of encryption as we know it.

Many cryptographers who are implementing real-world security systems are less concerned about the quantum future than they are about today's cleverest hackers. After all, people have been trying to factor efficiently for thousands of years, and now the only known method requires a computer that doesn't exist.

Thomas Decru, a cryptographer at KU Leuven in Belgium, says the quantum threat must be taken seriously, but it's hard to know if RSA will fall to quantum computers in five years or longer—or never. "As long as quantum computers do not exist, everything you say about them is speculative, in a way," he says. Pass is more certain about the threat: "It's safe to say that the existence of this quantum algorithm means there are cracks in the problem, right?"

The thorns of implementation

But we have to be ready for anything, says Lily Chen, a mathematician who manages NIST's Cryptographic Technology Group and works on the ongoing effort to produce post-quantum encryption standards. Whether they arrive in three years or 30, quantum computers loom on the horizon, and RSA, Diffie-Hellman, and other encryption schemes may be left vulnerable.

Finding a quantum-resistant cryptographic scheme isn't easy. Without a mathematical problem that is computationally hard, the last three decades of cybersecurity have played out like an increasingly intricate game, with researchers perpetually building and breaking—or attempting to break—new candidates.

The last three decades of cybersecurity have played out like an increasingly intricate game, with researchers perpetually building and breaking—or attempting to break—new candidates.

This push and pull has already emerged in the NIST post-quantum program. In February 2022, cryptographers found a fatal flaw in Rainbow, an algorithm that had survived three rounds of NIST's analysis. A few months later, after the NIST list had been winnowed again, Decru and his KU Leuven colleague Wouter Castryck announced that they'd broken another finalist, an algorithm called SIKE.

SIKE, which was developed a few years ago, was the brainchild of a collaboration among researchers and engineers at Amazon, Microsoft, the University of Versailles, and elsewhere. It is based on a special mathematical map, called an isogeny, that is made up of connections between elliptic curves. These maps can be turned into an encryption for communication, and outsiders can't eavesdrop without knowing the maps.

At Leuven, Decru and Castryck devise ways to use these so-called isogenies to build new, faster encryption approaches. They broke the most difficult version of SIKE in just a few hours of computing time using an ordinary desktop computer. (Since then, other groups have found ways to do it even faster.) What's more, Decru and Castryck did it almost accidentally, and only a few weeks after SIKE had been declared an alternate NIST finalist. "We weren't trying to break it at all," insists Decru. "We just tried to generalize it."

Chen says the case of SIKE—and Rainbow before it—illustrates a real-world tension that drives efforts to find quantum-proof algorithms. On one hand, she says, "you have to find a problem which is hard for both quantum computers and classical computers." On the other is implementation: transforming that hard problem into one that can be used in a real-world cryptographic system. Even with today's well-defined problems, Shorter says, it's very difficult to predict and prevent every loophole in every operating system and device on the market today. "And then there's interoperability testing and certifications and other tests," he says, "to make sure they are not only implemented correctly, but also securely."

The mathematical problem SIKE is based on seems computationally hard because there are so many different maps that could be constructed between curves. It may even be a one-way problem—and therefore quantum-proof. The flaw was in the design, which revealed too much of the transmitted information. Decru and Castryck cracked it because they inadvertently found a way to expose enough connecting points to give away the entire thing.

Other schemes have fared better. The first post-quantum encryption algorithm to be standardized, CRYSTALS-Kyber, delivers security through an approach that involves problems on lattices, mathematical objects that can be modeled as arrays of points. (There are five main families of post-quantum cryptographic methods. Isogeny and lattice approaches are two of them.)

CRYSTALS-Kyber is a general encryption scheme, like RSA, that can be used for tasks like securing online communication. Three other approved algorithms are designed to authenticate digital signatures, ensuring that digital documents haven't been fraudulently signed. NIST plans to standardize these by spring 2024. Another three (it was four until SIKE was broken) could also be standardized in the next few years, as long as they survive further rounds of scrutiny.

But unless mathematicians can prove whether one-way functions exist, says Pass, the patterns that have always characterized cryptography will continue. "We're back to this cat-and-mouse game, where it's a game between algorithm designers proposing new candidate constructions and other designers trying to break them," he says. Unless, of course, he—or someone in his field—can come up with an implementable, provably one-way function to settle the matter of encryption forever.

Until that time, cryptographers will remain in a messy limbo in which convincingly robust encryption schemes can be trusted—but only until they can't.

The perfect math problem could take us out of this limbo, but it can't be some sticky mess cooked up by an armchair algebraist over a long weekend. It must strike a balance between math and cryptography, with computational hardness on one side and easy implementation on the other. Stray too far from either of those properties, and it becomes vulnerable—if not now, then in the future. Hanging in the balance is the past, present, and future security of everyone's data, everywhere. No pressure. ■

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Reinventing shop class

Above: Emily Pilloton-Lam is the founder of Girls Garage, which provides experiential learning for kids through hands-on design and building projects.

Opposite: “We teach students how to use power tools,” she says, “but also how to channel their own power.”

Girls Garage creates space for its students to build the world they want to see. By Allison Arieff

Emily Pilloton-Lam didn’t grow up in a particularly handy household, but she did spend hours and hours outside building treehouses out of logs and sticks: “I was more a spatial and physical thinker,” she says. “And making spaces and changing my environment was one of the earliest ways I began to make sense of the world.”

After studying architecture at UC Berkeley and then at the School of the Art Institute of Chicago, she realized that the traditional world of architecture was not for her. “I quickly discovered that I don’t work well at a cubicle, or for a boss, or without getting to build the ideas that started on paper in front of me,” she says.

She kept coming back to what made her fall in love with building: working with her hands and with other people on projects that mattered. So in 2008, at age 26, she founded a nonprofit called Project H Design (which became Girls Garage in 2013), to equip youth with the personal power and the literal power tools to build the world they want to see.

Based in Berkeley, California, Girls Garage is a workshop space created for young women, ages nine to 18, to build things together without what Pilloton-Lam calls “the social layers and calculus of a gendered construction site.” (Currently, only 3.4% of construction trade workers are female.) Pilloton-Lam, whose 2021 TED talk “What if women build the world they want to see?” has over 2.5 million views, works with a team of female instructors, many of whom are program alumni. The immaculately organized, light-filled space has a fully outfitted woodshop (with both power tools and hand tools—all sessions begin with safety training) as well as a print studio. The girls and gender-nonconforming youth who come here might join a weeklong workshop building a chair or making mosaics, or spend a summer or semester on more involved projects (recent ones include a mobile chicken coop for an elementary school, outdoor furniture for a community garden, a bus stop in collaboration with a state transit authority, and bookshelves and benches for a library space in transitional housing). Some 58% of students who participate do so for free or at a reduced fee.

The architecture, engineering, and construction industries are famously slow to innovate. While Girls Garage isn’t trying to push students into the trades, it is, Pilloton-Lam explains, helping to jump-start change in the construction industry through its alumni and projects: “I love the idea of the ‘old guard’ doing a double take when they see an all-female Girls Garage construction site—young and old, all races and identities. I love the idea that our 21-year-old alumna is the project engineer for a multimillion-dollar project in Silicon Valley, and that a jobsite has to answer to her. I think innovation happens when people are

COURTESY OF GIRLS GARAGE

JACS DE LEUW

challenged (or sometimes forced) to reexamine their assumptions about who's in charge of what and who's supposed to do what."

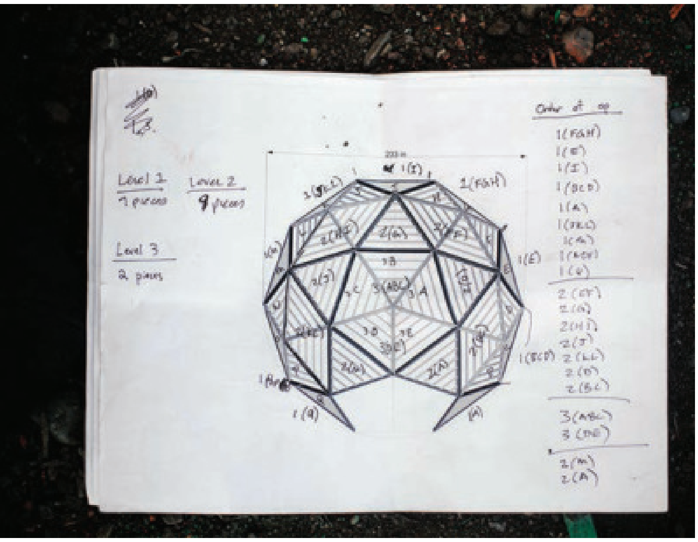
Building at Girls Garage, she continues, "is less about choosing a future path [than it is about becoming] a creator, a builder, an activist, and a young person with both technical and leadership skills that they might apply anywhere." That said, hundreds of students have come to Girls Garage to either nurture or discover their love of the industries that shape the built environment. Alumni have gone on to college programs in civil engineering and architecture or into apprenticeship or certificate programs in welding. "The idea that these young people came to Girls Garage as fourth and fifth graders and are now in spaces and rooms and jobsites as a different type of leader is incredibly gratifying to watch," she says.

This year, the organization is celebrating its 10th anniversary by moving into a new, larger space (5,000 square feet, double its previous digs), which will allow it to run more classes, take on even grander construction projects, and expand the number of participants. The move, says Pilloton-Lam, "is symbolic of something of such great promise": that our students "are the authors and builders of the kind of world we all want to see, and they have the space and support to make it so." ■

Above: The dome was the largest construction project they'd ever tackled, says Pilloton-Lam, and "was the ultimate test of our geometry skills."

BRYAN MELTZ

Below: Using reclaimed redwood, a chop saw, and impact drills, students built a 20-foot geodesic dome for the Eames Ranch farm garden in Petaluma, California.



Above: Students prefabricated the 40 triangular frames within the Girls Garage workspace before installing the project onsite in April 2023.

Left: The Advanced Design/Build cohort show off the garden dome, which will function as a sculptural structure for gourd vines and other climbing fruits.

BRYAN MELTZ; COURTESY PHOTO (BOTTOM)

Left: In July 2023, Girls Garage's Builder Bootcamp built two chicken tractors for Willard Middle School in Berkeley.

Below: Girls work on a cedar sauna for Shelterwood Collective, a Black-, Indigenous- and queer-led land-stewardship organization.

Above: Students learned how to use basic power tools, like the miter saw, drill, and impact driver, to frame and assemble the walls of the mobile chicken coops.

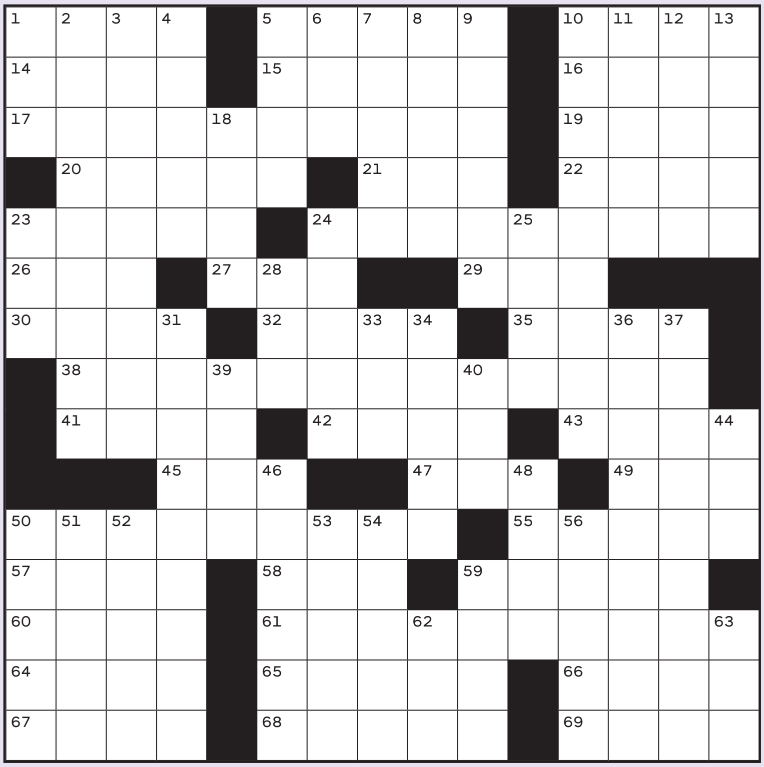
COURTESY OF GIRLS GARAGE

Above: The crew finished the accessible sauna project, made from redwood and cedar, onsite in a forest in Cazadero, California, in three days.

Creative solutions

By John-Clark Levin

Many of the hard problems humanity faces have resisted conventional fixes for decades. From insecure data to chemo-resistant cancers, transformative breakthroughs will likely require outside-the-box solutions—as suggested by the need to complete four answers by placing a letter outside the box of the grid in this issue's crossword puzzle.



ACROSS

1 Clerical robes
5 Strategic course-correction, in startup lingo
10 Test software release
14 Shell, for MIT crew
15 Holocene or Pleistocene
16 Its capital is Vientiane
17 Potential solution to the hard problem of dirty energy
19 Major in astronomy?
20 Half of an '80s sitcom duo, with 25 Down
21 Massachusetts engineer Whitney, who invented the cotton gin
22 Bombard with plasma, as in microchip manufacturing
23 Power-saving mode for computers
24 Potential solution to the hard problem of data privacy
26 Rocket launch location
27 Explorer Hendrickson, after whom the most complete known *T. rex* fossil is named
29 Hammer home?
30 "A Sorta Fairytale" singer Tori
32 Traffic stopper?
35 Stun, in a way
38 Innovative … and, literally, how you need to solve 17, 24, 50, and 61 Across
41 Fitbit unit
42 Tech debut of 2011
43 Like Turtle mode in Sim City
45 *The Name of the Rose* author Umberto
47 Classic Ford
49 CRISPR material
50 Potential solution to the hard problem of non-decomposable waste
55 More unfriendly
57 Icebreaker?
58 Toy sound?
59 Program distributor
60 Starch-yielding palm
61 Potential solution to the hard problem of cancer
64 Snack featuring Nabisco's cross logo
65 Call to mind
66 Pigeon coop
67 Marx not in *Duck Soup*
68 Web locations
69 Had down

DOWN

1 *Aladdin* monkey
2 Manhattan Project test location
3 Saved from impending disaster
4 Took the wrong way?
5 Cartoon skunk Le Pew
6 NASDAQ debut, say
7 Y, "sometimes"
8 Big name in kitchen sponges
9 Trebly
10 Chesapeake Bay delicacies
11 The pale blue dot in Voyager 1's "Pale Blue Dot" photo
12 Puccini opera about an opera singer
13 Alternative to Kirin and Sapporo
18 Playful bites
23 Place where masks are still seen indoors
24 Rosary units
25 Half of an '80s sitcom duo, with 20 Across
28 Sea urchin, on a sushi menu
31 Polish product?
33 L.L. Bean competitor
34 PC shortcut for "copy"
36 Keep plugging away
37 Clear
39 Lab safety org.?
40 Google result
44 "The ultimate realization of modern technology," per Don DeLillo
46 Some Oklahoma natives
48 Satellite signal receiver
50 "There, there …"
51 *Schitt's Creek* star Catherine
52 Cell's ancestor
53 Fountain near Rome's Spanish Steps
54 "Otherwise …"
56 It often precedes mating
59 Salt Lake City football team
62 Scratch (out)
63 Laser gun sound effect

John-Clark Levin is a journalist and author from Ojai, California.

SOLUTION TO JULY/AUGUST PUZZLE

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