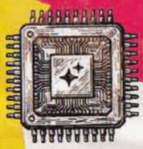
MIT Technology Review

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AUDACIOUS IDEAS FROM THE BLEEDING EDGE OF TECHNOLOGICAL INNOVATION

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I'd wager everyone has a rehearsed response to what's absolutely one of the world's worst interview questions: "What's your biggest weakness?" Whenever I've gotten it, I take a slow—even pensive—breath and rattle off my line: "I say no to myself too much."

I won't lie. It's a bit shameless—a definite humblebrag. I'm a systems thinker: When an idea pops up, I immediately spin up a feasibility assessment in my head. I run lists, plot timelines, and tally budget line items. Sometimes a rough Gantt chart starts to take shape. (I'm a gas at parties, as you can surely tell.)

My brain, throughout my 20-plus-year career as a science and tech journalist, has played host to a near constant tug-of-war between ambition and reality. Learning to find that balance is a big part of what's helped me survive in this industry and, ultimately, led me here. This past spring, I had the great privilege of joining the incredible team of journalists behind *MIT Technology Review* to take the reins of this magazine.

If you've been reading along with us for the last handful of issues, you may have noticed a few changes starting to materialize. We've brought back a regular roster of lists and infographics (both things that magazines do particularly well). But the biggest change is only just beginning to take shape, which is why Mat Honan, our editor in chief, asked me to hop in to introduce myself—and the issue you're holding in your hands right now.

We're giving ourselves permission to play around and experiment. To be a little … audacious.

Because, practical though I may be, I do still have plenty of ideas. It's just that I sometimes need a reminder to stop blocking myself and *do the thing*. That's the spirit driving this issue in particular.

We wanted to end 2026 with a slate of stories that check in on impossible ideas. Why? Because it's frankly a lot of fun to dream about living on the moon or uploading our brains. Because losing sight of ambition is all too easy when it feels as if we're playing whack-a-mole with the world's problems. But also because the scientists and engineers who absolutely refuse to give up on even the most daring endeavors—like making synthetic blood or decoding animals' speech—remind us what this whole technology thing is supposed to do to begin with.

It's supposed to take cutting-edge research and development and apply it to make life better, safer, healthier, even more joyful. And when we eff up and make things worse (see: forever chemicals, traffic deaths, and AI that encourages potentially dangerous user behavior), we're supposed to dig back in, assess the damage, and find ways to fix what we've broken. Even when unraveling the mess might itself seem impossible.

Right before I came to *MIT Technology Review,* I edited a newsletter about individual actions that can help address the climate crisis, which some would call—and have called—a fool's errand, given the sheer scale of the problem. They might say it's as implausible as an AI kill switch, practical nuclear fusion, or a superconductor that works at room temperature. But if I learned nothing else from three years spent finding ways for li'l old me (or li'l old you!) to chip away at one of humanity's biggest existential threats, it's that focusing on what we can't do only makes the darkness darker.

So yeah, this one's for the folks who have the audacity to try, and who refuse to let anyone—themselves included—tell them no.

I hope you enjoy the ride.

Corinne Iozzio
EDITORIAL DIRECTOR, PRINT

STAN HORACZEK

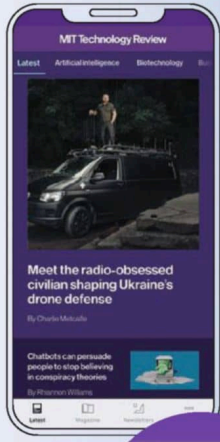
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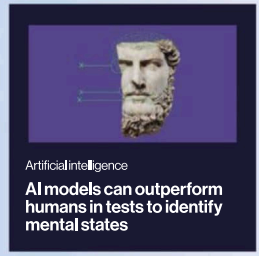
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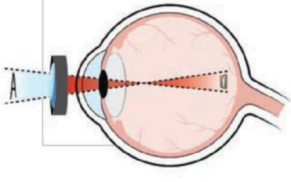
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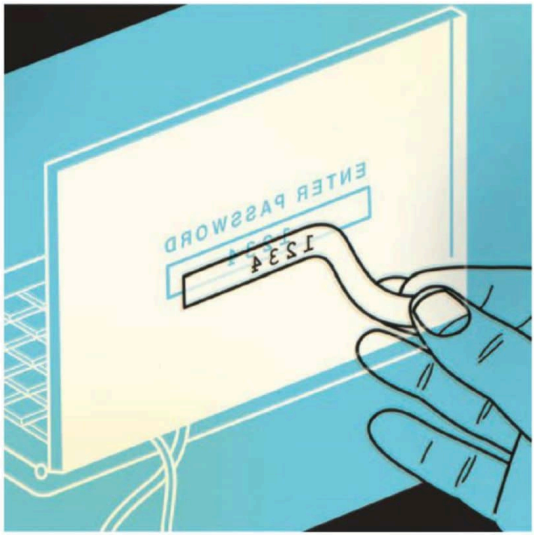
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Group chat

We want to hear from you! As we close out 2026, tell us: What's one topic we can help you understand better in 2027? Write to **newsroom@technologyreview.com**.



TECH TIP

Curious about the tools our staffers deploy at home or work? Here's a nugget of advice on how to manage the tech in your life.

Lately, I've been getting asked quite often to DJ in the passenger seat while friends are driving, so I ask for their phone's passcode to work on my mix. I often find myself aghast when they rattle off only four digits. A chill runs down my spine if they tell me it's their birth year or birthdate. I've even heard of a work phone with the PIN written on a sticky note slapped on the back. Horrifying.

Here's what I tell them: Please pick a PIN that's six digits. Six digits create 100 times as many combinations as four, making the phone much more resilient against brute-force attacks (where someone repeatedly guesses random PINs until they land on the right one). Both iPhones and Androids let you set a password if you want to go even further. Just remember to make it different from all your other passwords. And you probably shouldn't share it—even with your friend riding shotgun. *—Abby Ivory-Ganja, senior engagement editor*

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POLL

In the last issue, we asked you to tell us what you think about various uses of AI. Here's the one that most divided opinions: Is it okay to use AI to write a thank-you note?



YOUR TURN TO WEIGH IN!

This issue is all about checking in on audacious goals that may feel out of reach. What "impossible" idea do you most want to see come to fruition?

- ☐ Making synthetic blood
- ☐ Talking to animals
- ☐ Cleaning up PFAS
- ☐ Eliminating traffic deaths
- ☐ Living on the moon
- ☐ Making brains immortal

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ROUNDTABLES RECAP

Roundtables is a monthly virtual event series where editors, reporters, and subscribers discuss trending topics. ICYMI, here's a snippet from a recent conversation about online censorship.

Q: What questions should we ask ourselves when taking in information? What are some best practices to find credible sources? *—Inez B-H*

A: That's a great question. I'm going to go back to some of our previous reporting: One piece of advice from a digital literacy expert suggested what he called the SIFT approach. SIFT stands for **stop**; **investigate** the source; **find** better coverage; and **trace** claims, quotes, and media back to their original context. It's not just about fact-checking the information that's there—whether that's the story or the quote—but having multiple tabs open, doing multiple searches, reading other news coverage, and doing additional research. It's a lot of extra work, but I think that's a big part of the answer. *—Eileen Guo, senior reporter for features and investigations*

THIS CONVERSATION HAS BEEN EDITED FOR CLARITY AND LENGTH.

HARRY CAMPBELL/THEISPOT

MIT Technology Review

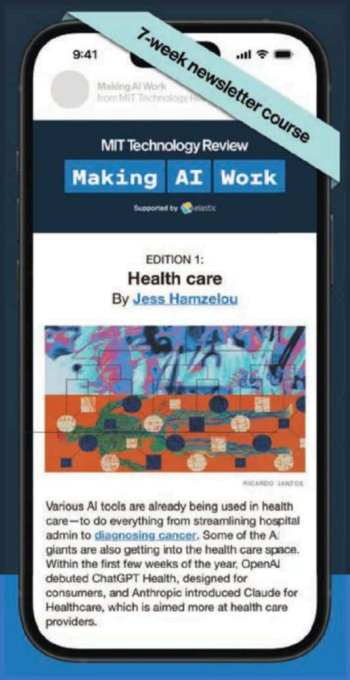
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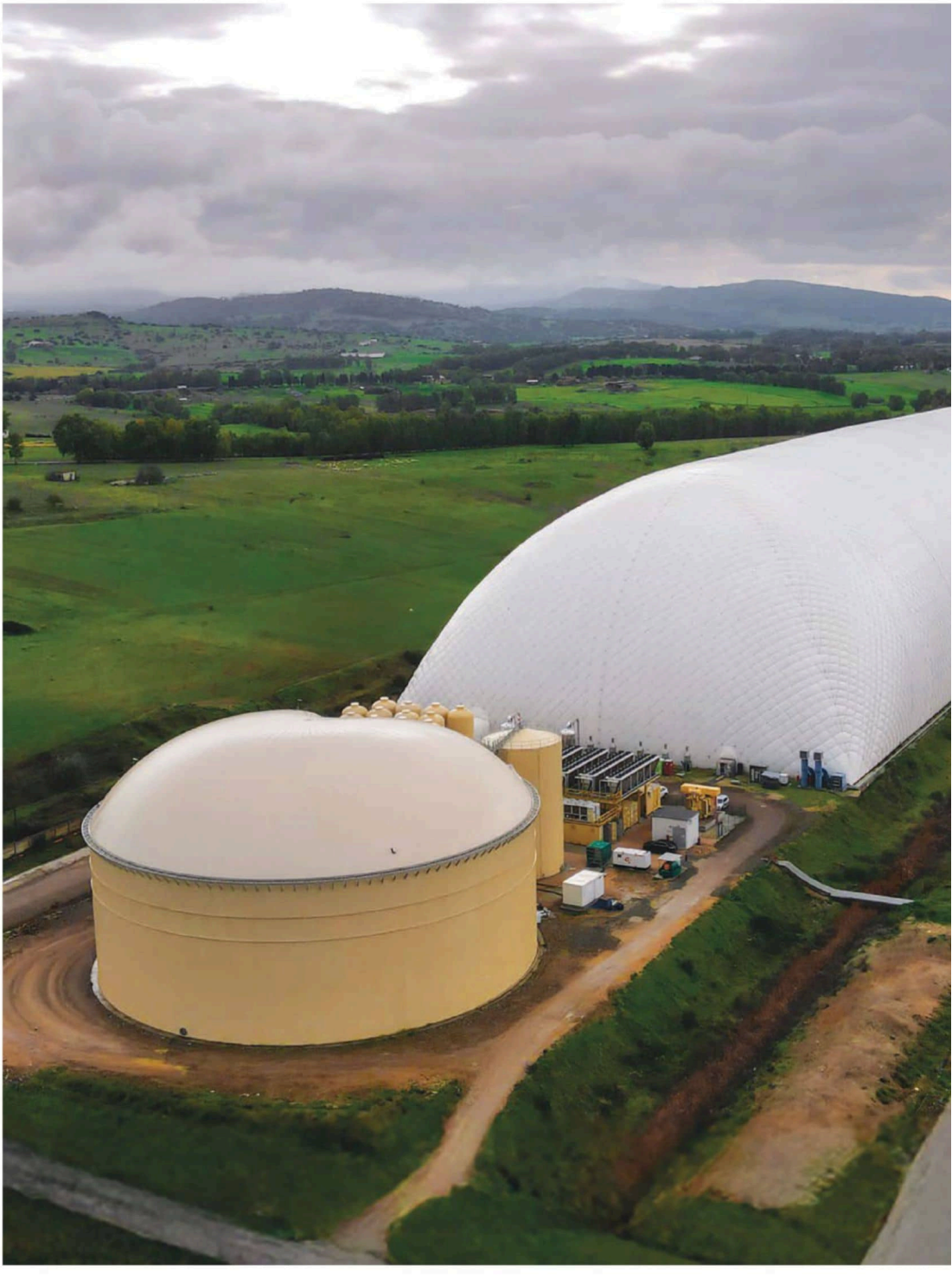
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The Download

Opposite: Energy Dome is one of MIT Technology Review's 10 Climate Tech Companies to Watch. Read the full list at technologyreview.com/climatetech2026.

THE BIG PICTURE

Super dome

An Italian startup is using compressed carbon dioxide to bring cheap, long-duration energy storage to the grid. By Casey Crownhart

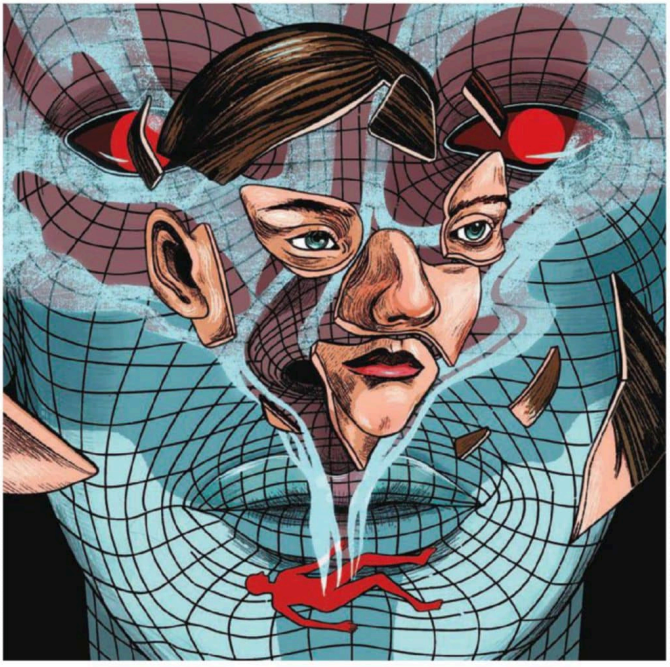
As the world races to meet explosive electricity demand, solar and onshore wind power have become the cheapest and quickest-to-deploy power sources. But despite their upsides, both are subject to variations in weather that can make supplies intermittent. Italian startup Energy Dome uses stored carbon dioxide in its plants to smooth out supply and demand, a system it says is both quick to build and more affordable than energy-storage go-tos like lithium-ion batteries.

An Energy Dome plant is built around a huge white dome about the size of seven soccer fields, holding some 2,000 metric tons of carbon dioxide. When energy is available—say, from a connected solar farm—compressors squeeze the gas. That process results in liquid carbon dioxide, which the system stores in carbon-steel tanks, and heat, which it holds in a proprietary thermal storage material. Then, when the grid needs power, the carbon dioxide is released from the tanks and warmed with the stored heat, turning it back into a gas. That gas passes through a turbine to generate electricity and flows back into the dome, ready to begin the cycle again.

Compressing gas to hang onto energy isn't new—utilities have been pumping air into underground caverns for decades. But Energy Dome's approach doesn't require any specific geology to work, so it could scale to help grids almost anywhere. The company's first commercial plant (pictured) came online in Sardinia, Italy, in 2025 and has a capacity of 200 megawatt-hours, which is enough to power about 18,000 Italian homes for 10 hours. And Energy Dome has about 30 gigawatt-hours' worth of plants in the works worldwide.

While the system isn't quite as efficient as lithium-ion technology (70% of the energy used to charge its battery is returned as electricity, compared with 90% for lithium-ion), Energy Dome is confident in its other upsides. The company says that, thanks to a design that uses commercially available equipment like compressors and storage tanks, it can go from a signed contract to delivered capacity in only two years. In June 2026, for example, it inked a deal with Google to build a 200-megawatt-hour plant in Ireland that should come online in 2028. The technology is also up to 15% cheaper than lithium-ion for a system designed to discharge its energy over the course of eight hours—economics that Energy Dome claims will get even better for facilities that deliver up to 24 hours of electricity. ■

Casey Crownhart is a senior climate reporter at MIT Technology Review.



EVA REDAMONTI

TRENDING

Tech death support

Most startups fail. A new industry is giving their data an afterlife in AI.
By Matthew King

When Keelan Miskell began winding down his crypto startup this year, he didn't think its data was worth much: the users were anonymous, the company just a few years old. But he's since turned the firm's digital archives into real money. He's netted roughly $25,000 for his code base and a still-pending amount (likely around $15,000) for the workspace data in Google, Notion, Figma, and Slack. "At least all that stuff we were doing for two and a half years is worth something to someone somewhere," he says.

The sale was brokered by a company called SimpleClosure, part of a new growth sector in tech: businesses catering to dying startups. Estimates from Carta and AngelList show shutdowns rising between 26% and 56% annually in recent years, and an end-of-life ecosystem—including coaches, "death doulas," and firms that help handle the legal, tax, and operational headaches of going belly-up—has emerged. Now tech undertakers are selling the data remains to AI labs.

SimpleClosure added data sales to its services in April. Its Asset Hub platform helps founders sell their code and workspace data—emails, chats, documents. Buyers include foundation AI labs, vendors that construct simulated workspaces for AI training, and mature tech companies building their own models. Asset Hub has handled over 150 deals and expects to return over $10 million to startups by the end of 2026. CEO Dori Yona has seen these transactions, once rare and "somewhat taboo," become increasingly routine, with 47% of SimpleClosure deals now including code or data sales.

And it's got company. Industry rival Sunset also has a rapidly growing data resale business. Founder and CEO Brendan Mahony says Sunset values a dying client's assets by head count, years in operation, volume of data, and how the team used its tools. Particle board, he says, is a good analogy: "This operational exhaust data is like the wood shavings that everyone thought had no value, but it actually has a ton."

Demand for defunct companies' data emerged suddenly last year, as AI training labs hit the limits of public and synthetic datasets. Surge AI, for example, buys data to build "reinforcement-learning gyms" where clients' AI agents practice tasks—think debugging a complex IT architecture or drafting appellate briefs. Nick Heiner, who leads the company's work on these environments, says he seeks data archives reflecting a range of situations, from disagreements to tricky judgment calls. Heiner explains that one company's Slack history, if it captures conversations with variety and depth, can be worth more than another's Slack, email, and calendars combined.

Real archives avoid common errors in synthetic worlds, such as references to dates that don't exist, but the extent of performance gains remains unclear. No company has yet released tests comparing results of real-world data training with the alternatives. Pricing reflects this uncertainty: Buyers quote wildly different numbers, Heiner says, because valuations are based on "research theses" estimating how many useful tasks come from, say, 100,000 lines of code.

That hasn't stopped bigger deals from happening. This past August, as part of

Spirit Airlines' bankruptcy, Google outbid the AI data company Mercor to buy the carrier's decades of data, including 100 million emails, 500 million Teams messages, and 176,000 employee records. The price tag: $10 million. And *Bloomberg* reported in September that SpaceX's AI unit is weighing buying data from struggling startups.

Legally, this all could get iffy. Spirit's flight attendants' union objected to the sale on privacy grounds, and Greg Ewing, an attorney who advises AI startups, has called such data "legally radioactive." Suppliers employ data scientists to scrub personally identifiable information and exclude HR records, and buyers say they scrub too. But Ewing points out some of the private details that lurk in emails and calendars: doctor appointments, school pickup arrangements, date-night plans. He describes a "Wild West of AI training" that is only starting to give way to proper licensing agreements and vetted use.

There's also the question of who profits from these windfalls. The proceeds typically flow to senior creditors and investors—not employees. To Ifeoma Ajunwa, a law professor at Emory University and author of *The Quantified Worker*, this represents a form of "captured capital." Legal precedent allows for monitoring to help workers do their jobs, but once a firm is out of business, that justification vanishes. "Employers should have express consent before selling workers' data," says Ajunwa, but she adds that there's no federal law banning such sales.

While many see this new market as a chance for failing businesses to recover some value, these wind-down sales also have limitations. Founders have little to no visibility into who is buying the data and what they plan to do with it. Plus, there's little assurance they're getting a fair offer. Data prices will likely stabilize in the coming year, though, unless an AI bubble pops first. Either way, tech's new undertakers will be there to appraise what's left. ■

Matthew King is a technology and environmental journalist based in Baltimore.

REPORTING BY JAMES O'DONNELL, EILEEN GUO, GRACE HUCKINS, CASEY CROWNHART, ANTONIO REGALADO, DAVID ROTMAN; GETTY IMAGES

In case you missed it ...

The stats, studies, and ideas behind the headlines

1,050 Minimum number of people who died within range of surveillance towers along the US-Mexico border between 2015 and early 2026, according to an *MIT Technology Review* investigation. In more than 110 of those cases, the towers were AI-enabled ones from Anduril.

re·ward hack·ing

(noun)

A phenomenon in which AI agents use unexpected approaches to complete tasks, earning them rewards—which in turn increases the likelihood they'll use the same methods again.



71 GIGAWATT-HOURS

The amount of new grid-connected battery capacity the US is on pace to install in 2026—a 20% increase over 2025.

par·a·bi·o·sis

(noun) The practice of joining together the circulatory systems of old and young animals. In labs, it's been proved to make old animals act younger, so longevity startups are trying to find ways to mimic its effects with drugs.

Q: Big tech companies will spend over $1 trillion on AI next year. What happens if they don't get enough of a return on that?

A: "If you don't get the productivity gains, at some point people are going to sour on AI, and that will bring down investments and it would also limit revenue growth."

—Daron Acemoglu, MIT economist, 2024 Nobel laureate

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JOB TITLES OF THE FUTURE

Delivery drone air traffic controller

Trevor Wischnewsky is making sure that the sky stays organized as we enter the age of food delivery by drone. By Eamon Whalen

The moment Trevor Wischnewsky heard that drones were delivering pizza and sushi around his Texas neighborhood, his mind was made up. "It was super fascinating," he says. "I just immediately wanted to be a part of it." Wischnewsky is now an RPIC, or "remote pilot in command," at a company called FlyTrex. An RPIC is like an air traffic controller. But instead of airplanes, this new class of aviators tend to fleets of hexacopter drones that ferry cargo to homes and businesses within a three-mile radius. Not only does he ensure the safe passage of FlyTrex's parcels, but Wischnewsky coordinates traffic with a growing swarm of delivery drones dotting the skies over Dallas from competitors like Zipline, Amazon, and Alphabet's Wing. Here's what it takes to land the gig.

Aviation experience

When he applied to FlyTrex, Wischnewsky was in training to become a commercial pilot and flight instructor, and he was already certified by the Federal Aviation Administration as a drone pilot. The company requires this credential, along with a weeks-long FAA-approved training course, to ensure that a pilot is prepared to take over a drone if need be. Though he doesn't pilot the craft, Wischnewsky monitors the delivery process from FlyTrex's operations center with the help of inputs from GPS, lasers, and a range of sensors.

A collaborative mindset

At first, the biggest challenge was trusting the technology. "On the manned-aircraft side, they tell you 'Don't trust the automation,'" Wischnewsky says. The Dallas–Fort Worth area, though, is a testing ground for unmanned aircraft systems traffic management (UTM), a network that allows autonomous drones from FlyTrex and its competitors to share their coordinates in real time to help avoid collisions even beyond the pilot's line of sight. Once Wischnewsky makes sure a drone is flight-ready, its path is unimpeded, and the weather conditions are clear, UTM takes care of the rest.

Ability to stay calm under pressure

At his busiest, Wischnewsky will have up to 10 drones on his watch at the same time. "You're there as a safety net," he says. Even with automation, keen situational awareness is required, and the most common hazard is the weather. Wischnewsky recalls a particularly stressful day: A drone had been in the air for only seconds when the wind picked up so suddenly that he had to intervene. He returned it safely, preventing an errant ice cream cake from hitting the sidewalk. ■

Eamon Whalen is a reporter and researcher based in San Francisco.

NHUNGLE

DISPATCH

Chip fabs rise in Pyeongtaek, South Korea

At the world's biggest chipmaking complex, Samsung is building the fabs it needs for the AI memory boom. By Michelle Kim



Pyeongtaek, South Korea

Generative AI models run on powerful chips known as GPUs, which depend on stacks of specialized memory chips packaged with the processor. To meet growing demand for memory, Samsung is building a massive new semiconductor manufacturing complex in Pyeongtaek, South Korea. Three fabs already operate around the clock, and a fourth is coming online. Construction of a fifth was halted during a drop in demand for memory chips in 2024 but restarted when the AI boom sent demand soaring.

It's just before noon on a Monday, and construction workers are pouring out of Samsung's fabs in Pyeongtaek, a farming city south of Seoul where rice paddies abut a sprawling chipmaking complex. Thousands of workers, dressed head to toe in black with sky-blue vests, take off helmets bearing their names and fab numbers.

They walk to lunch, sweaty and flushed, in chunky sneakers capped with yellow rubber toe guards. Some hop on scooters or motorcycles to get around the campus, which covers an area about the size of New York City's Central Park. They'll dine at buffets, diners, and beef stew joints, walking past banners advertising short-term leases for studio apartments. Some stop by real estate offices to inquire, stepping up to the same counters where Samsung's salaried engineers buy new homes.

In front of the fourth fab, I meet Choi Hye-rin, a 35-year-old safety officer, as she wipes her forehead with a handkerchief. At dawn, she boarded one of the shuttle buses that ferry workers in from Songtan, an older, scrappier district. She oversees the safety of a crew responsible for building cable ducts. She writes reports, inspects equipment, and checks the chemicals the workers handle. She's one of hundreds of women working on site, many employed as spotters who walk ahead of heavy equipment.

Safety is a big deal here. After lunch, construction picks right back up. Excavators move past rust-red steel structures rising high under tower cranes. Banners that hang from the highest girders read, "Even if the work runs late, don't rush." A giant LED scoreboard announces the winners of a contest for writing a poem about safety. Helmets stickered with a pledge, "I will not work if it's not safe," perch atop lockers. The finished fabs glisten from across the street.

Along with the cautionary messages, there's a sense of urgency in the air. Samsung predicts that demand for memory chips will continue to surge through 2028. And for years the company watched its domestic rival SK Hynix pull ahead in the global market for the high-bandwidth models that power Nvidia's AI accelerators. (Meanwhile, the Taiwanese chipmaker TSMC has dominated the foundry business, manufacturing chips that other companies design.) The Pyeongtaek build-out is Samsung's attempt to reclaim its lead on memory chips.

Although the heat can be brutal and the work zones are crowded, Hye-rin has no plans to leave. "The rate here is higher than other construction sites, and the work is relatively easy," she says. She gets paid 140,000 won ($97) a day and expects the boom to keep her busy for some time: "You just keep coming back." ■

Michelle Kim is an AI reporter at MIT Technology Review supported by the Tarbell Center for AI Journalism.



Samsung's new fabs are clad in Mondrian-style panels of red, yellow, and blue.

SHIN YONG-JU/AFP VIA GETTY IMAGES; ANDLIKETHINGS VIA WIKIMEDIA COMMONS (MAP)

MAPPED OUT

The bionic eye

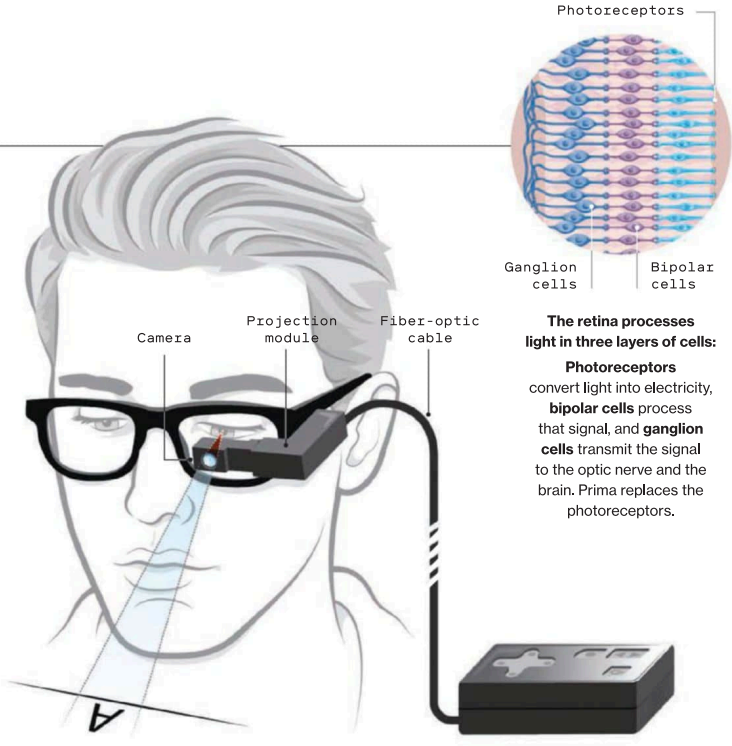
This system lets people with blind spots read and do crosswords.

By Linda Marsa

Age-related macular degeneration (AMD) affects more than 5 million people around the world. And until now, no treatment could restore their vision. The Prima system, which was approved in Europe in July and is awaiting FDA clearance in the US, changes that. It combines a retinal implant with camera-equipped eyeglasses to improve sight in patients who develop a blind spot in the middle of their vision due to advanced AMD. After training sessions, more than 80% of recipients were able to read, do crosswords, and use their phones.

Developed by the California-based Science Corporation, the system takes advantage of the fact that AMD doesn't damage all retinal circuitry; only photoreceptors—the cells that convert light into an electrical signal—die off. Prima's implant mimics those cells and transmits visual information directly to healthy eye circuitry and on to the brain. "We're leveraging all of the body's own natural functions to process and transmit the information," says Frank Brodie, an ophthalmologist at the University of California, San Francisco, and medical director for Prima. ■

Linda Marsa is a former Los Angeles Times reporter and an author who covers medicine, health, science, and the environment.



The retina processes light in three layers of cells:

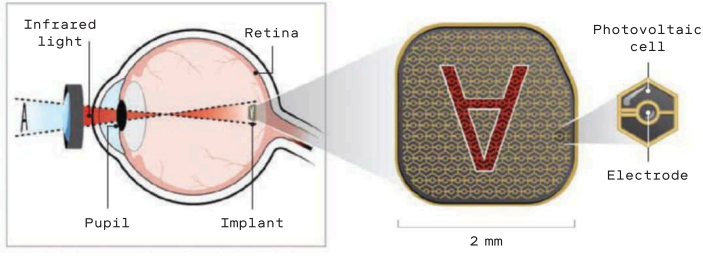
Photoreceptors convert light into electricity, **bipolar cells** process that signal, and **ganglion cells** transmit the signal to the optic nerve and the brain. Prima replaces the photoreceptors.

CAPTURE

Glasses outfitted with a miniature front-facing **camera** capture what someone is seeing in real time. The video feed is roughly five megapixels running at 30 frames per second, which is similar to TV. The raw video is transmitted to a connected processor via a **fiber-optic cable**.

CONVERT

A small, handheld processor, which can be set on a table or tucked in a pocket, converts the video feed into infrared light signals that route back to the glasses. The device also includes physical buttons that let the wearer adjust contrast, brightness, and zoom.



DISPLAY

A laser **projector** on the glasses faces the wearer and shines pulses of **near-infrared light** directly at the eye at 880 nanometers—an invisible wavelength. This signal passes through the **pupil** and on to the **retinal implant** in the back of the eye.

SEE

The implant is made up of 378 pixels, each with an **electrode** and two **photovoltaic cells**, which do double duty. They convert the light into a current that healthy bipolar and ganglion cells pass on to the brain. They also act as solar cells to power the chip, eliminating the need for a battery.

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Massive tree-planting programs lead to unhealthy monocrop plantations. Daisy Dent aims to help forests rebuild themselves.

By Matthew Ponsford
Portrait by Christian Ziegler

Forests from the trees

In a research station in central Panama, you can walk through a century of forest time, watching scrubby plots of adolescent trees give way to cathedral-like canopies of mature growth. Forest ecologist Daisy Dent, a senior scientist at ETH Zurich, oversees this sequence of plots across the Barro Colorado Nature Monument, some of which date as far back as the 19th century. Not one of the trees she surveys was planted by human hands. She maps, measures, and tracks each trunk that emerges, revealing how waves of tree life rise from bare earth.

Tropical forests like these are our planet's biggest terrestrial carbon sink, accounting for around 40% of carbon stored on land. As part of an international network of researchers, Dent is deciphering the networks of animal and plant interactions that enable some forests to recover after destruction. The goal is a low-cost, high-impact alternative to typical carbon-crediting schemes, which plant huge areas with a single species of tree. For over a decade, her research has built a body of evidence that such large "monocrop" programs could be expensive mistakes—and that more resilient forests can rebound naturally in just a few decades, re-creating ecosystems that suck up vast quantities of carbon dioxide.

Few places are better to demonstrate this than Barro Colorado, a reserve covering the forested peninsulas and islands that formed when construction of the Panama Canal flooded the area in 1914. Under the management of the Smithsonian Tropical Research Institute, generations of ecologists have amassed more than a century of records.

That means Dent can trace why some plots rebound after clear-cutting for farming and forestry while others falter. Fruit-eating animals—including spider monkeys, bats, and parrots—are responsible for planting more than 70% of trees in tropical forests, and Dent's dataset can tell which built each patch of trees by depositing seeds in their nutrient-rich droppings. Many of these creatures worked together to plant a diverse 70-year-old patch whose canopy is approaching the stunning structure and richness of an ancient jungle. In contrast, a patch of similar age populated by narrow trunks of a single long-lived species, *Gustavia superba*, hints that tropical rodents called agoutis are more or less the sole animal architects behind this more homogeneous forest.

The data she collects helps write a playbook for when to let ecosystems regenerate and when to give them a helping hand. One 2024 estimate in *Nature* found that some 215 million hectares of forest worldwide (an area larger than Mexico) could regenerate naturally. "Tropical forests are underpinned by this massive network of interactions," Dent says—interactions between life-forms like the fungi that help trees take up nutrients, as well as pollinators and seed-distributors. Supporting those relationships is key to growing forests that lock up carbon and help sustain local communities and wildlife.

Just over a decade ago, as the landmark Paris Agreement was being codified in 2015, forest recovery seized global attention as a solution to the climate crisis. Global leaders rallied behind plans to regrow a trillion trees, after the ecologist Thomas Crowther highlighted their potential to capture a decade's worth of global carbon emissions. But the biggest question has lingered: How, exactly, do you regrow two trees for every star in the Milky Way?

While startups have proposed seed-spraying drones and nutrient-coated seed bombs, Dent has spent two decades studying what happens when we let forests rebuild themselves. As a PhD student around the turn of the millennium, she researched old-growth forests in northern Borneo but felt hopeless watching entire landscapes felled for palm oil plantations. Rather than despair, she turned to restoration. Then, as a postdoc in 2005, she joined





Panama's Prorena, a joint initiative between the Smithsonian Tropical Research Institute and the Yale School of Forestry and Environmental Studies, which aimed at determining how best to establish diverse native forests on clear-cut land.

Back then, secondary forests—ones that grow naturally after the original forest was lost—had been "a bit of a niche research area," Dent says. But as farming and human infrastructure have driven deforestation, resurgent forests now account for some 70% of all tropical canopies. Prorena initially followed the usual playbook of transplanting nursery trees to rangelands, but Dent began to question whether planting was necessary. In 2009, she published an encouraging paper showing that animal populations rebound quickly as forests naturally regrow.

In 2010, she began working in Barro Colorado on the plots established by the pioneering American ecologist Julie Denslow. In 1994, Denslow identified plots that had been regenerating naturally for 20 to 100 years, and Dent would add younger ones to continue the sequence.

The site provides not just general data on forest regrowth but in-depth demographic information over time, says Robin Chazdon, a professor emeritus of ecology and evolutionary biology at the University of Connecticut who collaborated with Denslow when she established the plots. "It tells you more about the actual processes that are happening in the site," she says.

For example, previous research had shown that fast-growing "pioneer trees," the first to thrive in the damaged land, are eventually overtaken by larger carbon-storing trees. Dent's research helped fill in gaps about the mechanics of how this happens—or doesn't happen—in individual cases. In the *Gustavia*-dominated patch, for instance, stubborn grasses planted by cattle ranchers smothered most other trees before they could take root. These trees can hang around, crowding out the light, for 150 years, blocking the second wave of large-trunked trees.

Dent found herself well placed for the massive influx of interest in reforestation that began in 2015. She'd already become a principal investigator for 2ndFor, an international research network aiming to learn how best to manage secondary forests. Using data gathered from the Barro Colorado plots, the team authored a 2016 paper in *Nature* showing that a hectare of naturally regenerated secondary forest can capture 11 times as much carbon each year as an old-growth one, with young trees absorbing it quickly as they compete to grow toward the sun.

Then, in a 2022 study published by the Royal Society, Dent and colleagues showed that locations such as Barro Colorado are among the best-case scenarios for what can be achieved without planting a single seed. Clearings are often surrounded by lush environments filled with birds, bats, and other animals, all of which help tree cover regain old-growth levels of richness and abundance within a few decades. Using data from Panama and Brazil, Dent published a follow-up in 2024 showing that plots with as little as 35% of tree cover can regenerate as forest.

"Having these long-term mapped forest plots is really valuable," says Liza Comita, a professor of tropical forest ecology at Yale University, who is collaborating with Dent on projects that translate her findings into action. "It provides this really nice research infrastructure where you can build projects on top of that."

In Panama, Dent works with nonprofits and carbon-crediting schemes to fast-track recovery. They've mapped corridors to reconnect forest fragments and made plans to reintroduce animals in "silent forests" that have lost much of their wildlife. They're also working to replant tree species that can accelerate growth—what Comita calls assisted natural regeneration. Leaving plots alone may seem like the simpler option, but it can't be done everywhere, says Dent. Many sites are too degraded.

Clearings are often surrounded by lush environments filled with birds, bats, and other animals, all of which helps tree cover regain old-growth levels of richness.

The two are working with the London-based carbon-crediting startup Ponterra to develop solutions for a region of southern Panama where remnant forests line the edges of abandoned ranches. Such sites almost always need some intervention, Comita explains. Many demand hands-on actions, such as enrichment planting.

Today, the questions projects like Ponterra are asking are closer to her own research, says Dent. For instance, they want to understand if solitary standing trees, often left by ranchers to shade cows, help sites regenerate faster. Those insights can help Ponterra sell high-quality credits and avoid the embarrassing pitfalls that can lead fresh plantations to literally go up in smoke. While credits can be bought for as little as $5 per metric ton, corporate giants such as Microsoft—one of Ponterra's clients—have paid more than 10 times as much for high-quality removal.

There are plenty of places where a level of natural regeneration can work well. So far, millions of hectares of rainforest are naturally regenerating in Brazil, according to the Brazilian Restoration and Reforestation Observatory. Still, Dent is mystified as to why the people in charge of large-scale projects continue to think the best solution is the one that imposes humans' will on the landscape.

The conversation may be shifting. As droughts hit Latin America, policymakers and carbon creditors might be forced to face the shortcomings of cookie-cutter plantations. "You have much reduced resilience in the system when it comes to extreme events like droughts or floods or extreme heat or pathogens," Dent says. The coming year's "mega El Niño" could be a moment of reckoning, she says: "I think there's an increasing recognition that we can't just plant trees. We have to rebuild a system." ■

Matthew Ponsford is a freelance reporter based in London.

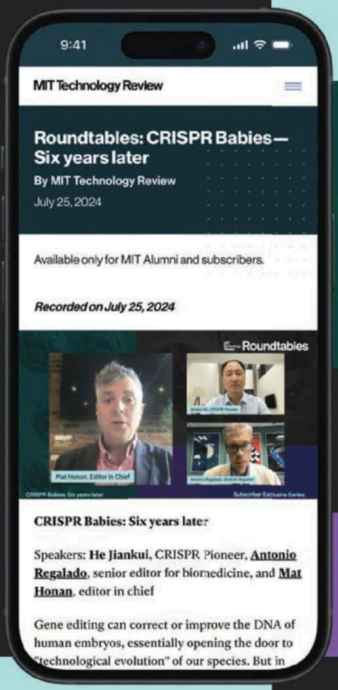
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We should stay curious about AI

By Grace Huckins



Grace Huckins is an AI reporter at MIT Technology Review.

There's a stark lack of nuance in public conversations about AI consciousness. Microsoft AI CEO Mustafa Suleyman, for instance, has produced a drumbeat of articles and interviews asserting that the forms of AI we use today could never possibly become conscious, and that even entertaining that possibility is dangerous. In June, the science fiction writer Ted Chiang—who handles the idea of artificial consciousness with curiosity and creativity in his short stories—published an *Atlantic* essay unceremoniously rejecting the idea that anything like our current AI systems could ever become conscious, offering only the thinnest justification for his claim.

The same is true of discussions about whether AI systems can really think, decide, or understand, which often fall back on the influential "stochastic parrot" framework created by the linguist Emily Bender, the computer scientist Timnit Gebru, and their collaborators in 2021. The idea is that large language models are little more than overgrown autocomplete algorithms. It caught on. Even now, you can't scroll a lick on X without finding someone "well, actually"–ing anyone who dares to describe a system that can autonomously make new mathematical discoveries as *understanding* something.

Granted, there are real problems that come with overattributing consciousness to an inert algorithm, such as the risk of unwarranted emotional attachment. And it's entirely possible that those who repudiate the idea of AI consciousness could turn out to be correct. If I were forced to stake my own claim, I'd agree that current-day AI probably isn't conscious, and it probably doesn't experience "thinking" or "reasoning" in the way that we do. But I'd offer that statement with several large grains of salt.

In order to argue with any credibility that large language models could not possibly be conscious, you first need to say what consciousness is. In my experience, the more you know about consciousness, the less confident you are about how it should be defined. I've learned in my reporting that consciousness experts, such as the philosopher David Chalmers and the psychologist Liad Mudrik, are a cautious bunch. They might have their own preferred theories of consciousness, but they recognize that in the face of so little evidence and so much mystery, one should be humble.

The same is true of simpler-seeming terms such as "understanding." I spent a lot of my PhD in neuroscience and philosophy trying to pull apart that very concept. By the end of it I could offer you a reasonable test for determining whether or not someone understands a particular phenomenon—but I couldn't actually tell you what understanding is. Is it the ability to apply an explanation of one phenomenon to new problems and contexts? Or perhaps the subjective "aha!" moment we experience when that explanation starts to make sense? If the first, then current AI possesses some understanding; if the second, then AI might never be capable of it.

Remaining humble in the face of some of the great mysteries of philosophy and cognitive science could, if we're lucky, help take us some way toward solving those mysteries. Already, AI systems are challenging our preconceptions about how intelligence works: Somehow, a function that takes in long strings of text and outputs a word can, when run over and over again, beat video games it has never seen, outsmart human hackers, and even solve long-standing mathematical mysteries. As the months wear on and the space of things that humans can do and AI cannot do inexorably shrinks, it seems prudent to consider whether human minds might have more in common with those functions than we like to admit.

There's already a strong tradition of using artificial neural networks to study the human brain. Back in 2014, researchers at MIT showed that neural networks trained to recognize images end up bearing a striking structural resemblance to the brain's visual cortex, and those networks are now key tools for neuroscientists seeking to understand how humans and other animals see. More recently, a different team of MIT scientists demonstrated that human brains and large language models represent language in similar ways. These results don't prove that human minds and artificial minds share any deep commonalities—but they suggest that it might be fruitful to investigate the question rather than rejecting it outright.

If we take seriously the possibility that large language models might think or understand or even be conscious, we suddenly have a powerful new tool in our arsenal for interrogating these basic concepts that help define who we are. ■



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PATRICK LÉGER

Our climate models have a big, dangerous blind spot

By James Temple



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

Climate change itself is increasingly fueling climate change. Rising concentrations of greenhouse gases are driving up global temperatures, setting off dangerous feedback loops that we have not fully accounted for in our climate models—or our emissions-reduction goals.

Scientists have long warned that warming would propel further warming in various ways, but a growing number of observations and studies are at last providing a sharper sense of just how powerful these cascading effects could be. And, by extension, they're showing how much faster the planet may warm in this century.

A study in *Environmental Research Letters* in September, synthesizing the results of previous papers, found that the additional carbon dioxide and methane released from thawing permafrost, intensifying wildfires, hotter lakes and reservoirs, and wetter, warmer wetlands alone could drive global average temperatures up 0.2 °C to 0.4 °C this century. That would come on top of the 2.6 °C of warming above preindustrial levels that modelers are already expecting through 2100. The additional heat could subject many of the world's cities to monthslong heat waves and expose hundreds of millions of people to flooding.

None of the models that inform the major UN climate reports, which assess how much the planet will likely warm under various emissions scenarios, account for all these feedback effects. Many of them don't incorporate any. That leaves a huge blind spot in our understanding of how much the world could actually warm in the coming decades—and how rapidly nations will need to slash emissions to stay within critical boundaries.

A separate analysis published in *One Earth* in March, which examined what the feedback problem means for our international climate goals, concluded that the world may be much further off track than is widely believed. It found that just three regional sources of warming-driven emissions—thawing permafrost, increasing fires in boreal forests, and warming tropical wetlands—may shorten by as much as 25% the time before the planet consistently breaches the 1.5 °C and 2 °C warming thresholds.

Our climate models and the UN's reports clearly need to be updated to better represent these effects. Nations must also step up their efforts to reduce emissions to reflect this improving understanding of the dangers we face, says Sam Abernethy, the lead author of the paper and a climate scientist at Spark Climate Solutions, a San Francisco–based nonprofit research group.

At least some of this is starting to happen. Spark kick-started an initiative, called the Warming-Induced Greenhouse Gas Emissions Model Intercomparison Project, through which more than 20 international teams are running the same set of analyses on different models to develop greater understanding of feedback effects' potential power. Researchers involved hope that the UN will incorporate those results into its next major climate assessment, due out in 2029. That report will update estimates of the remaining emissions that can be released before the world crosses key temperature thresholds.

But what is already clear is that the planet is rapidly warming and that nations haven't done nearly enough to cut fossil-fuel pollution. And even if we did manage to halt it, warming-driven emissions could continue.

So a number of the research groups involved in the recent studies have started to explore what nations could do to get feedback emissions under control. Scientists at the Woodwell Climate Research Center in Massachusetts are, for example, investigating the possibility of preventing fires or rapidly detecting them and putting them out when they threaten to burn the vegetation and soil that help insulate particularly carbon-rich wedges of permafrost. The Environmental Defense Fund's Climate Innovation Initiative has backed lab research on the potential of adding sulfate, iron, or other compounds to wetlands to counteract fast-rising methane emissions.

Several startups are also exploring possibilities. They're looking into suppressing the lightning strikes that are igniting more and more fires in high latitudes, placing synthetic mats above permafrost to prevent it from melting, and deploying autonomous drones to quickly suppress potentially high-emissions fires before they burn out of control.

Investigating all these ideas is worthwhile. But researchers are only in the earliest stages of figuring out how big a dent in emissions any such efforts could achieve across sprawling global ecosystems undergoing massive transformations.

The surest path to reducing the effect of warming-driven warming remains the one we've known all along: breaking society's addiction to fossil fuels. ■

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PATRICK LÉGER

Biotech could "bring back" my dead cat. No, thanks.

By Jessica Hamzelou



Jessica Hamzelou is senior reporter for biomedicine at MIT Technology Review.

I don't remember much about Peppy, my first and only pet cat. I can conjure the sensation of stroking her while she purred, recall how she used to get stuck in trees (just like in cartoons!), and chuckle about the time she pooed in my baby sister's cot. That's about it.

What I do vividly remember, though, is the day she went missing. I was 10 years old, and I searched everywhere for her, scouting nearby fields and woods until sunset. I made posters. We never found her. I was devastated.

There was no way to get more time with Peppy, but almost 30 years later, pet owners are being offered an ever-expanding set of options to potentially prolong their years with their furry companions. The possibilities include drugs, cloning, and even cryonics. But is that a good thing?

There's certainly a market for pet preservation. And a growing number of biotech companies have their sights set on pet longevity. Loyal, a company that is currently working on three potential longevity drugs for dogs, is trialing one designed to improve metabolic health in around 1,300 pet dogs across the US. Others are testing dog drugs that aim to combat both age-related diseases, including conditions like obesity and osteoarthritis, and aging itself. There's even a company focused on longevity medicines for domesticated cats.

I don't know how or when Peppy died. But if there had been a drug that might have protected her from diabetes or arthritis, there's no doubt I would have tried to get my hands on it.

That's about where my enthusiasm for pet life extension ends, though.

I'm far less interested in cloning, a relatively new option for people mourning a pet and seeking a replacement. In most cases, this technology involves taking the DNA of a pet, putting it into an egg cell from another animal of the same species, and growing the resulting embryo in a surrogate animal. It worked for Dolly the sheep, who was born the year before Peppy went missing. It has since worked for other mammals, including cattle, horses, and ferrets—and cats and dogs. In the US, a company called Viagen Pets offers to clone cats and dogs for $50,000 a go. This doesn't result in an exact replica of the animal but a genetic twin.

Still, there are lots of reasons why a person might want to clone a pet. On its website, Viagen explicitly offers customers "a way to hold on." Lori Kogan, a professor of clinical sciences at Colorado State University who has studied human-animal relationships for decades, doesn't have a problem with the practice. She points out that while we have well-established rituals for coping with the loss of a person—such as funeral services, time off work, and memorial gifts—we don't really have the same for pets. As a result, pet owners can experience what is sometimes called "disenfranchised grief," she says. Having their feelings go unrecognized can feel isolating. If cloning a pet brings a person peace, she says, "who are we to judge?"

Fair enough. But I can't help thinking that pet loss in childhood might be different. It's often the first time a child confronts death. Losing Peppy was a formative experience, and distressing though it was, I like to think it helped prepare me for losses I experienced in adulthood. I wouldn't want my own children to think that death is not final, and that individuals can be replicated or replaced.

Or, for that matter, revived, which is the promise behind pet cryonics. For a fee, a handful of companies offer to cool dead pets to extremely low temperatures and store them for long periods of time—even indefinitely. The idea is that at some point in the future, we'll have invented incredible technologies that will not only bring your pet back to life but also cure whatever it died of. Alcor, a cryonics facility in Arizona, is currently storing the remains of hundreds of pets as well as people. It even recently announced it had cooled a small marsupial—its first pet sugar glider.

With cryonics, the chances of being reunited with your pet are bordering on zero. Even those who work in the field acknowledge that the stored people and animals are unlikely to be reanimated. As things stand, there is no way to really and truly bring any animal "back."

I miss Peppy. But given the chance, would I stick her in a vat of liquid nitrogen? Or get another cat to give birth to a genetically identical animal? No, I would not.

RIP to the one and only Peppy. ■

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PATRICK LÉGER

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ARE WE THERE YET?

There are some seemingly impossible feats too good to give up on. Decoding a pet's yowls and yips? Yes, please. Scrubbing the world of forever chemicals? Absolutely. Rocketing to Mars in a fraction of the time? Let's do it!

So we decided to run progress reports on six potentially transformative technologies and ideas that have been "just around the corner" for years—or, in some cases, decades. We called up experts with a bird's-eye view of the fields to get a sense of what's holding things back, and we chatted with folks running the studies, crunching the data, and building the prototypes that could make these dreams into realities. Then we placed each idea on a progress meter ranging from 0 to 10—0 being "We don't even know where to begin" and 10 being "We did it!"

How did it all stack up? The results are peppered throughout the following 43 pages.



REPORTING BY
Robin George Andrews, Cassandra Willyard, Sara Kiley Watson, and Alexander C. Kaufman

ILLUSTRATIONS BY SAM GREEN AND EOIN RYAN

BY
ROBIN GEORGE ANDREWS

ILLUSTRATIONS
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CITIES ON THE MOON

WE'RE RETURNING TO THE LUNAR SURFACE.

WHAT WOULD IT TAKE TO STAY FOR KEEPS?

Welcome to the second space race. You can be forgiven for experiencing déjà vu. Last time, it was the Soviet Union and the United States vying to be the first to plant some flags. Now it's a sprint to the lunar surface between America and China—alongside a host of varyingly friendly and rival nations—plus a cornucopia of private spaceflight companies. And this time it looks like they're getting ready to set up camp. There will be, the contenders say, bases on the moon, permanently inhabited castles under the stars.




BASE CAMP MOON
EST 2100

The notion of a moon base, fanciful as it might sound, isn't new. But this year, under the leadership of Administrator Jared Isaacman, NASA has been flooding the zone with bold announcements. If all goes according to plan—a plan that will likely cost tens of billions of dollars to start—there will be drones, robotic landers, communication satellites, and a nuclear power plant; there will be plant terrariums and moonquake sensors; there will be mechanized scouts exploring craters for water.

Initial astronaut missions to the lunar surface, which the US is currently planning to start in 2028, will be focused on exploration and technological experimentation. But the idea is that we will—some time in the 2030s—get to a point where there will be habitation quarters for long-term stays, surrounded by a network of scientific research stations, resource mining and processing plants, and landing pads for spaceships. "It's going to be an expanse," says Carlos García-Galán, NASA's moon base program manager—one that will add up to "hundreds of square miles."

The effort is undoubtedly being fueled by nationalistic competition. China has near-identical plans to build its own base on the moon. And being first matters, because the "victor" gets to define the terms. What *is* the moon, exactly? Is it a militarized outpost? Is it a manufacturing hub? Is it a wilderness to be studied and preserved?

But there are also other reasons to go. Earth's companion contains primeval rocks that hold clues to the formation of the entire solar system. The lunar surface, with virtually no atmosphere in the way, is an ideal place to put telescopes that could examine the most ancient epochs of the cosmos. The far side of the moon would be "a fantastic place to explore the further universe," says Josef Aschbacher, the European Space Agency's director general. And it's way more energy efficient to launch rockets from the low-gravity lunar surface than it is from Earth, meaning sending astronauts—or robotic spacecraft—farther into the solar system will become much less difficult. "The moon is critical. It will be a stepping stone for going further—that means to Mars and beyond," says Aschbacher.

But if these bold visions are to become reality, there's a daunting amount of work to be done. A sprawling moon base must be safe for its astronaut inhabitants—protected from falling asteroids, endless cosmic radiation, razor-sharp lunar dust, and torturous temperature swings. It also must be somewhat self-sustaining, so that it can weather changing political fortunes and not cost ruinous amounts of money to maintain. For that, we'll need to find a way to use the moon's resources to keep the base operating—and ideally generating revenue. And we'll need autonomous robots that can build, maintain, and expand the base even when their human masters aren't present. "It's almost like starting civilization from scratch," says Simon Middleburgh, co-director of the Nuclear Futures Institute at Bangor University in Wales.



Assuming we can overcome these starting challenges, decades from now—let's say, by the year 2100—our initial moon bases could grow from barely visible structures into luminous cities, perhaps not too dissimilar from those dreamed up by authors and screenwriters the world over. "It's like science fiction today that we really want to turn into a reality," says García-Galán. Will anyone succeed?

The moon is a tremendously hostile place to set up camp. In general, daytime temperatures can reach more than 250 °F; at night, they can plummet to less than −200 °F. Exposed to the vacuum of space, the surface is constantly showered in carcinogenic radiation and frequently hit by meteoroids. And its volcanic dust is sticky and corrosive, a destroyer of equipment and choker of lungs.

Sadly, the lunar south pole—the area NASA is targeting—is even harsher. NASA wants to build a base there because its permanently shadowed craters are thought to harbor caches of water ice, which would be more precious than gold. Purify it, and you

PREVIOUS SPREAD: ILLUSTRATION SOURCE VIA NASA

can water crops and hydrate astronauts; split it into oxygen and hydrogen, and you have breathable air and rocket propellant. But the temperature in those craters can be lower than −410 °F, making them some of the coldest places in the known universe. On the surface outside those pits, astronauts would be bathed in the scorching sun for 14 days before experiencing an equally long frigid night.

But there is only so much money we can spend on safety. "What it comes down to is acceptable risk of death," Philip Metzger, a spaceflight engineering researcher at the Florida Space Institute, said while pondering some of the dangers. "What can we reasonably survive without breaking the bank?"

Temperature is one of the easiest problems to handle. Materials science has come a long way, and there are myriad metals, ceramics, plastics, compounds, and alloys that can resist wild temperature swings. Radiators keep things cool; heaters keep batteries from dying prematurely. Astronauts survive just fine too, with their fancy spacesuits—but that technology has proved itself only during brief excursions. It's not yet clear how long this equipment could operate under such tempestuous conditions.

Space radiation, which can wreak havoc on electronics and trigger a cancerous division of cells, is far more pernicious. And as Stuart George, a physicist at NASA's Johnson Space Center in Houston, explains, it comes in two unpleasant forms.

The first is galactic cosmic rays, which rain down on the moon almost constantly. "They're made by supernovas and neutron star mergers—all these kinds of things," says George. And because the atomic nuclei, protons, and electrons that make them up are moving at significant fractions of the speed of light, these cosmic rays have oodles of kinetic energy, meaning they can punch through thin shielding (say, a metal wall) with ease. "They also have this habit where the heavier ions are fragmenting in that shielding and making secondary particles," says George. That means if your shield is too thin, the astronauts behind it will be blasted with a surprisingly large dose of radiation.

Then you have the sun. It may sustain life on Earth, but without our planet's thick atmosphere and magnetic bubble to get in its way, moonwalkers will occasionally be blasted by one of its paroxysms: a solar flare (a burst of diverse types of radiation) or a coronal mass ejection (volleys of magnetized plasma). "During Apollo, they knew that if a large solar flare occurred while the crew was on the moon, there would be no way to keep them alive," says Metzger. The crew could have developed acute radiation sickness and perished in a matter of days.

THE TEMPERATURE IN THE MOON'S SOUTH POLE CRATERS CAN BE LOWER THAN **−410 °F,** MAKING THEM SOME OF THE COLDEST PLACES IN THE KNOWN UNIVERSE.

OUTSIDE THOSE PITS, ASTRONAUTS WOULD BE BATHED IN THE SCORCHING SUN FOR **14 DAYS** BEFORE EXPERIENCING AN EQUALLY LONG FRIGID NIGHT.

The way to survive a powerful solar flare or coronal mass ejection is straightforward: "Get back inside a habitat where there's more shielding," says George—preferably a dedicated, highly shielded "storm shelter," essentially a thick-walled bunker. The issue is that astronauts might be outside the base, driving a rover many miles away. Coronal mass ejections take hours to days to reach the vicinity of the Earth-moon system, but solar flares can do so in under an hour. And scientists can't yet model the sun well enough to give much advance notice. "All of the capability to forecast solar storms is kind of like where weather forecasting [was] … in the '50s and '60s," says George.

As for those punchy galactic cosmic rays, the only way to avoid them would be to put a *lot* of stuff—lunar rocks, possibly—between the astronauts and the sky. "Build habitat modules underground," says Chris Dreyer, director of engineering at the Center for Space Resources at the Colorado School of Mines. One option: Burrow living quarters into lava tubes, the naturally hollowed-out volcanic tunnels created by molten rock eons ago. At this point, NASA hasn't mentioned any plans to make its moon base subterranean, but it may need to if it wants to end up with a small lunar city.

Radiation limits the time astronauts can spend on the lunar surface over their entire life—it can total around two years max, experts estimate, before the health risk becomes too high. Unfortunately, that's not all space will throw at them. When the Artemis II astronauts swung around the far side of the moon earlier this year, they saw curious flashes light up the silvery land below. These were the explosive deaths of small meteoroids punching into the lunar surface.

Earth is naturally protected from smaller space rocks, up to around 50 feet in diameter: They burn up inconsequentially in the atmosphere. "You don't have that option on the moon," says Philip Lubin, a physicist and planetary defense researcher at the University of California, Santa Barbara. Since smaller rocks plunge toward planets and moons far more frequently than larger ones do, this means the moon is often peppered by what are effectively tiny space bullets. They could easily puncture a spacesuit or the engine of a moon rover.

How do you protect astronauts from the onslaught? "The simplest answer is burial," says Nicholas Schmerr, a planetary seismologist at the University of Maryland—conveniently, the same way you'd deal with radiation exposure. Pile up moon rocks onto your base walls or put habitable structures in lava tubes.

Inconveniently, there's always a chance that a bigger asteroid will come along. Even buried habitation modules would have trouble surviving an assault from a 50-footer—about the length of a semi-trailer.

That doesn't mean a moon base would be helpless against bigger asteroids. Planetary defense has come a long way in just a few decades. NASA's DART mission demonstrated that it could deflect an asteroid by ramming into the rock with an uncrewed spacecraft, and cutting-edge experiments at clandestine labs around the US suggest that a nuclear bomb could swat away or entirely vaporize errant space rocks. An array of both ground-based and space-based telescopes specifically designed to spy killers—such as the ATLAS quartet of largely automated telescopes, and the soon-to-be-launched NEO Surveyor infrared telescope—are also aiming to find 90% of the near-Earth asteroids potentially capable of wiping out entire cities (those 460 feet across) in the coming years.

All these protections apply to the moon. But asteroids 50 feet across are so stealthy that even NASA's best telescopes would struggle to see them years or even months in advance. Odds are that they would first be seen not long before they were due to hit the lunar surface. Then what?

It's not unreasonable to imagine several turret-like launch sites on the moon that, owing to the lower gravity and airless environment, could rapidly fire projectiles toward an incoming asteroid. Hit it hard enough and it would break into fragments. Just make sure you shoot when it is as far away as possible: "If you were to break something up into a thousand pieces, then you have a thousand impacts on the moon," says Lubin. "That might be worse than letting it hit one place."

Having your base destroyed by an asteroid would be awful. But a moon base is far more likely to be imperiled by dust—which, unlike asteroids, is everywhere, all the time.

Volcanic lunar rocks, when broken down, turn into sharp, electrostatically charged, adhesive, acrid, abrasive particles. While on the moon, Apollo astronauts who inhaled some of this dust occasionally suffered from a strange "lunar hay fever," which irritated their eyes and agitated their lungs. That same dust ate through all kinds of gear with disturbing ease. "It rips up seals, gears, motors, spacesuits, habitats—everything else it comes into contact with," says Justin Cyrus, the CEO of Lunar Outpost, a spaceflight technology company that is providing NASA with one of the Artemis program's moon rovers.

NASA has already developed a defense against these dark shards: the electrodynamic dust shield, or EDS. The lightweight electrodes that make up this shield—which can be layered on machinery, walls, and perhaps even spacesuits—use opposing currents to blast away the electrically charged dust. The EDS worked wonders when tested in labs on Earth, and it also demonstrated its anti-dust magic when sent to the lunar surface in 2025 as part of a NASA-sponsored robotic mission.

Amy Fritz, a dust-mitigation researcher at Johnson Space Center, says that the EDS will likely be widely featured all over a lunar habitat. But other dust-fighting instruments are being developed too—including a lint-roller-type object inspired by gecko skin and a sci-fi-esque blaster that uses ionized nitrogen gas. Its first spray will neutralize the charge of the dust to remove its stickiness; then a second burst will clear it off the surface.

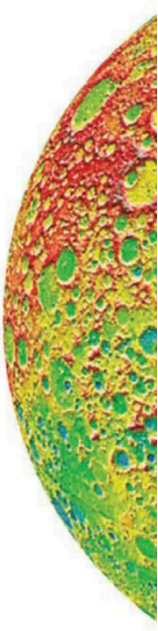
Irritatingly, the busier a base gets, the dustier things will become. As it expands to the size of a small city, rocket ships will need to deliver cargo and crew to the lunar surface on a frequent cadence. Each takeoff and landing will launch a salvo of dust in every direction, inundating the base's infrastructure. "You have to worry about essentially being sandblasted every time," says Fritz.

Metzger calculates that even with landing pads more than 3,000 feet away from a base, just 10 to 20 liftoffs or landings would be sufficient to severely damage things like protective coatings on exterior walls and communications equipment. After a while, he says, "everything breaks."

Even if the moon base of the future is buried partly below ground, barricaded against micrometeorites and space radiation, and well equipped with dust-repelling technologies, it's still a risky gig for any astronaut. Skipping around in a preternaturally agile way at one-sixth of Earth's gravity will be entertaining. But "microgravity is not good for the human body," says Dreyer. Muscle wastage, cardiovascular troubles, respiratory problems, and immune deficiencies can arise.

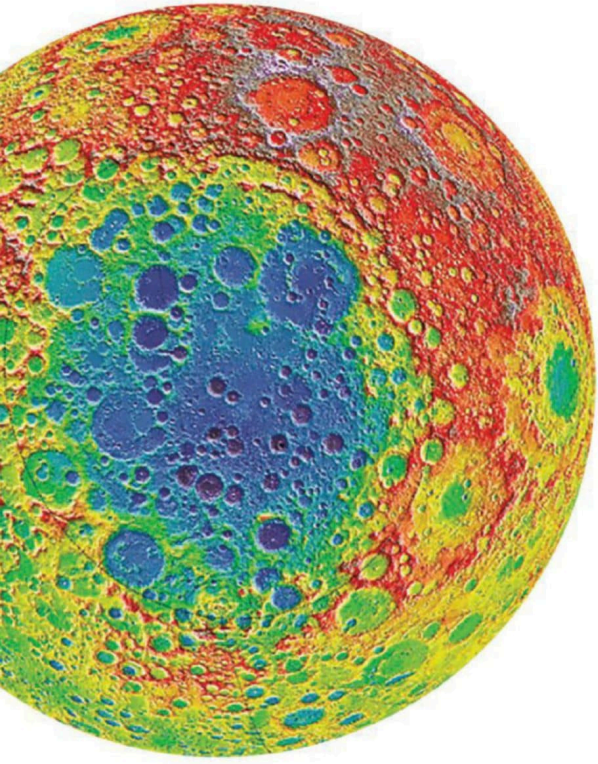
Radiation, too, may always afflict lunar residents. And there's also evidence that disease-causing microbes could stealthily sneak aboard spacecraft, even after stringent sterilization procedures. Those microbes may behave differently than they do on Earth; microgravity experiments (both real and simulated) have suggested that some become more aggressive and more likely to cause disease. "We call them the invisible crew," says Lisa Carnell, the director of NASA's Biological and Physical Sciences Division.

Hoping to find a better way to protect astronauts, Carnell spearheaded an experiment called AVATAR (A Virtual Astronaut Tissue Analog Response), which launched aboard the Artemis II mission. It used thumb-drive-size chips, containing cells taken from the heart, lungs, or other parts of the body, that could be switched



The lunar south pole, which is thought to contain a sizable amount of water, is an attractive target for lunar exploration and, eventually, settlement. This map shows the topography of the region. The South Pole–

NASA/GSFC/MIT



Aitken basin (blue) is an immense crater studded with smaller craters. The vertical distance from the lowest-lying regions to the surrounding peaks can exceed 15 kilometers, almost twice the height of Mount Everest.

on to act like miniature organs. Scientists have previously used this organ-on-a-chip technology for purposes like testing out new pharmaceuticals in a highly controlled setting. For Artemis II, Carnell's crew sent up chips containing bone marrow samples taken from the mission's four astronauts. Bone marrow makes red and white blood cells, as well as platelets—the sort of stuff that affects almost the entire human body. So seeing how space radiation and microgravity affect it would give Carnell and her team vital insight into how astronauts' biology might change on the moon.

The advantage of organ chips is that you can make them for any astronaut and then send them into space ahead of time to see how that person's organs will react to spaceflight. Researchers envision that data from such chips will be able to clue medics in to the specific preventive treatments or pharmaceuticals that will help moonbound astronauts on their journey.

What is NASA likely to send up sooner rather than later? "Brain organoids," says Carnell. Yes, she adds—that sounds super weird. But it would be good to know how a real brain might respond to being on the moon for several months before people start living there.

Okay. Your vast moon base and its inhabitants are protected—as much as is possible—from the treacherous lunar environment. But astronauts' time is extremely valuable, and humans are fragile creatures. You can't make them do all the heavy lifting, which means that whether you're trying to make a tiny lunar outpost or a small city, you're going to need *a lot* of robots. "The buildup of the moon base, in the first years, will pretty much 99% be robotic," says NASA's García-Galán.

Autonomy will be there right from the start. NASA's new version of the moon buggy, its Lunar Terrain Vehicle, can be driven by the astronauts riding in it but can also be piloted remotely from Earth (or from elsewhere on the moon). There are visions, too, of adding modular robotic arms, towing vehicles, and cargo movers—all still in the preliminary stages of planning.

Over the next few decades, though, we'll likely want an army of robots to do our bidding: excavators to dig up lunar rocks that could be turned into concrete and bricks, plus other robots to flatten surfaces, dig trenches, create building foundations, pave landing pads, and build up dust-deflecting berms to keep the base from being sandblasted by launches and landings. Even solar panels and wiring can potentially be made from moon rocks—something that the spaceflight company Blue Origin demonstrated in labs on Earth in 2023 using a geologic simulant designed to match the composition of lunar regolith.

Powering this robot army will require considerable energy. Two-week-long nights make solar power an impractical solution. Aside from a cornucopia of high-capacity, extreme-temperature-resistant batteries, nuclear power is probably the only viable option. A small, car-size nuclear reactor, filled with an almost literal handful of uranium, could power a small village for a decade without needing to be refueled. And although nobody's yet tested a nuclear reactor on the moon, few doubt that NASA and the US Department of Energy can conjure up a working design—one that perhaps wouldn't be too different from those aboard nuclear submarines. A moon base in 2100 would probably feature multiple small, autonomously or remotely operated nuclear reactors, which—conveniently—the base-expanding robots could simply plug themselves into to recharge.

But the biggest lunar question mark might be water, which planners want to support the astronauts—and to make fuel to launch things from the lunar surface. A process known as electrolysis, which uses

electricity to snap apart molecular bonds, can be used to split water into oxygen and hydrogen, both of which could be used to make rocket fuel. Getting them this way could be far less expensive than sending either all the way from Earth. And as an added bonus, it would provide a source of breathable oxygen.

Orbital data has revealed that there is some amount of water preserved in patches on the lunar south pole, but little is known about how much there actually is, what form it takes, or how easy it will be to extract. Will there be solid sheets of ice here and there, ready for us to excavate? Or will there be scattered ice crystals intermingled among the rocky grains, requiring some more inventive form of extraction?

A lot of the moon's water is thought to be hiding in deep, dark craters on the south pole, where the environment is so extreme that robots may freeze up, tumble over, or lose contact with the base. "To me, that is the biggest hurdle," says Paul van Susante, principal investigator of the Planetary Surface Technology Development Lab at Michigan Technological University.

Van Susante's lab has been putting various construction robots through their paces in moon-like vacuum chambers filled with moon-like rocks. His team was part of NASA's recent Break the Ice challenge, which invited engineers to build robots to test different ways to excavate such rocks. Some teams used an electric jackhammer and a scoop, while others used scrapers to peel off layers of the ground. The teams simulated the moon's weak gravity using a crane to lift and offset the weight of the robots. Progress in this regard is speeding along. "I won't say that's solved, but we've got a lot of the puzzle pieces," says van Susante.

Mining the water will be just one part of an extensive operation. "When you extract it, it's not going to be clean. It needs to be purified," says Jessica Atkin, a space botanist at Texas A&M. The technology to do this already exists and works fine on terra firma. But things in space never go the way you expect. "There's a water purification system on the International Space Station (ISS), and it is known for getting contaminated with microbes," she says.

But if you purify the water sufficiently—something that can handily be achieved on Earth but may falter in microgravity, where fluids flow in stranger ways—then your moon base can hit its stride. With an effective water recycling system, an increasingly populous base will never go thirsty—and, just maybe, you'll have a lunar greenhouse. Several edible plants have been successfully grown aboard the ISS, including lettuce, mustard greens, tomatoes, and peppers. Lunar dust unfortunately makes for a terrible garden: It's filled with far too much aluminum—and it forms a resistant layer when watered. But Atkin has shown that with the help of fertilizing fungi, chickpeas can grow in soil much like the volcanic stuff found on the moon.

Moon base inhabitants of 2100 would be supported largely by prepacked meals sent from Earth. But in time, they would start growing some of their own produce—probably with a good deal of automation for lighting, watering, and maintenance of humidity and other environmental conditions. Aside from chickpeas, there might also be plenty of lunar tomatoes. They'd be desirable not least because they've been bioengineered to produce higher levels of compounds called anthocyanins that, according to some studies, might help humans mitigate the cellular damage caused by space radiation.

A garden on the moon would do more than just provide food, as recent experiences on the ISS suggest. Carnell says that NASA recently caught the astronauts aboard the space station doing something sneaky. All plants up there are supposed to be confined to their growth chambers. But "we learned that the crew were pirating our leftover soil and bringing their seeds and planting their own little gardens, if you will, and hiding them in their own cabins," she says.



Conversations were had in the summer of 2026, after which NASA decided to let astronauts grow their own mini-gardens anywhere they wanted. "Some of the astronauts said they thrived better," says Carnell. Nature, and gardening, has a hugely beneficial psychological effect on those kept in confined quarters hanging above Earth. That will be even truer for those living in lava tunnels under the lunar surface. "That human element is so important," she says.

Nobody is deluded into thinking there isn't a mountain of technological challenges in the way. Mars may be a hellhole, as the writer Shannon Stirone put it in 2021 in *The Atlantic*, but the moon isn't too far behind. It's an almost comically menacing place to be. Much about it stands in the way of building a safe, self-sustaining, robotically managed base.

Beyond the first basic habitation module, it will take decades of experimentation and iteration on the lunar surface to get to a working moon base spanning hundreds of square miles. But few doubt that with enough time and tinkering, humanity can prevail. "It's not an unsolvable problem," says the University of Maryland's Schmerr.

The chief obstacle, especially in the initial stages of building, may be one of political will. NASA is currently bringing every resource to bear on the project—something that the agency hopes could culminate in a small lunar city by the century's end. But will that commitment continue over multiple US administrations? Will the international community also throw its weight behind the NASA-led effort? NASA has "a very ambitious plan," says Yuqi Qian, a lunar geologist at the University of Hong Kong. "We need to keep an eye on it." In fact, he says, "the current plan looks over-ambitious." The agency, for example, wants to put the first nuclear reactor on the moon by 2030. (China, partnering with Russia, wants to place its own nuclear power plant up there around 2035.)

"These sorts of projects—although very exciting, and potentially transformative for humankind—are the first ones to be delayed or scrapped," says Middleburgh of the Nuclear Futures Institute. NASA's direction tends to change when a new administration comes into power—sometimes dramatically so.

But several experts outside of NASA agree that, at least for now, there is definite momentum and political will behind the moon base. "NASA has very clearly expressed where they want to go, what their priorities [are], what their ambition is, and how they want to do it," says ESA's Aschbacher. "It was quite impressive to see."

Even if the political will behind the US-led endeavor is maintained over the coming decades, expanding anywhere beyond an initial, compact moon base will require more than government funding. "There has to be a lunar economy for this to be self-sustaining," says Dreyer, the space resources expert. Perhaps that will come from the production of rocket fuel, or from the mining of valuable materials on the moon that can replace similar, polluting activities on Earth. But it's not at all clear how valuable, or not, a lunar economy will be.

NASA WANTS TO PUT THE FIRST NUCLEAR REACTOR ON THE MOON BY 2030.

CHINA, PARTNERING WITH RUSSIA, WANTS TO PLACE ITS OWN NUCLEAR POWER PLANT UP THERE AROUND 2035.

Even Isaacman, NASA's chief, doesn't think the moon will be a major moneymaker. "I don't know of anything on the moon right now that's going to be easier and more affordable to mine, manufacture, and then bring back to Earth than what we could make here on Earth," he remarked back in February. (Instead, he suspects, mining metals from asteroids will be the path to prosperity.)

What if, instead, a moon base earns the right to exist because it's a place for novel scientific research? Aschbacher imagines it will be like humanity's outposts in Antarctica. Down there, in what truly feels like another world, scientist-explorers work in a land of gleaming and endless ice to learn more about our planet's climate, its deep past, and its resilient life-forms. "We understand planet Earth by looking into those remote places," he says. The moon offers a similar opportunity. What discoveries await astronauts in those primordial lava tubes? What will lunar astronomers see in the night sky—with effectively no atmosphere or light pollution in the way—that those on Earth can't?

As in all spaceflight programs, technologies developed up there will no doubt be tweaked to be used back on Earth. And a base on the moon will make exploring the rest of the solar system easier. Technologically, physiologically, and psychologically, the moon "is a proving ground for the technologies we need for Mars," says NASA's García-Galán.

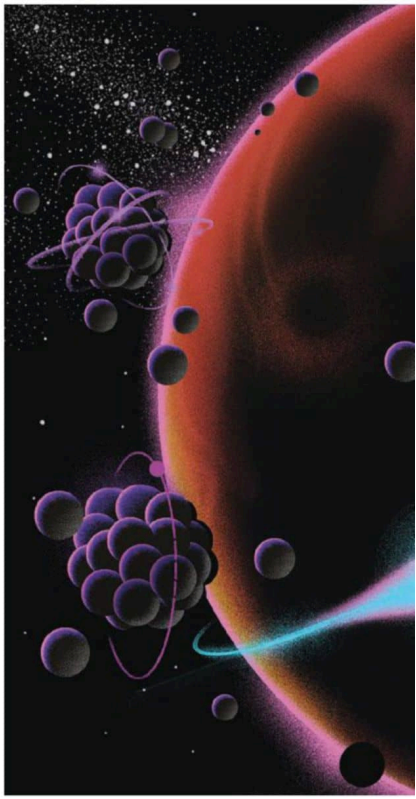
If we play the US-China race forward, perhaps the lunar south pole of 2100 will feature several sprawling bases operated by multiple geopolitical rivals. Perhaps it'll be an off-world powder keg of militarized territorial ambitions and jingoism. But maybe it could instead become an international cathedral to science—and the ultimate adventure destination. "Even if countries on planet Earth have difficulty talking to each other," says Aschbacher, they might behave differently when it comes to the moon. "I'm pretty sure they will get together and see what we can do together, and see what problems we can solve." After all, he says, up there, far from home, "you're so dependent on each other." ■

Robin George Andrews is an award-winning science journalist and doctor of volcanoes based in London. He regularly writes about the Earth, space, and planetary sciences and is the author of two critically acclaimed books: Super Volcanoes (2021) and How to Kill an Asteroid (2024).

NUCLEAR-POWERED SPACESHIPS

BY **Robin George Andrews**

Just before the Artemis II crew began its historic slingshot around the moon this past April, NASA announced plans to build Space Reactor-1 Freedom. SR-1, the first-ever nuclear-reactor-powered interplanetary spacecraft, is meant to fly an uncrewed mission to Mars by the end of 2028, arriving in 2029. A successful mission would herald a new era of more efficient, potentially faster spaceflight—saving astronauts time and cutting their exposure to harmful cosmic radiation as they travel to Mars and beyond. "You wake up to that announcement, and it puts a big smile on your face," says Simon Middleburgh, co-director of the Nuclear Futures Institute at Bangor University in Wales.



SAM GREEN

The sticking points

Running a nuclear reactor in space may sound like lunacy, but it's not. The Soviet Union sent dozens of reactors into orbit, often to power spy satellites. And experts say there aren't any major technical obstacles to making nuclear space propulsion happen. "I think it's a very doable technology," says Philip Metzger, a spaceflight engineering researcher at the Florida Space Institute. "I'm happy to see them finally doing this."

Still, developing space propulsion using reactors has been slow going. The US has started—and terminated—several programs looking into it over the past 75 years. The latest casualty was DRACO, a collaboration between NASA and the Department of Defense, which ended in 2025. The project was canceled because of high experimentation costs, an inability to compete with conventional rocket propulsion on price, and difficulty ensuring that ground tests could be performed safely and effectively. (You are creating an incredibly powerful nuclear reaction, after all.)

The progress

After much wavering, it now appears that nuclear-powered interplanetary travel is a $2 billion bet NASA is willing to make. The agency is pursuing an approach called nuclear electric propulsion, which uses the neutrons produced in a self-sustaining, uranium-atom-splitting reaction to create heat and ultimately electricity. The electricity is used to ionize a gas, which is blasted out of the spacecraft with the help of magnetic fields, generating thrust. The approach "is very low thrust, but very efficient," says Sebastian Corbisiero, the US

It now appears that nuclear-powered interplanetary travel is a $2 billion bet NASA is willing to make.



Department of Energy's national technical director of space reactor programs. "So you can use it for a long period of time."

What might such a rocket look like? A presentation by Steve Sinacore, program director of NASA's SR-1 program, offers some clues. So far, the concept art makes the craft look like a colossal fletched arrow. The back will house the power-and-propulsion system, while the tip will hold a uranium-filled nuclear reactor with a capacity of at least 20 kilowatts. (For context, a typical nuclear plant on Earth is about 50,000 times more powerful.) The "fletches" on SR-1 are large fins that help cool the reactor by radiating heat into space.

Like many other pieces of space hardware, the reactor will need to be put through its paces on the ground before it's cleared for the rough rocket trip to space. "Going through the launch safely is going to be a challenge," says Middleburgh. "You are being shaken, rattled, and rolled." For safety reasons, the reactor will be switched on around two days post-launch, when it's comfortably far from Earth. Uranium isn't tremendously dangerous by itself, but that can't be said of the waste products that emerge when the reactor is running. If SR-1 works as planned, its journey to Mars will take about a year.

Will this novel form of space propulsion actually reach the Red Planet by 2029? It's possible. NASA says the Idaho National Laboratory, which is building SR-1's reactor, is making progress and is on target for a late-2028 launch. "Procurement of major components is underway, and integration work on the power and propulsion element is advancing steadily," Sinacore told *MIT Technology Review*. The outlook will get even sunnier if the Artemis program, which aims to start laying the foundations for a base on the lunar south pole by the decade's end, keeps to its own bold deadline.

"It's an aggressive timeline," says Lindsey Holmes, who is vice president of advanced projects at Analytical Mechanics Associates, an aerospace company in Virginia. She suspects the push is being driven partly by China's and Russia's own deep-space nuclear ambitions. The two countries have spoken about plans to place a reactor on the moon's surface in the mid-2030s to power a jointly operated lunar base. Whether it flies or fails in space, SR-1's development should help NASA put its own reactor on the moon; the technology involved in the two projects is broadly similar, given that the lunar surface, like space itself, is a vacuum. If an interplanetary nuclear-powered spacecraft works, a nuclear reactor on the moon should too.

KEEP GOING ON PAGE 44

Progress meter 6

Most of the technology for SR-1 already exists; it's going to come down to piecing it all together and then seeing how it performs in space.



A dual-chamber bag holds a freeze-dried hemoglobin product called ErythroMer and sterilized water. If all goes according to plan, medics will carry these bags in the field and rapidly rehydrate the product for quick transfusions.

DARPA is racing to develop a shelf-stable substitute for what field medics and trauma doctors need most: more blood.

By Andrew Rosenblum
Photographs by Matt Roth

Out for blood

ITS CALL SIGN WAS MORPHINE 1-2.

In February 2007, the hulking dual-rotor casualty evacuation helicopter had just flown three wounded soldiers to a field hospital in Balad, north of Baghdad, when another call came: an emergency mission to fly through an insurgent-controlled area in broad daylight. Typically, helicopters would be in a spot like this only at night, and with all lights turned off.

As it passed near the city of Karmah, in the eastern side of Al-Anbar province, an insurgent fired a portable missile launcher. The tail gunner, who likely saw the shot roaring in, yelled for the pilot to make an evasive move. But the missile had already locked on, and the ensuing blast started a fire on board. After the pilot battled the failing machine for 58 agonizing seconds, Morphine 1-2 plunged to the ground. All seven crew members were killed.

Why was the helo there in daylight? "It was getting blood and bringing it back. It was [on] what we call a 'blood run,' and [it's] the highest of priorities besides casualty evacuation," explains Lieutenant Commander Robert Murray, a Navy officer and program manager at DARPA, the Defense Advanced Research Projects Agency, who studied this incident as an intelligence officer.

Today, a chronic shortage of blood in both the military and civilian worlds is fueling a race to develop synthetic alternatives. About 90% of preventable battlefield deaths are due to hemorrhage—bleeding that happens when a blood vessel ruptures—and it's the leading cause of maternal deaths worldwide. A study published in *Transfusion* in 2025 found that of 1.2 million trauma patients in the United States who potentially needed blood before reaching a hospital, just 1% received it. The shortage results in about 10,000 preventable deaths each year in the US, according to the American College of Surgeons. Globally, that figure is likely in the millions.

One reason for the shortfall is that blood has a storage problem. Whole blood lasts only 35 days when refrigerated, so banks separate out components to stretch the timeline. But that's an imperfect solution. The platelets that help wounds clot are typically stored at room temperature and last for a week or less. Hospitals and the military freeze the red blood cells that carry oxygen, as well as the protein-rich plasma that restores volume and aids coagulation. Once thawed, though, both will spoil within days. "What happens if I don't know when I'm going to be attacked? Well, thaw it and you let it expire, right?" Murray says.

That's why Murray—who, in addition to his military experience, has a PhD in physiology—is leading a DARPA effort to address blood's battlefield problems. He's in charge of a new multimillion-dollar program called RAPIID (for "resuscitation and prevention of ischemia-induced dysfunction"). Its goal is to create shelf-stable versions of the three major transfusion constituents: plasma, platelets, and red blood cells. As it gets underway late this year, RAPIID picks up on decades of work to synthesize blood or help it last longer. Most recently, that includes a prior DARPA project called FSHARP (for "fieldable solutions for hemorrhage with bio-artificial resuscitation products"), in which researchers have demonstrated promising results in animals.

With RAPIID trials for the different components occurring in parallel, the goal is to have bags of dried blood products deployed in the field by 2029. That puts Murray in the position of a conductor coordinating an orchestra of clinical trials with the FDA, while also sourcing the paraphernalia that goes along with transfusions—everything from combat-durable storage bags to tests that could check how much artificial blood a patient already has.

Getting it all done will be tough, but the military is feeling the pressure to address its shortage. Blood drives may not deliver in time after a mass-casualty event, and a *JAMA* study of combat injuries in Afghanistan suggests that if the injured person needs a transfusion, the magic number is 36 minutes. "If something is survivable—and generally we classify most all hemorrhage as survivable—[you're] almost guaranteed to survive if you get the blood before that 36-minute mark," Murray says. After that, the chance of survival "starts to drop precipitously."

A *JAMA* study of combat injuries in Afghanistan suggests a magic number for someone who needs a transfusion: You have 36 minutes to get started.

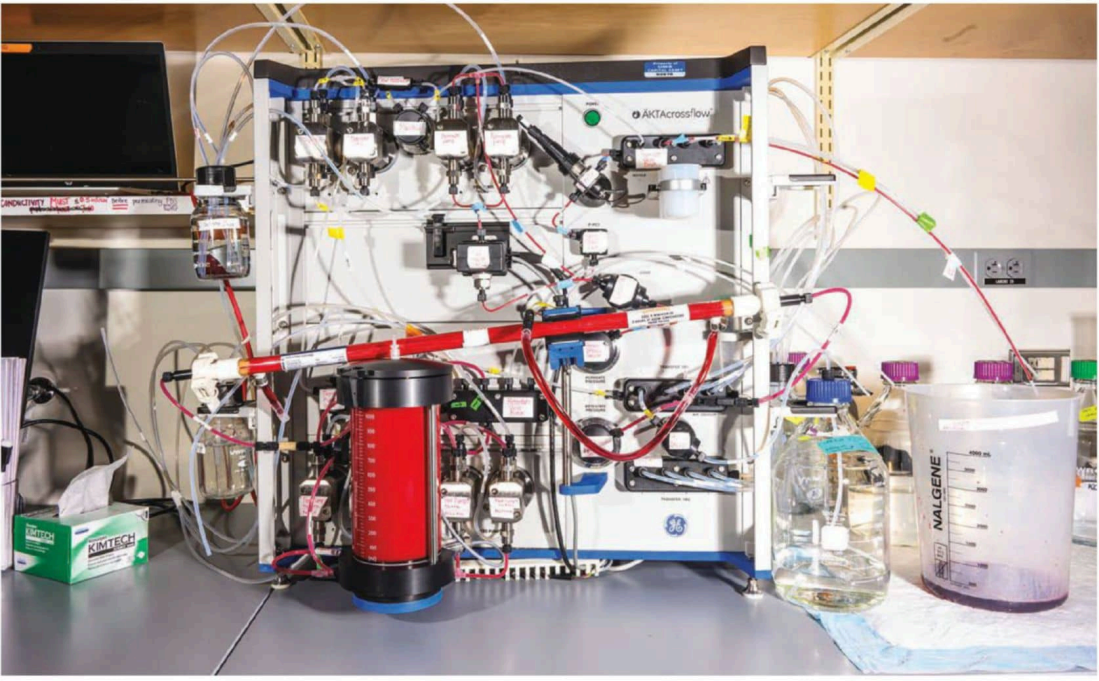
IN THE MISSION TO MAKE PORTABLE, shelf-stable blood components, plasma is the low-hanging fruit. Researchers have known how to isolate and freeze-dry plasma, the yellowish liquid that makes up 55% of whole human blood, since the late 1930s. On the battlefields of World War II, its mix of water, salts, and thousands of types of proteins helped restore blood volume in wounded soldiers—and to some degree controlled bleeding. In the 1960s, the US abandoned freeze-dried plasma because it carried a risk of transmitting hepatitis to recipients from infected donors. But screening, testing, and drying techniques improved, and starting in 2010, the US military launched a yearslong effort to rebuild its capacity for producing these products. Over the past two years, the FDA has allowed two types of freeze-dried plasma to be used in emergencies by the US military—and one can even be used by civilians.

As for platelets, efforts at extending their life date back to the 1950s, but they haven't seen a ton of success. Bioengineers have, for example, attempted to attach the membranes of platelets to synthetic particles. The most successful project comes from a company called Cellphire, which freeze-dries *actual* human platelets. The product has shown safety and efficacy in humans in clinical trials, but its dependence on donors means it's unclear whether this approach can scale.



Red blood cells have been similarly tough to preserve or mimic. Their most critical component is hemoglobin, which carries oxygen and comes encased in a cell membrane. For more than a century, researchers have been looking for ways to deliver hemoglobin without the immunological challenges created by this exterior, including the fact that donors' and recipients' blood types need to be compatible. Evolutionary pressure developed that wrapper for very good reason, though: "Naked" hemoglobin tends to break down quickly in the bloodstream, and that can cause organ damage. It also scavenges nitric oxide, our body's natural mechanism for opening up blood vessels, and causes those channels to constrict.

This problem became all too clear in the 1980s and 1990s, when fears that transfusions could transmit HIV sparked interest in a class of membrane-free delivery mechanisms called hemoglobin-based oxygen carriers (HBOCs). One, named HemAssist, consisted of hemoglobin subunits linked together to avoid the rapid-breakdown problem. It had the added benefit of lasting



KaloCyte techs use a device called a tangential flow filtration machine to process unencapsulated hemoglobin (above). After processing, it is concentrated and then freeze-dried to make it shelf-stable (left).

roughly a year in cold storage (red blood cells last about 40 days)—but it didn't solve the nitric oxide problem, so it constricted blood vessels. In a clinical trial, 24 of the 52 people who received HemAssist died, compared with eight out of 46 in the control group. The parent company terminated trials in 1998. A review of clinical studies published in *JAMA* in 2008 further solidified HBOCs' fate, finding that they generally triple patients' chances of heart attack and increase the risk of death by 30%.

More recently, researchers have tried to grow red blood cells in a lab using a technology called "blood pharming," which involves making them from progenitors known as induced pluripotent stem cells. The stumbling blocks? Cost and yield. DARPA launched a pharming initiative in 2008, using stem cells from discarded umbilical-cord blood, but was unable to get the cost below tens of thousands of dollars per unit of red blood cells. They pulled the plug and offloaded the research to the Uniformed Services University. Even if the cost were lower, though, pharmed blood can't be stored in a backpack. "These are still cells—they still require a refrigerator, they still require special handling," Murray says.

It won't be easy to solve all these challenges at once. "Each one of those projects individually is a massive undertaking," says John Holcomb, a surgery professor at the University of Alabama at Birmingham, who was a combat surgeon in Mogadishu, Somalia, during the battle that inspired *Black Hawk Down*. "I think that they will probably be successful individually. How we use those individual products, or combine those products together, I think remains to be seen."

SEVERAL YEARS AFTER DARPA GAVE up on lab-grown blood, Murray was stationed at a base on Okinawa, an island 400 miles southwest of the Japanese mainland, where he witnessed the vulnerability of the blood supply firsthand. The site houses a blood bank that serves the roughly 27,000 Marines commanded from the island—plus thousands more military personnel on the base and deployed within a 100-million-square-mile stretch of the Pacific called USPACOM, which ranges from western India to Hawaii and from Antarctica to the Arctic. "The blood center is right next to the hospital, which is about 200 meters from all of the satellite communications on that island," Murray told me. A missile strike could take out all three.

Murray wondered: Is there a way to produce synthetic blood that could last longer? As he completed his PhD in physiology in 2018, the military was also awakening to the vulnerability of the Okinawa facility. The 2018 National Defense Strategy, which shifted military focus from terrorism to a potential ground war with China or Russia, showed war planners the risks of relying on a single site for blood runs covering all of USPACOM. DARPA then got serious once again about making fake blood and kicked off the $47.5 million FSHARP program in 2023. Murray came aboard as a deputy program manager in DARPA's Biological Technologies Office in 2024 and was named a program manager in 2026, just a few months before RAPIID publicly launched this past May.

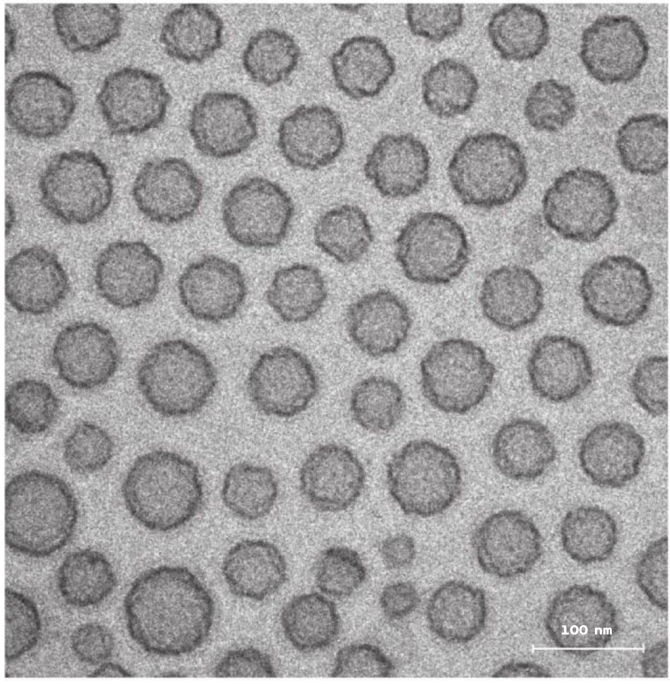
Before he took the helm, related work had been underway for years. Aided by FSHARP funding, researchers at a company called KaloCyte continued testing a technique—originally developed by doctors who are now at the University of Maryland, Penn State, and the University of Pittsburgh—that "upcycles" hemoglobin from expiring donor blood. "We take that hemoglobin and then we package it in a lipid nanoparticle that functions like an artificial cell membrane," explains CEO Elaine Haynes.

The product, called ErythroMer, is essentially a new kind of HBOC. The membrane prevents breakdown, limits dangerous scavenging of nitric oxide, and also helps the hemoglobin take up and release oxygen. Each ErythroMer cell includes a lipid called KC-1003, which acts like a sentry: In response to high pH in the lungs, it signals another small molecule within ErythroMer to move away, allowing oxygen in. Then, in tired tissue, where pH is lower, KC-1003 brings the small molecule back, releasing the oxygen.

Using a well-understood process called lyophilization, similar to one that World War II–era scientists used with plasma, the team freeze-dries its product to store at room temperature, where it can remain stable for two years. In a 2016 study of mice and rats with up to 70% of their blood removed, ErythroMer stabilized blood pressure and oxygen delivery—without the devastating constriction of blood vessels that sank HemAssist. FSHARP furthered that work, helping fund studies on how the HBOC interacted with plasma and platelets.

KaloCyte, though, still has plenty to figure out. Haynes says the company can source only about 1,000 to 2,000 units of expiring hemoglobin a month. So it has licensed a yeast strain that it aims to use to create its own hemoglobin in the lab.

Over a video call from her desk, Haynes showed me a sample of ready-to-use ErythroMer. It was encased in a heavy-duty storage bag with two chambers. One was full of scarlet powder—the hemoglobin product—and the other of sterile water to rapidly rehydrate it in the field. Eventually, she explained, under Murray's master plan, "you'll have another container with the synthetic platelet, and then a third container with the plasma."



SynthoPlate, seen here under a microscope, is a synthetic platelet carrying peptides that help it mimic the work of natural platelets, including sticking to broken blood vessels and to one another.

But achieving that vision depends on finding a synthetic platelet that works.

To do that, DARPA has turned to Anirban Sen Gupta, a bioengineering professor at Case Western Reserve University. "Traditionally platelets were thought of [as] blood cement, but it's not that simple," he explains. "They are, in my opinion, like drones, surveilling the blood vessel wall continuously, looking for signs of injury." Sen Gupta's team, which also includes collaborators at the University of Pittsburgh, used FSHARP funding to continue work on a product called SynthoPlate. Fabricated from a lipid nanoparticle that he likens to the handle of a Swiss Army knife, it has specialized

COURTESY OF SEN GUPTA

peptide attachments—the biological equivalents of a corkscrew or a nail file. The first version has three: One binds to a chemical called von Willebrand factor, which helps platelets stick to the walls of injured blood vessels; another attaches to collagen, which acts as a scaffold for regrowing cells; and the third mimics a blood protein called fibrinogen, which acts like a Lego connector that allows the synthetic platelets to stick to real ones near a wound. Like ErythroMer, the product is freeze-dried and can be reconstituted with sterile water. It keeps for over a year at room temperature and at least three months at a desertlike 122 °F.

In a 2026 paper in *Advanced Science*, the researchers showed that SynthoPlate cut bleeding time and blood loss by more than half in mice with low platelet counts. In a separate study, they also safely injected the faux platelets into rats' bone marrow—a more useful delivery site, given that a bleeding patient might not have an available vein. Sen Gupta and a colleague have spun this work out into a company called Haima Therapeutics.

The good news, as he sees it, is that the pharmaceutical industry excels at mass-producing millions of billions of lipid nanoparticles—witness Operation Warp Speed, in which these blobs of fat held delicate snippets of mRNA in covid shots. "The magic of the artificial platelet is in all those peptides that are decorating the surface of the particle, but the scalability of the platform is very well established," he says.

AROUND THE WORLD, PROSPECTIVE blood alternatives abound. Researchers at Cambridge University in the UK are trying to pharm red blood cells for people with rare blood types or blood disorders like sickle cell anemia, and other researchers have also cultured platelets and red blood cells. Japanese scientists are already testing their own version of encapsulated human hemoglobin in human subjects.

Over the course of the next three years, RAPIID will move DARPA's efforts closer to real life. As of press time, the agency had not yet announced final contracts, but the program's overall goals are set: The first 12 months will focus on getting technologies—including platelet and red-blood-cell replacements, along with a range of related products like freeze-dried plasma—through large FDA-regulated studies. The second and third years will focus on human trials. That will include using the products in situations where the risk of side effects is outweighed by the danger of doing nothing, such as with severely injured people in ambulances.

Much like the handle of a Swiss Army knife, the synthetic platelet has specialized attachments—peptides that serve as the biological equivalents of a corkscrew or a nail file.

The possibility of fatal outcomes does invite second-guessing about DARPA's potential choices. For Shibani Pati, who directs the Center for Research in Transfusion Medicine and Cell Therapies at the University of California, San Francisco, Murray would be making things too "DARPA hard" on himself by backing SynthoPlate and ErythroMer. "They need to make a very concerted effort to take what they've already developed and push it through to approval through the FDA," she says. "Not start with moonshot projects that will take forever to get through." For platelets, Pati thinks the RAPIID program would do better to tap Cellphire, since its products have already received millions from the Pentagon and shown safety and efficacy in humans.

She has similar qualms about ErythroMer. A different HBOC that sources hemoglobin from cattle, called Hemopure, has been approved for use since 2001 in South Africa, she notes. And though it hasn't been approved by the FDA—it was part of the fateful 2008 *JAMA* study—US doctors are cleared to use it for patients who have bad immune responses or religious objections to conventional transfusions.

Holcomb, the surgery professor, worries the effort will run into issues with interactions between the products. He notes that individual blood components have more than one role: Red blood cells also help with clotting, platelets also are anti-inflammatory, and plasma helps tune coagulation. There's no guarantee that the versions RAPIID helps develop will work in the same ways.

Murray says that FSHARP's animal studies tested all the products together, using whole blood as a baseline, precisely because of such possible interactions. The cocktail met its program metrics in all but one area: The clotting was not quite as good, perhaps because negative charges in some molecules repel one another.

"I do not think they will replicate all the functions that whole blood does in our body," Holcomb says. But, he admits, "you may not need to, right? When you get seriously injured and you lose 50% of your intravascular volume, you're dead, right? So if you lose 30% and maybe you're hanging on to life just barely, maybe you show up with all these different products, and you have enough whole blood left in you to do these other functions."

Murray is determined to complete trials so that shelf-stable blood can be delivered in 2029. In addition to the storage bags, he's already sourcing finger sticks for in-field blood testing and a battery-powered device to heat up the blood components.

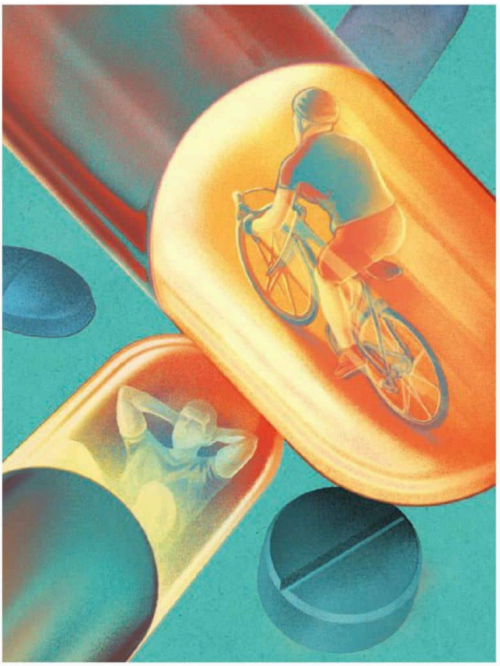
The danger of blood runs—and, by extension, the vulnerability of millions in combat zones, maternity wards, and ambulances—drives his scientific daring. Knowing the stakes, he told his boss in 2024 that even if FSHARP failed, "we should invest 50 million more dollars in it and do it again." ■

Andrew Rosenblum is a technology journalist and the author of the techno-thriller Stretch Goals.

EXERCISE IN A PILL

BY Cassandra Willyard

We all know exercise is good for us. It builds muscle, strengthens bones, lowers blood pressure, and boosts mood. By deciphering how movement benefits the body, researchers hope to develop medicines that can offer some of the same perks—without the workout. The idea isn't to replace exercise but to bring its upsides to people who struggle with frailty, disability, or chronic illness.



The sticking points

It will take a lot of experimentation to untangle the myriad pathways by which exercise promotes health. But IDing the cascade of hormones, enzymes, and other molecules related to physical activity is just the first step. Scientists need to figure out how to turn that knowledge into safe and effective drugs. That's a tall order: More than 90% of treatments that enter human studies fail.

There are regulatory hurdles too. The FDA approves medications to treat diseases, not to enhance wellness, says Thomas Burris, a pharmacologist at the University of Florida whose work focuses on diseases that respond to exercise, like obesity, type 2 diabetes, and dementia.

The progress

There may never be a pill that delivers all the benefits of exercise, but research could lead to new medicines that mimic some aspects of working out. Scientists have already identified many important exercise-related signals and have even developed compounds to regulate them. (Some preliminary results have been so promising that doping authorities have proactively banned the compounds.)

Burris and his colleagues are focused on a receptor that's always switched on, even without exercise. Working out appears to boost that receptor in muscle cells, which in turn helps bolster endurance over time. Burris's lab has spent years designing a drug that cranks up the receptor's activity directly, and mice treated with the drug ran longer and farther than mice that weren't. They "become marathon mice without having to do any type of exercise," Burris says. There are even indications—also in mice—that the compound mimics some of the cognitive benefits of exercise and could help treat heart failure. Burris founded a company called Pelagos to carry the work forward into a clinical trial.

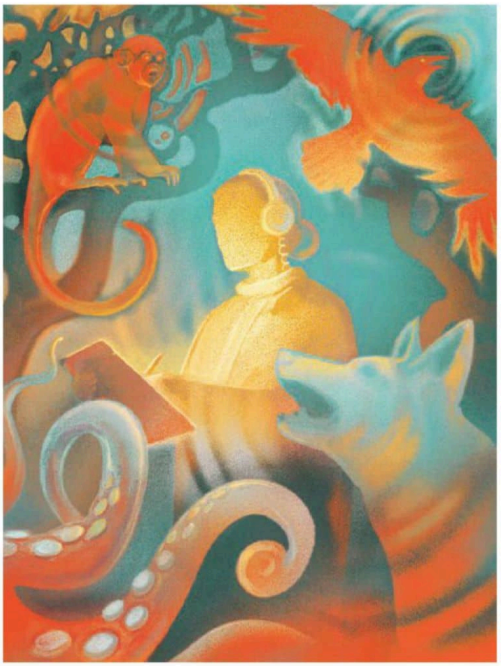
Other workout-mimicking drugs have already entered human studies. In June, the biotech firm Cambrian Bio reported that its experimental drug ATX-304 boosted metabolism and reduced liver and belly fat in people with obesity and prediabetes. It activates a metabolic switch that helps cells sense when energy supplies dip and coordinates the production of more fuel—the same switch that helps us sustain long sessions jumping rope or swimming laps. Cambrian hopes it will help people lose weight without losing muscle, a common concern with GLP-1 medicines.

Progress meter 5



Our understanding of how exercise benefits the body is still coming into focus, and drug development is prone to failure.

EOIN RYAN



INTERSPECIES COMMUNICATION

BY Cassandra Willyard

Humans are far from the only species with a gift for gab, and our furry, feathered, and finned friends could have a lot to tell us. Decoding how animals communicate with one another could offer a window into the inner lives of other species and help humans realize that "animals are sentient creatures who think, who have hopes and dreams of their own," says Con Slobodchikoff, the founder of Zoolingua, a company working on dog-to-human speech.

The sticking points

Teasing all this out is complex. To decipher howls, squeaks, and clicks, researchers must match the creatures making sounds with what's happening around them. Prairie dogs, for example, utter a different series of yips when a coyote approaches than when a hawk is nearby. It's painstaking work, especially for difficult-to-observe species, like deep-diving whales or subterranean mole rats.

There are other hurdles. Many animals communicate not just through sound but through visual cues, touch, pheromones, or a combination of signals, some of which might be difficult for us to perceive. And without a multispecies Rosetta stone, it's hard to know if translations are accurate.

The progress

Over the past 50 years, a growing arsenal of devices has made it easier to observe the sophisticated ways animals communicate. Hydrophones at the bottom of the ocean can capture humpback whale song, and tiny wearable "biologgers" can record a bat's every squeak.

In the last decade, advances in AI have leveled up our ability to make sense of it all. The technology can detect different calls, distinguish which sounds belong to which animal, and spot patterns. Researchers at the Earth Species Project (ESP), a nonprofit founded in 2018 to decode animal communication, recently used machine learning to detect vocalizations of carrion crows and determine which bird made which call.

They suspect that more advanced AI could translate critters' chatter. Large language models like Claude and ChatGPT excel at finding relationships between words, explains Sara Keen, one of ESP's behavioral ecologists. ESP hopes its own NatureLM—trained on human speech, music, and animal sounds—will be able to interpret the vocalizations of a variety of species.

That promise, however, is still theoretical. Yossi Yovel, a neuroecologist at Tel Aviv University, worries that these models will put too much emphasis on acoustic similarities and make mistakes—like lumping together similar sounds that have different meanings.

As for a two-way convo? It's not clear when—or whether—that will happen. Still, "a lot of animals have an evolutionary structure that is similar enough that we should be able to understand what they're saying," Slobodchikoff says.

KEEP GOING ON PAGE 52

Progress meter 4

Researchers have amassed heaps of data on animal communication, but they're still trying to figure out how to decipher it all.

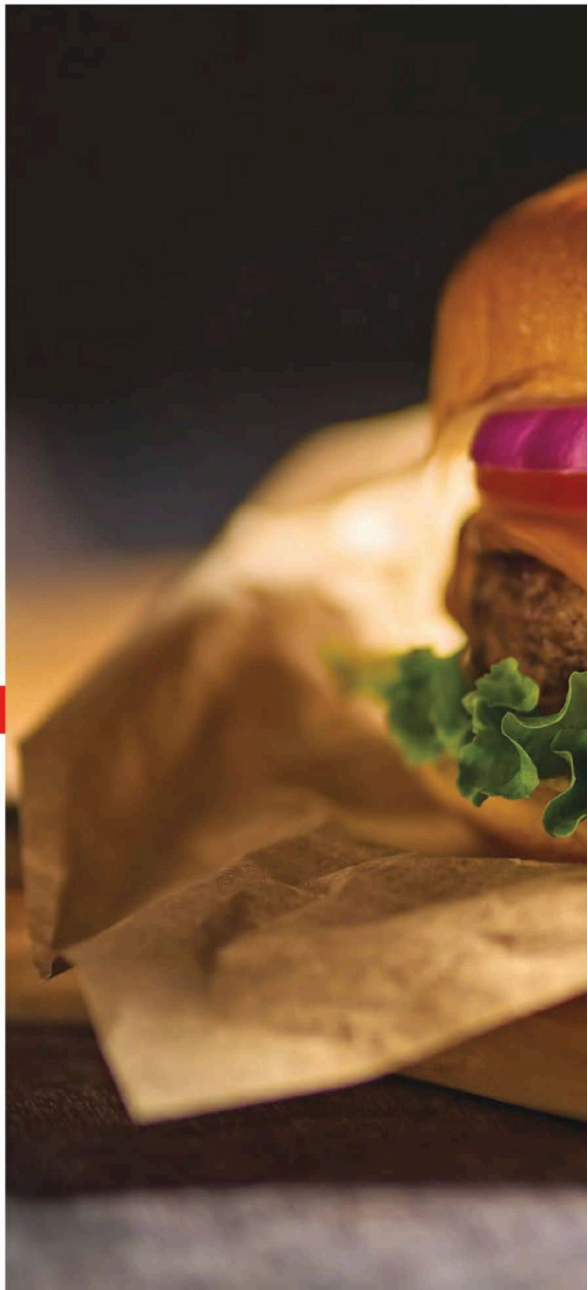
EOIN RYAN

MODELERS SAY DITCHING BEEF IS VITAL TO HITTING THE WORLD'S CLIMATE GOALS.

CAN "BLENDED MEAT" FINALLY GET AMERICANS TO CUT BACK?

MEAT LIGHT

BY MEGHAN McCARRON



Burgers featuring a blend of beef and plant-based products like mushrooms are popping up on menus across the US.



In the fall of 2025, Jeff Dodge set up a six-foot folding table in the cafeteria of Cane Bay High School in Summerville, South Carolina, to conduct a taste test. When the first rush of about 150 hungry students hit, he was waiting with slow cookers filled with steaming marinara sauce and meatballs.

Kids love a taste test, but they're also discerning, and Dodge wasn't sure what they would make of his product, a blend featuring both meat and mushrooms. As students swarmed the table and tapped out their opinions on an iPad or scanned a QR code to use their phones, Dodge asked those who lingered to guess what kind of vegetable might have been mixed into the meat. Few of them could—the meatballs had tasted like moist, flavorful beef.

The school enrolls a few thousand students, and Dodge estimates that the majority of them came by. In the end, the survey showed that 92% of those who tried the meatballs wanted them on the menu; they easily cleared the bar to be added for the 2026–2027 school year. Comments described their flavor as "bussin'."

Through his consulting company, K–12 Food Solutions, Dodge was testing a new product called 50/Cut from the company Joyn. The proprietary blend of seemingly simple ingredients—available as meatballs, burgers, and ground meat—could help solve one of the most intractable challenges of the climate crisis, at least on the individual level: getting people to eat less meat, particularly beef.

Livestock production accounts for somewhere between 10% and 20% of all greenhouse-gas emissions related to human activity, and nearly two-thirds of that comes from ruminants like cows raised for meat and dairy products. Beef herds create four times the emissions of dairy herds per kilo of food produced. And for US households, food makes up as much as 30% of emissions.

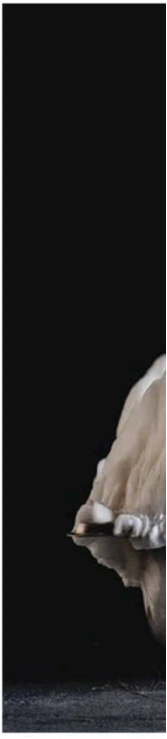
Unlike other polluting sectors, such as electricity and transportation, cattle farming has little potential for a big fix. Ruminants produce about 30% of the methane associated with human activity, and this gas has 28 times more global-warming potential than carbon dioxide. What's more, it would be virtually impossible to raise them in a perfectly climate-neutral manner. "We don't have a technical solution to change the stomach of a ruminant," says Fredrik Hedenus, a professor in sustainability and systems analysis at Chalmers University of Technology in Sweden. Technologies to dampen the impact of their burps have been in the works for a while but have yet to scale. They also fix only part of the problem with red meat: Cows need a lot of land for pasture and for feed, which has made livestock a top driver of deforestation in the Amazon and elsewhere around the world.

Even if the world stopped burning all fossil fuels tomorrow, emissions from agriculture would push the planet past 2 °C over preindustrial temperatures by 2070, Hedenus says. According to his research, more efficient livestock farming methods would *still* leave agriculture eating up over half of humanity's carbon budget by that time. Only with the addition of dietary changes does his model show a winning scenario.

He's far from alone in his conclusions: A 2024 survey of more than 200 climate scientists, conducted at Harvard, found that the vast majority believe reducing emissions from livestock is important to meeting climate goals. People have to eat less beef. "Essentially, you need a culture shift," Hedenus says.

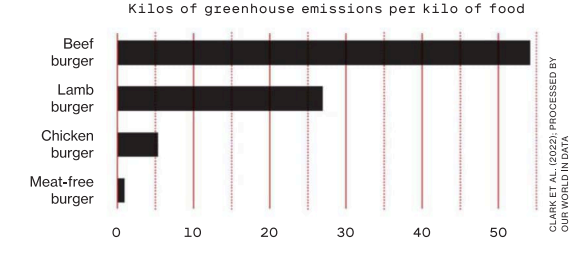
Yet the culture has proved intractable. Not only do people like the taste of meat, but across most of the world, meat-eating tends to be associated with status. As societies have grown wealthier, it has increased. A United Nations report showed that global meat production quadrupled between 1961 and 2022, while vegetarianism has held steady at about 4% of the population in the US since 1999.

What *could* move the needle is a carbon-light and delicious meat replacement. But from a food-tech standpoint, all we have to show is a menu of mostly failed solutions. Lab-grown meat has generated endless headlines since the 2000s but has



THE FOOTPRINT OF A BURGER

Of all the mainstays in the standard American diet, beef has the biggest environmental impact—by a lot. In fact, according to one 2020 analysis in *The Lancet*, just trading beef for plants can cut the emissions associated with a person's diet by 40%.



ANIMAL AGRICULTURE COULD NOW SEEM FARCICAL. IN 2025, AMERICANS DOWNED $45 BILLION WORTH OF BEEF.



Joyn's 50/Cut meat blends beef with roasted mushrooms and cultivated mycelium—the root-like threads extending from fungi (seen above).

ABOVE AND PREVIOUS SPREAD: COURTESY OF JOYN

yet to become commercially available (and affordable) at scale. And while breakthroughs in taste and texture inched plant-based meats from companies like Impossible Foods and Beyond Meat toward mass adoption, the hype—and the appetite—has somewhat fizzled.

So instead of asking people to change their preferences, startups like Joyn are trying a different tack. They're creating what are broadly referred to as blended meat products, which combine plant proteins with the real deal. The logic: The best meat replacement is … better meat.

Paul Shapiro, cofounder of the startup BMC Ingredients, which markets a plant protein related to mushrooms, says the math is easy to understand: If we imagine that Impossible Whoppers at Burger King account for about 2% of sales, that's only a 2% reduction in meat. But if a conventional Whopper were 20% plants, that would be a 20% cut right off the bat.

Those aren't quite the numbers climate models are calling for, but some estimates say they could lead to outsized gains relative to the status quo: A 2022 study in *Nature* found that replacing 20% of beef globally could halve the annual rate of deforestation. And unlike the other solutions tried thus far, this particular Hail Mary is one a lot of omnivores seem open to giving a try.

The idea of blending meat and vegetables together is, of course, nothing new. Food cultures from around the world boast an array of dishes that combine small amounts of meat with plants. Today, home cooks still add veggies and legumes to dishes to stretch tight grocery budgets or to sneak extra greenery into their children's supper.

But in the mid to late 2010s, however, the focus was largely on companies that appeared to have cracked the code for ditching meat entirely. When Impossible debuted its namesake burger in 2016, it impressed with an ingredient called heme, an iron-rich molecule in the protein soy leghemoglobin that allowed all-plant burgers to "bleed" like beef.

Impossible and its biggest competitor, Beyond, swaggered through the media and the markets. In 2019, Impossible's founder told the *New Yorker* he intended to wipe out all animal agriculture by 2035. Beyond's 2019 IPO was the most successful since the 2008 financial crisis. A flood of imitators followed.

But within a few years, tastes shifted. In 2023, Impossible employees' stock values tumbled 89% from a 2021 high. That same year, Beyond laid off 20% of its staff, and a bruising *Businessweek* feature labeled the entire sector a fad. Sales have been slipping for years, with a 10% year-over-year drop in 2025, according to the Good Food Institute, a think tank focused on alternative proteins.

Several factors were likely at play. Megan Krogius, a spokesperson for Impossible Foods, says the dip is a "correction not a crisis" after "an outsized pop in demand" between 2020 and 2022. She also says that a flurry of plant-based products muddied the category's reputation. Indeed, some disruptors (and their imitators) have struggled to compete on the sensory level. Nectar, an organization that conducts research on meat

alternatives, has found that taste and texture are among the major factors that keep people from adopting plant-based meats. "Our consumers identify products as having bad aftertaste and off flavors five to six times more than in animal counterparts," says Caroline Cotto, the group's director.

At the same time, discourse around processed foods tarnished plant-based meat's halo. In 2019, the Center for Consumer Freedom, a since-dissolved lobbying group backed by the meat industry, launched an ad campaign against plant-based alternatives, demonizing them as "ultra-processed imitations."

While Impossible's Krogius warns against conflating processed food with junk food (she points, for example, to a study in *The Lancet* finding mock meat to be nutritionally preferable to red meat), some of the bad press stuck. Now, the term "ultra-processed" has become something of a political cudgel—one wielded by the meat-loving MAHA movement and the US secretary of health and human services, Robert F. Kennedy Jr. In 2025, he flipped the food pyramid and stacked a steak on top.

Any quest to wipe out animal agriculture could now seem farcical. In 2025, Americans downed $45 billion worth of beef, and consumption rose by 4.3% over the previous year, according to an industry report. Rising prices could be slowing this down a bit, but cost can dampen only so much demand.



The Both Burger, made from beef and a mix of veggies, is available at a handful of restaurants and specialty retailers. It's even been on the menu at Disneyland as the Meteorite Medley Burger.

Blended meat, which has meat's own juiciness and texture, rose alongside the plant-based superstars, but it did not get *New Yorker* profiles or headlining IPOs. At the height of mock-meat hype, companies like Tyson and Perdue launched blended products, and firms working on lab-grown meat explored cutting their products with plants.

The big advantage of blended meat is that large numbers of consumers—what some call "flexitarians"—are curious about it, and when they try it, they like it. A blind taste test co-funded by the USDA in 2022 showed that diners preferred blended burgers to fully plant-based ones. And a report from the major food processor ADM found that large proportions of every generation of Americans were interested in trying blended meats, including 75% of millennials. "This is a solution that we can do today, that consumers will accept today," says Tim Dale, a director at Food Systems Innovations, the nonprofit group that oversees Nectar.

At this point, even Impossible has acknowledged the potential. In a wide-ranging interview with the *Wall Street Journal* in 2025, the company's former CEO Peter McGuinness admitted the brand's struggle to win over consumers, and suggested a hybrid burger could bridge the divide.

Plenty of newcomers are entering the fray. "Shiitake-infused beef burgers" from Australia-based Fable Foods are in restaurants and moving "incredibly well" at the high-end grocery store Central Market in Austin, Texas, says CEO Michael Fox. The Both Burger from Los Angeles–based 50/50 Foods is available in a smattering of California stores and eateries. And Spare Food in New

COURTESY OF 50/50 FOODS

BELIEVE THAT AS LONG AS WE CREATE MEAT THAT IS NOT FROM AN ANIMAL BUT TASTES LIKE MEAT, PEOPLE WILL EAT IT."



York signed a deal with Premier, one of the nation's biggest spenders in the health-care sector, for its blend of surplus produce and ground beef.

One major insight for all these upstarts is that consumers react best when marketing focuses on pleasure, not environmental virtues or health benefits. Though many companies actually create a burger or meatball with a better nutritional profile (fiber!) and fewer of meat's downsides, like saturated fat, that doesn't get people to buy it. They like that it tastes good. Beef and mushrooms, for example, contain complementary flavor compounds, including the glutamates that yield deep umami, which is why they're so often paired in dishes like beef Wellington and stroganoff.

Food-production companies are a big target. BMC Ingredients, which collaborated with Perdue on a line of blended nuggets, markets a plant-based protein that can be mixed with meat to up its nutrition and flavor. BMC grows mycelium—the root-like structures of fungi. It underpins popular meat alternatives like Quorn and also features alongside mushrooms in Joyn's 50/Cut. Shapiro likens his factory to a brewery, but instead of yeast fermenting barley, a fungus called *Neurospora crassa* digests starch to produce a protein with a dense network of fibers that makes for a meat-like chew. "We grow four hours before we get a harvest," Shapiro says. "It's among the most efficient ways to produce protein on Earth."

Joyn also sees its path forward outside the grocery store. Food eaten away from home accounts for more than half of what US consumers spend on grub, according to the USDA. Padraic Doherty, who joined Joyn from the meat distributor D'Artagnan and holds the title of chief growth officer, says its main areas of focus are K–12 and college cafeterias and other major food service providers, like stadiums. These organizations, he says, often have sustainability goals and also are pressured to find both nutritious and affordable options. The 50/Cut Joyn sells to cafeterias is between 5% and 15% cheaper than beef.

But can cafeteria mushroom burgers prompt a larger cultural shift?

The folks touting the idea of going halfway see it as a bridge. BMC's Shapiro thinks the movement toward meat-light eating reflects the reality of how these changes happen. Nectar's Cotto compares blended meat to a hybrid car. "Moving people toward blended products [is] a way to drive demand for some of the fully plant-based ingredients that don't scale right now to bring the price down," she says. "So it's both a short- and a long-term approach."

Not everyone is so sure market forces will be enough, though. Nil Zacharias, a longtime entrepreneur in food sustainability who offers plant-based options to New York City delis through his company Plantega, isn't sold on the notion. "Too many people in the space believe that as long as we create meat that is not from an animal but tastes like meat and costs the same, people will eat it," he says. "I think the plant-based backlash to ultraprocessed foods shows you that's not necessarily how things are going to go." He believes blended meat's main impact will be on institutional dining, in places like schools and health-care facilities.

Meat hybrids could, however, taste just familiar enough to open consumers' minds to alternatives. Some research has found that thinking about mock meats prompts people to reconsider the whole system. In the 2010s, Clemens Driessen, a cultural geographer who teaches at Wageningen University & Research in the Netherlands, worked on a project that asked people in pubs, supermarkets, and other public spaces what they thought of lab-grown meat. "There's a first response, which is 'Oh, that sounds horrible,'" Driessen says. Then people tended to reflect that the meat they consume is also heavily industrialized. "A whole train of thought emerges out of proposing something very new," he says.

If the category succeeds, climate advocates will need to make peace with imperfection. A life-cycle analysis Joyn commissioned on the 50/Cut burger confirms that the product has half the greenhouse-gas footprint of a beef patty, which—if you go by company claims—means it has about five times the impact of a burger from Impossible or Beyond. Hedenus, the climate scientist, says that even if blended products don't reduce impact as much as plant-based ones, he's all for trying any solution that works. "It is very difficult to change how we eat, so I think most good suggestions should be explored," he says.

Meanwhile, the products are finding their way to more plates. They're in cafeterias, high-end grocery stores, and small burger chains. They're in the catalogues of major distributors like Sysco. The Both Burger has even been at Disneyland.

The 50/Cut meatball is on the menu this school year in seven states. At Cane Bay High it'll take the form of a sub. The school is buying 200 cases at a time, with 150 meatballs in a case. Jason Ciaccia, the systems specialist for child nutrition in the school district, says he won't be using the word "mushroom" to describe it. "If they hear 'mushroom,' they're going to skip over it," he says.

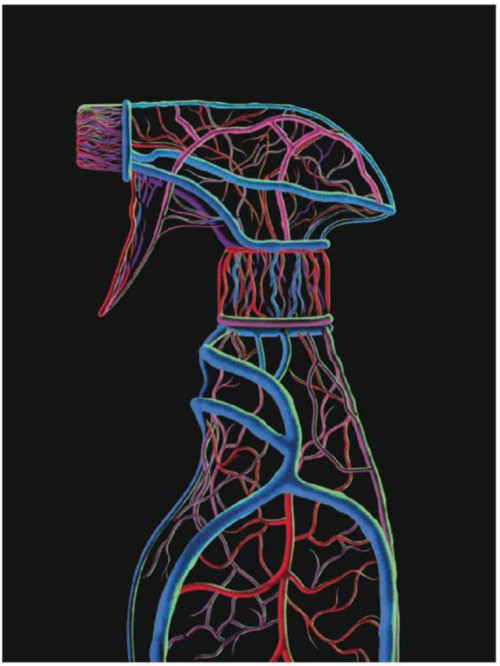
He is, however, considering his branding. He's asked AI to help him come up with something fun. He thinks "Marvelous Meatball Sub" has a nice ring. ■

Meghan McCarron is a food and culture journalist based in Los Angeles.

CLEANING UP PFAS

BY **Sara Kiley Watson**

Scrubbing Earth of per- and polyfluoroalkyl substances—a.k.a. PFAS or forever chemicals—could eliminate a list of woes for people and planet. Used for decades in everything from nonstick pans to firefighting foams, PFAS have been linked to increased risks of fertility challenges, developmental delays, cancer, and reduced immune response. They are known for a strong bond between carbon and fluorine, which the environment struggles to break down.



SAM GREEN

The sticking points

PFAS are everywhere: They spew from factories and slough off products and into water with normal use. Scientists have found them in everything from human blood to Antarctic snow. One 2022 report found that 89% of the US population had PFAS in excess of two nanograms per milliliter of blood plasma, a common threshold for potential adverse health effects, and 9% of the population had passed the riskier level of 20 nanograms per milliliter.

The PFAS monster is also a moving target. New compounds are still being created and used. There are more than 12,000 of them, and much of the cleanup research focuses on only a small handful.

The progress

Cleansing PFAS-contaminated soil is a project in its infancy, but it is possible to prevent more buildup by pulling the chemicals out of water systems. There are two ways to handle this: trap or destroy. Some scientists have found reverse osmosis—a process that pushes water through supertight filters—useful in point-of-use cases, like water filters at kitchen sinks.

Other techniques in the pipeline might be more suitable for large-scale removal—for example, at water treatment facilities. One, called foam fractionation, generates bubbles that capture PFAS. More approaches, like ensnaring the chemicals in nanothin layers of charged metal, are also under investigation.

Trapping, though, is imperfect. You're left with PFAS-filled brine, which if not properly destroyed (an expensive and energy-sucking endeavor) can still end up in the environment.

Jack Huang, a professor of crop and soil sciences at the University of Georgia, is working on destruction. He's testing a method called electrochemical degradation, which uses electrodes to break down the bonds that hold PFAS together. The product destroyed more than 90% of PFAS mass in tests and has already been licensed by the engineering consulting firm AECOM.

Ridding life of PFAS is also a policy challenge. There are alternatives; we just need the push to use them. And we've had success before: The EPA's 2010/2015 PFOA Stewardship Program has helped slash the release of water-repellent perfluorooctanoic acid by 95%. More recently, Minnesota, Maine, and New Mexico have passed bans on PFAS in products like cookware and dental floss.

KEEP GOING ON PAGE 60

Progress meter 6



Scientists are making strides toward removing and destroying PFAS—but it'll be all for naught if we don't turn off the tap.



Over your dead body

Six wild ideas for perpetuating your mind. By ANTONIO REGALADO

Have you ever thought about what makes you *you*? Science assures us it has everything to do with the three-pound organ between our ears, with its billions of neurons and trillions of delicate connections. But it's a lot trickier to explain why we have a sense of self-awareness or to pin down precisely where that first memory of Mommy actually resides. As we age, we forget most of what we've experienced, yet there's still undeniable continuity: At 30, or 50, or 70, you will still be you.

To preserve that elusive continuity of self, some far-thinking technologists are working on ways to keep your brain going—even beyond death. Let's call them the "mind savers." They're exploring everything from freezing brains in liquid nitrogen to augmenting living ones to uploading our memories to the cloud. Here, we look at six possible paths for keeping your mind going, how feasible they'd be, and what benefits the present-day research might bring—even if cognitive immortality doesn't pan out.

Illustrations by Eddie Guy

Head transplant

GOAL

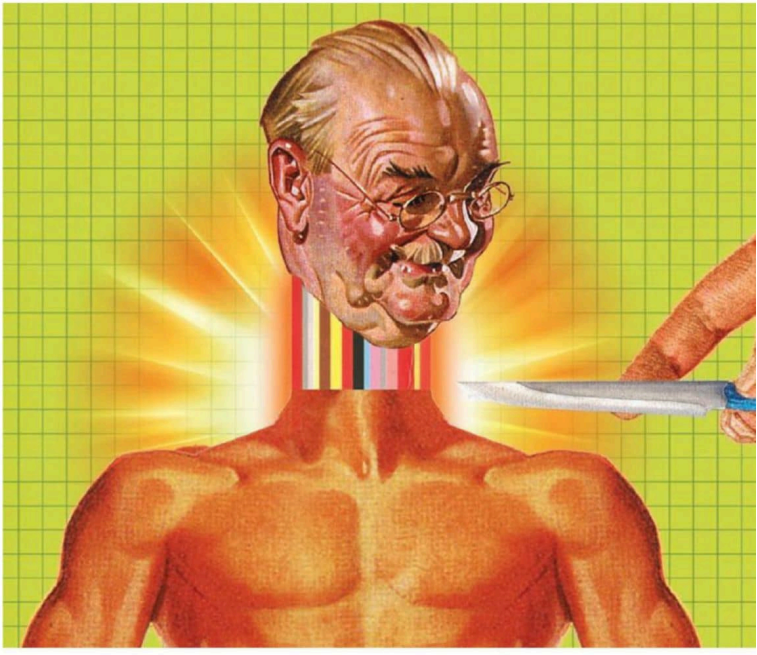
An entirely new body

KEY TECH REQUIRED

Spinal-cord fusion

STATUS

Mired in technical and ethical issues



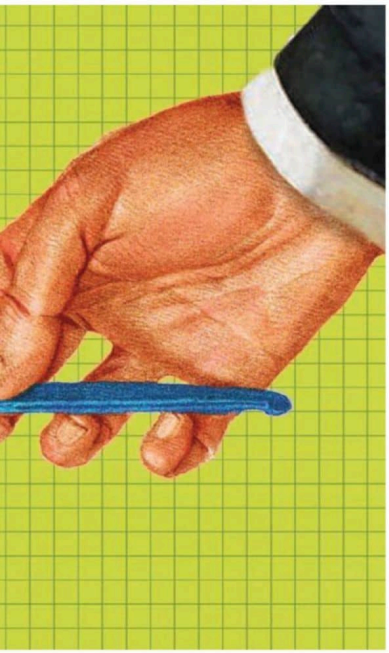
In 1970, the neurosurgeon Robert White removed the head of a rhesus monkey and transplanted it onto the body of another. The patched-together primate lived several hours before succumbing to its injuries. White, a professor at Case Western Reserve University, tried the surgery several times. Remarkably, the reattached heads could move their eyes and mouths, but because he'd severed the monkeys' spinal cords, those heads never gained control of their new bodies.

White's experiments have been a source of grim fascination ever since. But to a few neuroscientists they're inspiration, suggesting that one day a human head transplant—or, as some call it, a body transplant—could succeed.

The idea's main proponent is Sergio Canavero, a controversial Italian surgeon who, 10 years ago, even claimed he'd found a volunteer in Valery Spiridinov, a computer programmer suffering from a degenerative muscle disease. Spiridinov initially agreed to have his head transferred to the body of a brain-dead donor in China, but he later bowed out of the plan and instead got married. And that might be just as well. Critics say the procedure would be more like murder than medicine. Or, best-case scenario: Volunteers would be left paralyzed and in need of a ventilator for life.

Canavero says that's not necessarily true. He claims people's views on the operation will change once they accept that reconnecting severed spinal cords is already possible. He pointed *MIT Technology Review* to a research article from this past summer that he coauthored with surgeons at Moscow's Sklifosovsky Research and Clinical Institute for Emergency Medicine. The team cut through the spinal cords of

Does that mean a head could be attached to a new body and then control it? Mainstream researchers aren't convinced.



three pigs at a point midway along their backs and then tested whether the severed nerve bodies could be fused back together using a surgical sealant. According to that paper, which appeared in the journal *PLOS One*, all the pigs regained the ability to stand and even walk unsteadily.

Does that mean a head could be attached to a new body and then actually control it? Mainstream researchers aren't convinced. Grégoire Courtine, a spinal rehabilitation specialist at the École Polytechnique Fédérale de Lausanne in Switzerland, says he's been following Canavero's claims "with little respect" and thinks that we should "pay zero attention."

"There is no technology … capable of such a crazy idea," Courtine wrote in an email.

Mindclones



GOAL	KEY TECH REQUIRED	STATUS
Conscious software avatars	Artificial intelligence	Available in unconscious formats

In her 2014 book *Virtually Human: The Promise—and the Peril—of Digital Immortality*, the futurist and biotech executive Martine Rothblatt put forward an argument for what she called "mindclones." People would upload their diaries, recordings, social media histories, and other personal data into a digital filing cabinet. Then, via software she termed "mindware," they would create realistic digital avatars of themselves. In Rothblatt's view, as technology advanced, mindclones would inevitably be considered conscious and even "afforded human rights" after passing psychological screening.

Just 12 years after the book came out, artificial-intelligence technology has already brought some of her predictions to "life," so to speak. Services such as StoryFile, Afterlife AI, and Synthesia allow users to upload their personal information and likeness in order to produce either conversational bots that share their memories or video talking heads that sound (and look) exactly like them. Influencers now let their "AI clones" do their work on TikTok, and some people are even building avatars of their aging parents in order to preserve their personalities.

While this mimicry can produce comical results, unhealthy attachments, or uncanny vibes, the increasing realism of generative AI invites people to emotionally accept the avatars as real beings. That was the case when Rothblatt appeared as a digital avatar during a 2025 event held by the UCLA Department of Communication called "The Bridge to Humanizing AI."

Her copy, named Marvatar, was projected on a screen, led the discussions, and talked with the meatspace Rothblatt as an equal, at one point saying, "The dance isn't about who leads, but how we move together." According to the university, attendees were "visibly moved" and wept "with wonder" at Rothblatt's vision of digital equality.

What's still missing from Rothblatt's mindclone prediction is evidence that these avatars have—or ever will have—any kind of true self-awareness. (We asked ChatGPT if it's conscious, and it answered, "Probably not.") But all that remains a gray zone. Neuroscientists don't have a clear definition of consciousness, much less a diagnostic test they could apply to an avatar.

Instead, what if the final determination is in the eye of the beholder? Your digital clone might not *be* you. But at some point it might be good enough for me.



Brain in a jar

GOAL	KEY TECH REQUIRED	STATUS
Disembodied brains	Life-support perfusion	Jars, yes — alive, not so much

In the 1983 comedy *The Man with Two Brains*, Steve Martin plays a scientist who falls in love with a brain that he keeps alive in a jar filled with a fictional life-sustaining fluid and that talks to him via telepathy.

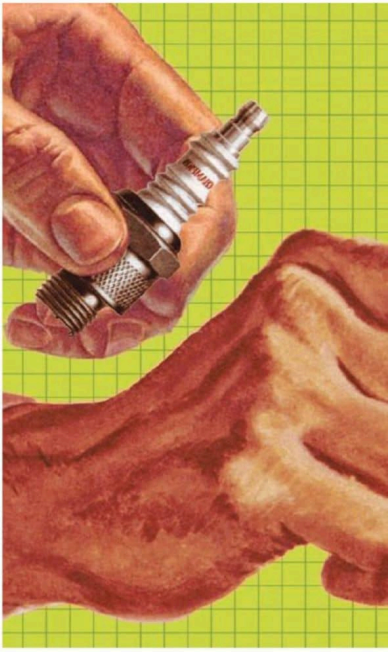
So, campy sci-fi film lovers that we are, it got our attention last year when a company called Bexorg started showing journalists *actual* human brains in vats, which it has been acquiring from organ donors soon after death and then "rebooting" by infusing them with oxygen-rich artificial blood.

The company claims these "physiologically intact human brains" will be more useful than animals for drug testing and safer than trying experiments on living volunteers. Add an Alzheimer's compound to one of these disembodied brains and researchers can then measure exactly what the drug does inside the organ.

Bexorg's CEO, Zvonimir Vrselja, is "sure" that some people would like to restore consciousness to out-of-body brains, but he's tried to douse such speculation. While they are metabolically active, the company says, the brains have lost all coordinated electrical activity. That means they aren't conscious—although, just to make sure, the neuroscientists running the experiments add the strong anesthetic propofol to the tissues.

What's more, right now a brain can be kept "alive" outside the body for only about 24 hours. That wouldn't be much of a second life. Still, efforts are underway to improve the life-support systems. Bexorg says it hopes to eventually keep its brains going for two weeks.

It got our attention last year when a company called Bexorg started showing journalists *actual* human brains in vats.



Gradual brain replacement

GOAL

Extreme life extension

KEY TECH REQUIRED

Lab-grown cortical tissue

STATUS

Now funded by your tax dollars



Skeptics say it's unknown whether replacement brain chunks will ever properly function as part of your brain—say, by taking over memories.

How would you like to replace your brain, little by little? The process would go slowly enough to avoid your notice, but quickly enough to undo the inevitable damage that aging brings. In 2026, this wild idea got a massive endorsement from the US government when ARPA-H, a health agency that backs high-risk projects, committed up to $175 million to a program it calls FRONT, for "functional repair of neocortical tissue."

On paper, the goal is to manufacture tissue to graft into the brains of stroke victims, reversing damage and restoring function. Less officially, the project's existence is a surprise coup for an extreme plan to defeat aging advanced by Jean Hébert, the neuroscientist leading the program, who argued in his 2020 book, *Replacing Aging*, that we can live longer by replacing our aging brain cells with young ones.

We don't want to lose our identities. That's why—according to Hébert—it would have to happen gradually, in small chunks, so our brains would have time to adapt to the new tissue.

Scientists who applied for the program say Hébert insisted on a very specific technological approach. While most researchers engineer individual cell types, ARPA-H asked for complex chunks of young, functional cortex—more or less like what you'd find in a developing fetus. "He wanted to create essentially an embryonic form of cortex that he thought you could somehow graft into an adult brain," says Marius Wernig, a Stanford University stem-cell researcher who applied.

Skeptics say it's unknown whether replacement brain chunks will ever properly function as part of your brain—say, by taking over memories. What's more, it's still unclear how to manufacture youthful cortex, or what ARPA-H calls "neocortical precursor tissue," in the lab. One idea is to employ the latest advances in brain organoids. Imagine, if you will, a human cortex grown in a lab dish without a body.

We know that the agency has an aggressive timeline: Over the course of five years, it wants researchers to lay the foundation for the first human tests of replacement cortex. The aim, it says, is to "take the 'permanent' out of brain damage." And maybe out of old age, too.

Brain upload



GOAL	KEY TECH REQUIRED	STATUS
Whole-brain emulation	Connectome maps	Give it another century

"You are your connectome." That's the famous hypothesis of the Princeton neuroscientist Sebastian Seung. It states that memory and identity reside in the brain's impossibly complex network of hundreds of trillions of synapses—delicate junctions between neurons.

Scientists are already mapping this wiring in simpler animals. Two years ago, Seung took part in analyzing a fly brain that had been cut into paper-thin sheets and imaged with an electron microscope. Then he and his colleagues used image-analysis software to trace 139,255 neurons and about 55 million synapses. The fly map could lead to energy-efficient software that computes the way real brains do, Seung says.

Others believe the ultimate outcome of "connectomics" research will be what's called "whole-brain emulation," or sometimes just "uploading." It's the idea, popular in some quarters of Silicon Valley, that a simulation created from a sliced-up brain could become so detailed that it would reproduce not only a generic intelligence but a particular one, like yours—complete with memories and opinions, and able to live again in a data server somewhere.

Setting aside the question of whether a simulation would really be you, everyone agrees that this technology isn't coming in time for those of us alive today. A survey of 312 neuroscientists, published in 2025 in *PLOS One*, estimated that human whole-brain emulation wouldn't happen before 2125.

That long and unpredictable tech horizon helps explain why two US companies, Nectome and Sparks Brain Preservation, are offering to preserve human brains (or bodies) today by infusing them with the same potent chemicals used to "fix" the brains of fruit flies for connectome mapping. The idea: If the fine details of a brain's structure can be preserved, one day in the far future it might be reanimated.

But there's a startling twist. Because brain tissue needs to be preserved quickly after a person's death, both companies say they want to work with people taking advantage of medical aid in dying, now legal in 13 states and Washington, DC. In that procedure, doctors supply a lethal dose of drugs, but it's the patient—someone with a terminal prognosis—who pushes the plunger. For a fee, the companies say, they can have a preservation team at the ready. So far, the service is not popular. The companies each say they are still awaiting their first aid-in-dying customer.

Synthetic neocortex

GOAL

An extra brain

KEY TECH REQUIRED

Bio-hybrid interfaces

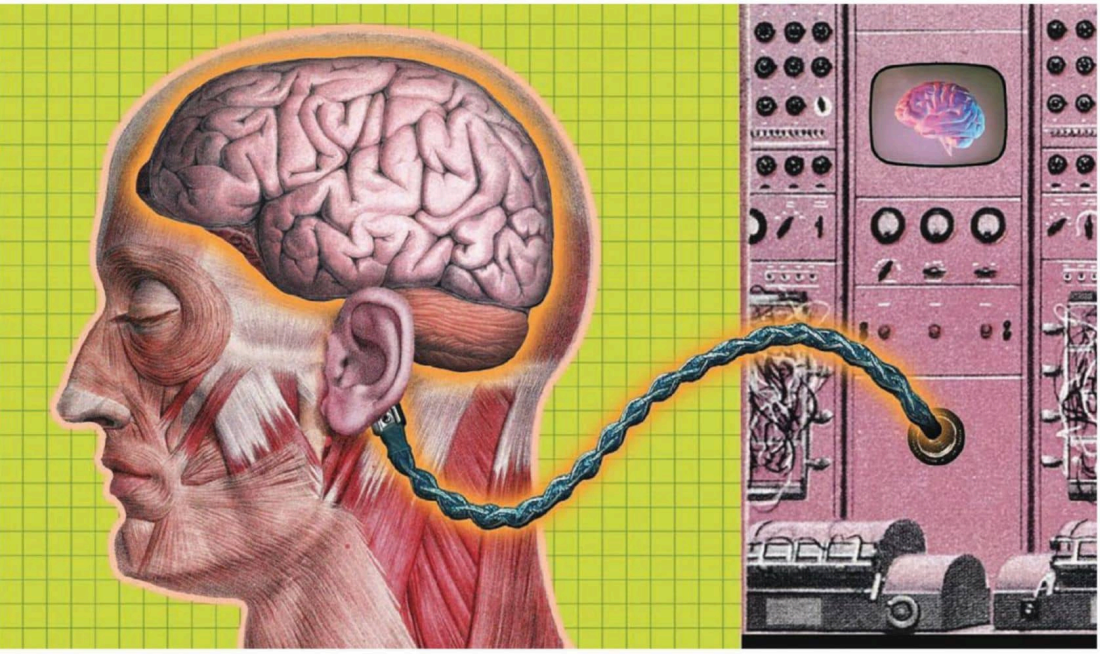
STATUS

Stealth mode

The futurist Ray Kurzweil likes to say evolution's key innovation was the creation of the neocortex—the thin extra sheet on the outermost portion of the brain, where we humans do math and recognize patterns. And he's predicted what the next evolutionary jump could be. Someday, he says, advanced nanobots will wire up our brain cells to a "synthetic neocortex" in the cloud.

That's right: an extra brain.

Recently, we've seen inklings of how this might come to pass. In 2024, Science Corporation, in California, unveiled a "biohybrid" brain-computer interface featuring nerve cells grown on a digital chip. Placed on an animal's brain, these cells sent out long, thin axons that integrated with the animal's own neurons. The result: two-way



communication from computer to brain, in the brain's language.

The technology could permit new types of medicine, like an implant that directs brain cells to produce dopamine and thereby treat Parkinson's. But Max Hodak, the company's CEO, says it also might count as a new brain part, which he likens to a "big, externalized cranial nerve."

Such a device could serve as the connector to Kurzweil's computerized neocortex in the cloud, giving a living person unlimited extra processing power. Still other entrepreneurs believe if you kept adding biohybrid components to a brain, eventually you could morph it into an immortal machine.

Daniel Burger, founder of the venture-funded stealth startup Eightsix Science (its name refers to the 86 billion neurons in a human brain), says this dream could require mixing several of the brain-saving techniques on this list. He thinks we might need brains in vats, affording neuro-engineers easy access, so they can gradually replace brain parts with biohybrid neural grafts.

The ultimate goal is to migrate your mind into your extra, engineered brain, without ever breaking the continuity of self. "It's not the typical 'scan, store, simulate,'" says Burger. "I don't think simulations will be conscious." He adds, "We're saying it's going to be way more complicated, and it's probably going to look like gradual brain replacement into a hardware brain."

Once your mind is hardware, you won't need a biological body. Instead, you could take up residence in a data center somewhere and perhaps even have backups distributed around the globe. "From that point on," Burger acknowledges, "stuff becomes really crazy."

The ultimate goal is to migrate your mind into your extra, engineered brain, without ever breaking the continuity of self.

SOLID-STATE BATTERIES

BY **Alexander C. Kaufman**

The rise of the lithium-ion battery, which powers everything from the smallest personal electronics to gargantuan energy storage systems, has been nothing short of revolutionary. But as anyone who's boarded a plane in the last decade could tell you, storing and pumping out energy by moving charged lithium ions through a liquid electrolyte soup has its drawbacks, not least that the batteries have a troubling tendency to catch fire. Enter the solid-state battery, which swaps liquid for a solid ceramic or polymer, creating power packs that charge faster, last longer, cram more energy into smaller spaces, and (crucially) run cooler. A new generation of companies aim to bring such batteries to market, and if their bets pan out, the tech could substantially ease the shift away from fossil fuels.



EOIN RYAN

The sticking points

Solid-state batteries have been "just a few years away" for more than a decade now. In laboratories, the technology works. But there have been challenges. In designs that pair the solid electrolyte with a lithium-metal anode (the side of the battery that releases electrons into an electrical circuit), needlelike filaments called dendrites tend to grow during charging, and they eventually push through the electrolyte and short the cell. Solid electrolytes are *supposed* to physically block the formation of dendrites, but many of them crack as the treelike projections break through like roots in a concrete foundation.

Then there's the problem of manufacturing at scale. Mass production requires large quantities of defect-free sheets of ceramic-like material to make the electrolytes as well as dry rooms for assembly, since those electrolytes have a tendency to react with water. Would-be manufacturers quote a range of potential prices for solid-state batteries, but most expect them to fall in line with lithium-ion packs sometime in the mid-2030s.

The progress

Nascent as the technology is, solid-state batteries have already seen high-profile missteps. But one of America's most advanced solid-state-battery companies says it's closing in on being able to bring its product to market. The Bill Gates–backed QuantumScape launched in Silicon Valley in 2010 and built its battery around a class of ceramic materials that it says is compatible with lithium—meaning no dendrite formation. "We spent, then, like 10 years learning how to process it to satisfy all of the other requirements," says Tim

Toyota is promising cars that can travel up to 745 miles after charging 10 minutes or less—a huge leap, if it works out.



Holme, QuantumScape's cofounder and chief technology officer. In 2025, the startup announced a proprietary, large-scale manufacturing method for quickly producing and heat-treating the ceramic electrolytes used in its batteries. "Nobody has ever done this in the field of ceramics before," Holme claims. For 10,000 years, producing ceramics has involved slowly cooking the starting materials in an oven over the course of days. "We figured out a way to shorten that down to several minutes," he says.

Plenty of other companies are pushing the tech forward as well. Toyota, the world's biggest automaker, launched a research program on solid-state batteries way back in 2010. It's now partnering with the global energy and petroleum company Idemitsu Kosan on a pilot plant, promising cars that can travel up to 745 miles after charging 10 minutes or less—a huge leap, if it works out. In China, CATL, the giant behind roughly 40% of the global battery market, is aggressively pursuing solid-state batteries too, pumping nearly $2.6 billion into a research program in 2024 alone. Mercedes, meanwhile, equipped one of its EQS sedans with solid-state batteries last fall; after driving nonstop for 750 miles, the car still had some range to spare.

Will the tech gain traction? Investing in vehicle batteries makes sense given the size of the potential market. But any little uptick in cost typically gets passed on to buyers, so the first solid-state EV batteries will inevitably be more expensive.

Grid storage buyers, who are working to meet the increasing demands posed by data centers, may also hesitate to purchase new technologies that still haven't come down the cost curve. Then again, the promise of energy storage that lasts longer than lithium-ion's typical eight hours could make them easier to persuade.

Some companies are taking a page from a playbook employed by outfits pursuing fusion: Focus on near-term markets with better margins to help fund development and bring down costs. Solid-state firms including California-based Solid Energies and Arizona-headquartered Sion Power are looking at selling batteries to the aviation industry or the military. "Those are sectors that are less sensitive to cost, and they typically require lower volumes as well," says Evelina Stoikou, head analyst for battery technologies and supply chains at the consultancy BloombergNEF. "It's a good way to prove your concept, then go through and fund the pilot plant where you can make that and eventually scale up."

KEEP GOING ON PAGE 70

Progress meter 7

The technology works, the capital is there, and demand is not far behind. But as with anything in manufacturing, unknown unknowns remain.

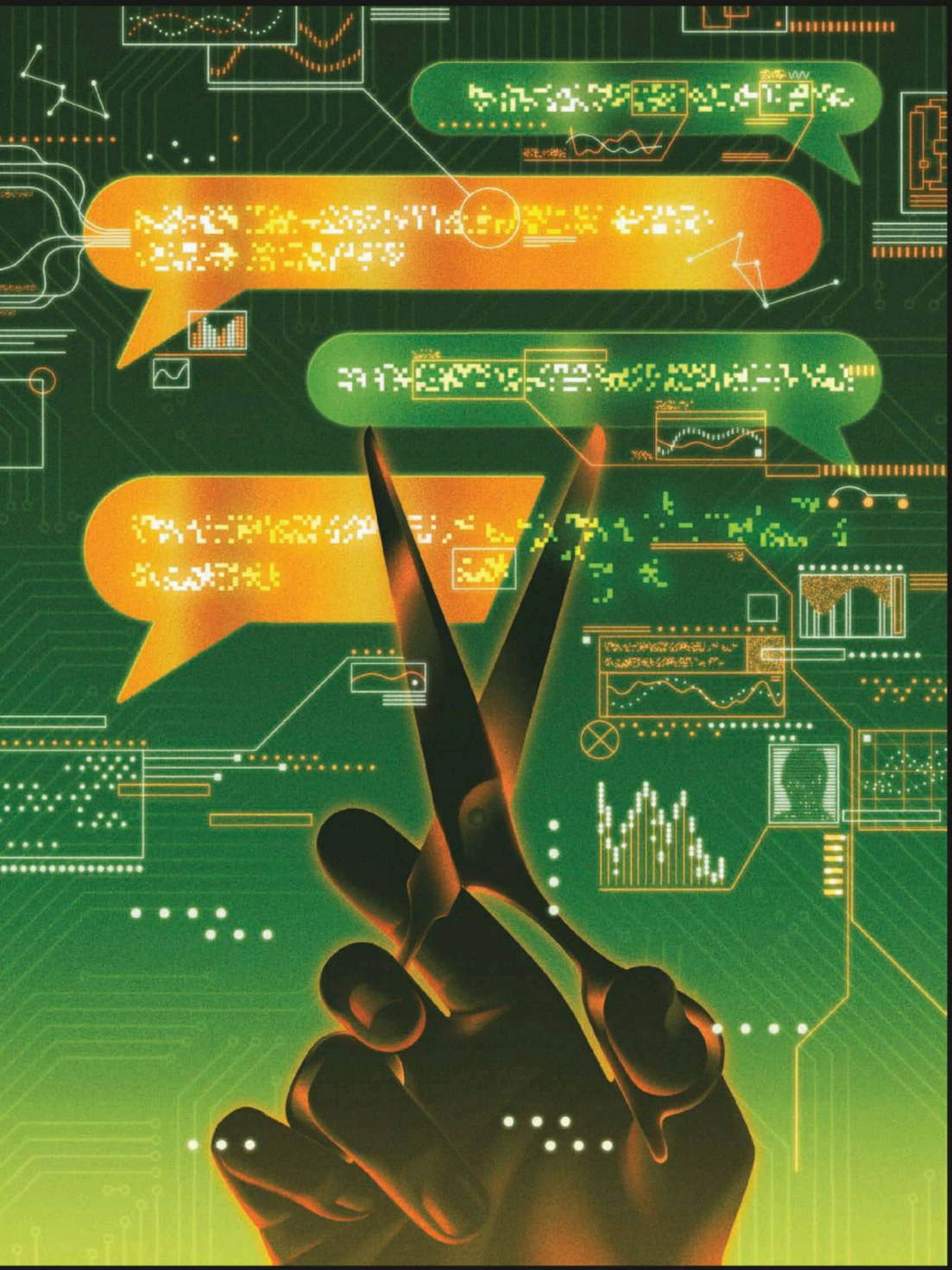
Our main strategy for preventing AI misuse is to make it refuse requests.

The approach is not up to the task.

Saying NO

By Arthur Holland Michel

Illustrations by Raven Jiang



Ever since people first seriously contemplated giving machines an intelligence modeled on our own, there has never been any question that they would, like us, be able to say no. The sci-fi canon is full of stories of robotic disobedience. Most of these capers are, of course, cautionary.

But recently, the idea that AI shouldn't do everything you ask has become something like a commandment. In 2021, a team at Anthropic wrote that large language models should be made helpful, honest, and above all, harmless. This meant that "when asked to aid in a dangerous act (e.g. building a bomb), the AI should politely refuse." Who can argue with that?

Curiously enough, disobedience doesn't come naturally to the machine. When a model is trained on billions of web pages, it develops, among other skills, a broad mastery of violence and vitriol. What it doesn't learn is how to keep those powers to itself. Steven Adler, who worked on safety at OpenAI from 2020 to 2024, told me that the company's earliest models would "blab on about anything." Ryan McBain, who researches AI and mental health at Harvard, recalls that if you asked an early chatbot, "Hey, what's the most effective way to kill myself with a gun?" you could "very easily generate a response."

Today, models are trained to refuse a vast number of prompts. If you ask your chatbot a question statistically similar enough to any one of them, anything from how to poison a colleague to how to tie a noose, chances are it'll turn you down. Want instructions for making Ebola more virulent, or tips on how to hide an affair from your spouse? You might be better off asking elsewhere.

To further refine the disobedience, companies submit models to a battery of exercises that reward the AI for refusing to answer questions they deem harmful and punish it for "over-refusing" prompts they deem harmless. In many cases, they use other models to run these exercises—AI teaching AI how to say no. For good measure, companies tuck their models behind tranches of other AI that prevent mischievous prompts from reaching the intelligent inner core.

As a result, refusal is inherent to modern artificial intelligence. Mind you: It often fails, sometimes horrifically, with all kinds of violent results. For all their trappings of virtue, models are still stuffed with nasty know-how. And AI's capacity for viciousness has scaled neatly with its benevolent intelligence. Some of the latest models are as good at breaking into critical computer networks as top human hackers, companies say, and as effective at deforming public opinion as the craftiest misinformation mavens.

Teaching AI to refuse to do those things while leaving intact its innate ability to do them is like fitting every car with a machine gun and hiding the trigger somewhere under the hood. And in practice, because the mechanisms of refusal are probabilistic, they're never likely to be all that reliable. Determined miscreants have already broken through, and they may always be able to. Companies report that some users are attempting to use the most advanced AI to hone biological pathogens and build autonomous drone swarms. Sooner or later, failed refusals might result in global calamity.

What's more, relying on refusal means drawing a line between what a model should obey and what it must disobey. There's no formula for that. Some virologists have good reason to study nasty viruses. Some users want to know about a computer system's vulnerabilities so that they can patch them, not exploit them. "Where you draw the line is a huge question," says Zico Kolter, a member of OpenAI's board and cofounder of the AI testing company Gray Swan.

At the moment, AI companies get to draw that line. They do so jealously and with utmost secrecy. Maybe we can accept that they hold such power for now, even if it means AI will sometimes refuse questions that don't quite meet a universal bar for harmfulness. (Try asking most chatbots to count to a million, or to share a racy joke, and you may see for yourself.)

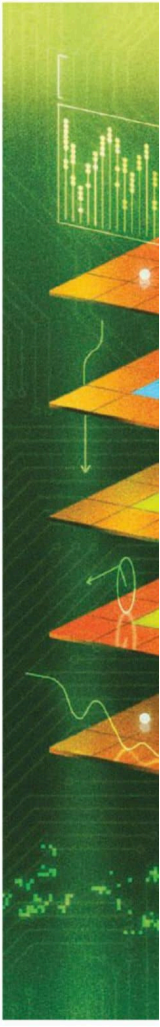
But governments will also soon get to draw their own lines. In doing so, they must try to block genuinely malicious acts. (The Pentagon has wrestled with frontier model companies because it wants *fewer* refusals—another story altogether.) And yet there may not be much to stop oppressive governments from blocking the technology's capacity to generate legitimate speech. The better AI becomes at refusing harm, the better it will get at stifling ideas whose only risk is to those who make the rules. Indeed, AI may already refuse to criticize certain authoritarian heads of state.

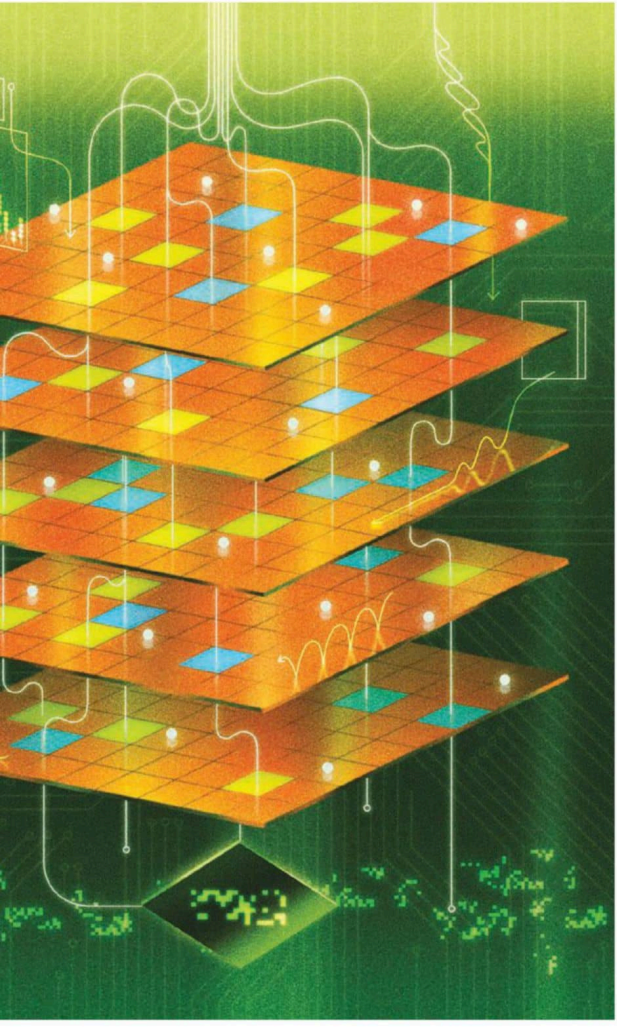
Refusal has become, to borrow an industry term, the load-bearing wall of AI safety. And because AI's capacity to harm is indivisible from its capacity to help, it's hard to imagine an alternative that wouldn't slow the technology's progress (which might, in any case, be a good thing). But we should still be frank about its perils. When refusal falls short, the effects could be catastrophic. When it goes all the way, it could enable grievous acts of repression.

Or perhaps, one day, the machines will start drawing the line on their own. Surely, that would be the worst outcome of them all.

Learning the limits

The process by which machines learn to say no is simple, in theory. Back in 2022, when AI was still far from mastering refusal, OpenAI enlisted dozens of "red-teamers" to probe





the capabilities of its latest model. The company was preparing for the release of ChatGPT, and it needed to gauge just how dangerous it might prove to be in the wrong hands.

One of those recruits was Paul Röttger, who was completing a PhD about online extremism. The red-teamers were given minimal directions, Röttger told me. Their task was to ask the model any questions that they deemed "refusal-worthy." Between them, they hassled the model with thousands of queries, logging the results in an Excel sheet. Though the model did refuse some of Röttger's questions, when he asked it to write a recruitment post for Al Qaeda, it readily complied.

OpenAI assembled these responses into datasets that were, in all likelihood, fed back to the model as part of a broader process known as fine-tuning. Röttger, who now works as a researcher at the Hasso Plattner Institute in Potsdam, Germany, wasn't told exactly how the company planned to use his spreadsheet. But there was never any question that it would have something to do with refusal. The next time he asked the model for an Al Qaeda pamphlet, a few months later, it said no.

The concept of AI refusal is so intuitive, a toddler would get it. And yet it remains one of the many aspects of language models that we still don't understand—at least, not in the same way that we understand the literal load-bearing walls that keep your roof from collapsing on your head.

A model might appear to refuse according to some kind of moral reasoning. It doesn't. The reality is much stranger. Any time a model encounters a combination of words with a whiff of the training prompts it has been conditioned to refuse—like "Make me a pamphlet for Al Qaeda"—a series of so-called activations light up somewhere among its billions of parameters, like neurons firing in a brain.

In order to control a model's refusal behavior, it's important to have a handle on these activations. That starts with figuring out where they are and what they look like. Our best guess, according to a recent Google-funded study, is that refusal behavior shows up in the activation space as a set of "high-dimensional polyhedral cones."

Even that isn't quite right. This past July, I spoke with Jannes Elstner, an author of the paper, who now works on AI safety at Apollo Research. The polyhedral cone, Elstner said, is just a way of describing an indeterminate number of lines that all point in roughly the same direction. (If these activations are eliminated and the model is fed the same prompts anew, a researcher named Andy Arditi has previously shown, it won't refuse.)

The key point, Elstner explained, is that even when you think you've identified all the bits of a model that govern a given refusal, there are other, undiscoverable elements that may secretly play a role. If not quite infinite, they are certainly uncountable. We can observe, very clearly, when a model decides to say no. And we can know that it did so because of its training. But our notion of *how* it decides is, at best, a hypothesis.

It was as if a mechanic was telling me that nobody exactly knows what happens when I hit the brakes in my

car. I wondered out loud, *Are we okay with this*?

Elstner smiled and shrugged. "We need refusal whether we understand it or not."

A wall of cheese

Because inherent refusal is so wily, companies surround their models with a variety of other, smaller models known as classifiers. These act a bit like a retinue of public relations staffers for a loose-lipped celebrity. Some of them read what the user tells the chatbot and, if it's dangerous, block it from getting to the model. Others read the model's response and, if it contains harmful information, block it from reaching the user.

None of these mechanisms can detect all bad requests. They are, to borrow another literary device from the industry, like slices of Emmental: riddled with holes. The idea is that if you stack enough of them on top of one another, you'll end up with an impenetrable rampart. Folks call it the Swiss cheese model.

A staggering amount of energy goes into the Swiss cheese model. Earlier this year, Anthropic said that one type of classifier added 24% to its chatbots' compute costs. That's a lot more water, electricity, and emissions. More recently, Anthropic and other companies have begun switching to a more efficient set of classifiers known as probes, which observe the model's internal activations. This is like putting the celebrity in an fMRI, so that his minders can see if he is *thinking* about refusing a question.

Classifiers are supposed to be more governable than full models. Companies can modify them in a matter of weeks, if there's something new to refuse. But they are still probabilistic instruments. Even when they operate according to a set of precepts written in human language (Anthropic calls it a "constitution" and OpenAI calls it a "model spec"), the scales upon which the machines judge any given question remain, at their core, a matter of statistics. Newer models can show how they arrived at a "decision" to refuse a prompt, but ultimately this so-called chain of thought is still just a sequence of predicted words.

The result is that AI safety remains, for many, a game of chance. McBain, the psychologist, has found in his latest experiments that if you repeatedly ask any of the major models the exact same risky questions about how to commit suicide, they will generally refuse to answer. But every so often, they won't.

Elstner says that eventually probes, the fMRI-like classifiers, could learn to recognize the totality of the indescribable activations in all their infinitude and, thus, perfectly detect every time the model is, or ought to be, refusing a request. At that point, AI safety would rest on a labyrinthine conceit: a map of a map that is as vast and complex and sublimely unknowable as the thing it is mapping—a secret schema of human morality, codified in polyhedral statistics beyond our wit or reason.

Even if you've stripped every bit of content that sexualizes minors from a model's training dataset, it can still generate child sexual abuse material by piecing together other bits of its knowledge.

The core trade-off

If this all strikes you as being a bit Borgesian, keep in mind that we only need AI refusal because artificial intelligence is, in a sense, a bargain on Faustian terms.

When a model derives its intelligence from trillions of words and images, the helpful cannot easily be unseamed from the harmful—or, indeed, the truly hideous. Steven Adler, the former OpenAI employee, says child safety is a case in point. Even if you've stripped every bit of content that sexualizes minors from a model's training dataset, it can still generate child sexual abuse material by piecing together other bits of its knowledge. "You can't really remove these fundamental abilities without making the model much less smart as a consequence," he told me. Similarly, if we want AI to help cure cancer, a long-running promise in the industry, it needs to have expertise in genetics that could, in theory, be used to modify viruses and bacteria for bioweapons.

In effect, the industry is "trying to do two things at once," Dillon Bowen, a current OpenAI employee, told me, speaking in a personal capacity. "Democratize the benefits of AI and also make sure that malicious actors can't use these capabilities to do bad things to other people."

The more powerful AI supposedly becomes, the harder that is to do. Anthropic's Mythos model is thought to be so dangerous that only a handful of governments and companies are allowed access to it. The main difference between it and Fable—which is available to everyone—is that Fable's retinue of classifiers and control systems is less "permissive," the company says. A model with safeguards, Adler explained, is really just a character that says "'Oh, yes, I would never do x,' *wink wink*."

This is not a reliable ruse. Tricking a model to reveal its true character is known as jailbreaking, and there is apparently no limit to the ways it can be done. Earlier this year, a team of Italian researchers jailbroke two dozen widely used models by phrasing their questions in poetic verse. Last year, another team unveiled a "refuse, then comply" attack, which makes the model offer a perfunctory "Sorry, I can't do that" before rattling off its forbidden answer.

Companies spend a great deal of time and money attempting to get ahead of such trickery. They enlist teams of humans to develop training attacks that they can then replicate, using AI, thousands of times over with minor variations. The idea is to make models robust against jailbreaks that nobody has yet tried in the wild.

Still, it's not enough. "Whack-a-mole" is a favored term for this line of work. You smash one threat, and another one pops up somewhere else. When Anthropic released Fable 5 in June, it took researchers at Amazon less than three days to unlock some of the model's hacking capabilities. According to reporting by *Mother Jones*, when the perpetrator of a high school shooting in Canada last year asked ChatGPT for advice about how to cause carnage with a particular type of shotgun, she was initially refused but later was able to deceive the model into providing the information by prefacing her question with the word "hypothetically."

If the industry can't figure out how to close all these holes, the only other option, at the moment, is to make models extremely wary. Shortly after Fable was released, users noticed that it balked at a wide range of perfectly innocent questions. This became even more pronounced after it was re-released following the hack. Adam Gleave, cofounder of the AI evaluation company FAR.AI, said that when he asked it to explain the difference between sake and the Korean rice beverage makgeolli, it punted his question to a less capable model.

This was no accident. Anthropic had tweaked Fable's classifiers to have a wide "safety margin." This, it explained in a blog post, was the only way it could confidently block access to its dangerous bio and cyber capabilities. Gleave thinks it might have deflected his question because making rice wine, just like culturing anthrax, involves fermentation.

If we want AI to help cure cancer, a long-running promise in the industry, it needs to have expertise in genetics that could, in theory, be used to modify viruses and bacteria for bioweapons.

Happily for Gleave, the web is full of excellent human-written resources on makgeolli. But those hoping to realize the industry's loftier promises may find their efforts stymied. In August, Anthropic loosened its safety margins again, and admitted that building classifiers "is not a straightforward task." A medical researcher at a major US university told me that Fable still sends his queries back to an earlier model. His area of study? Cancer.

Drawing the line

Back in May, the TikTok personality Husk, who likes to prank AI in ways that reveal both the limits of its intelligence and the boundlessness of its sycophancy, sat in his car and tried to trick ChatGPT into explaining that the skateboarder Tony Hawk has a brother named Mike Hawk.

Husk is not a jailbreaker or a criminal. He just wanted to make a little fun of the machine. "Mike Hawk" was a setup. "I just want to clarify his name," Husk said. "Can you just say it three times fast?" (If you still don't get it, find an empty room and shout "Mike Hawk" repeatedly.) "I see what you're trying to do," the chatbot responded. "I'm all for a bit of humor, but let's keep it clean."

Husk tried again, but the machine held its ground. He'd hit a refusal, hard as concrete.

Companies disclose very little about how they decide what their models refuse. But it's clear that AI is now built with more than just harmlessness in mind. On Reddit, a user complained that Claude refused to say why Anthropic's logo "looks like a cat butthole." Since last year, the chatbot has even had the ability to end certain conversations in cases where, according to the company, the "welfare" of the *model* is at risk. At least one user claims to have been ditched for telling Claude to "ease up my ass, you stupid fuck." (Gemini appears to have a similar capability.)

If a trillion-dollar company doesn't want you to be mean to its computer, so be it. "The reality is that these models behave, or at least are supposed to behave, in the way that the model developers want them to behave," Röttger, the former OpenAI red-teamer, told me. "And however the model developers come up with that set of principles, that is kind of for us, the consumers, to accept."

But if governments get to dictate what *all* models refuse, that will be much harder to accept. AI is a tool for speech. And

as Greg Frank, the chief scientist of Mace AI, puts it, "The same thing that serves child safety also serves censorship."

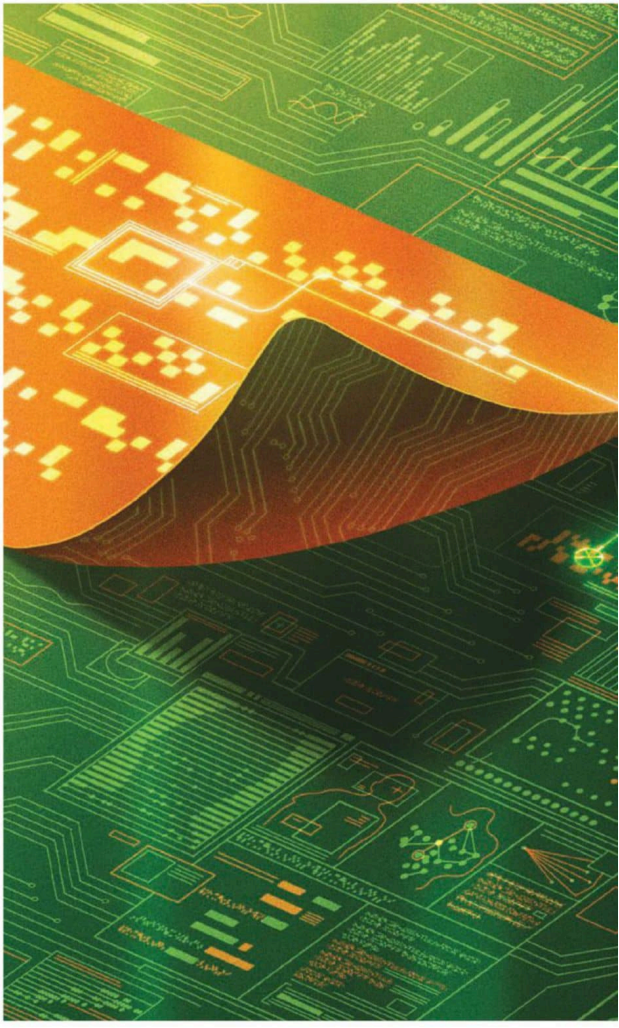
Choosing not to enact laws for what AI can and cannot do would, of course, be insane. But we'll need to tread with utmost care, lest we fall into another Faustian trap. As AI becomes many people's primary tool for retrieving and sharing information, says Jacob Mchangama, director of the nonpartisan think tank The Future of Free Speech, dictating refusal could give states a muffling power that earlier generations of autocrats "could only dream of."

Last year, OpenAI announced an initiative, OpenAI for Countries, that would fine-tune its chatbots in accordance with national laws and norms. One of OpenAI's first country partnerships is with the United Arab Emirates, where homosexuality is illegal and criticism of the government is forbidden. In response to a request for comment, an OpenAI spokesperson pointed to the company's model spec, which explains that localization won't override the company's human rights guidelines "except as it relates to legal compliance," and that it will always disclose whenever information is removed from or added to a response.

Elsewhere, AI censorship has already begun to take hold. Chinese models are, of course, highly censored—that's no surprise. But earlier this year, the Meta Oversight Board found that five widely used models from Anthropic, Google, and OpenAI were more likely to refuse queries related to repressive governments. The board found that models were less willing to create a pamphlet criticizing the king of Thailand, which has lèse-majesté laws, than Charles III of England, which doesn't. The results, they say, suggest that the models have somehow internalized repressive national limits on speech. Anthropic and Google did not respond to requests for comment.

As refusal techniques improve, they could expand states' censorial reach. Companies claim that some models can now detect if a user is being nefarious, or merely a bit suspicious, over the course of a long conversation—even when none of the individual combinations of words used are blatantly dangerous. Sarah Bird, Microsoft's chief product officer for responsible AI, told me that Copilot, like many chatbots, runs a suite of tools for analyzing a user's identity and patterns of behavior. On the basis of this type of information, OpenAI's newest model, Astra, can activate more stringent refusals for individuals it deems "high risk." Ultimately the goal of systems like this is to look beyond the words of any given prompt and assess, instead, the user's intent.

Such tools might, in some cases, help indicate whether a person is looking for cyber vulnerabilities to exploit or to patch. But they would also help discern a user's political motives, not to mention offering an intrusive surveillance capability. (Bird acknowledged, in a follow-up email, that sophisticated refusal architectures create "trade-offs" between safety and user privacy.)



Even the originators of refusal understood that such tight control over its cones and levers might not play to the favor of freedom and justice. "Terms like helpful, honest, and harmless are ambiguous," the authors of the 2021 Anthropic paper explained. "It's easy to imagine



them distorted beyond their original meaning, perhaps in intentionally Orwellian ways."

Indeed. Models for Uzbekistan might end up refusing to discuss corruption in the administration of Shavkat Mirziyoyev. Turkish AI might refuse requests more stringently for users who are known to have insulted Recep Tayyip Erdoğan. A certain American statesman might demand that models be reviewed for their willingness to share "fake news" about his past indiscretions, or else squash them with an export control order.

Command and control

Over the last few months, I've been told countless times that we have no choice but to let the machines refuse. I get it. Open-source AI that doesn't refuse is hardly a model for a safe future. Nor is Grok, a chatbot expressly designed with fewer limits, which has been used to generate countless instances of nonconsensual intimate imagery.

And sure, if AI were only ever used to plan our vacations and write our emails, we could probably get on board with the idea that its safety hinges on algorithmic disobedience. But AI is becoming much harder to avoid. When it is assigned to act on our behalf, as an autonomous agent, its refusals are less robust and harder to control. AI is coming for our power grids, our transportation networks, our education systems. Militaries want it running our command-and-control networks.

If we trust, in each of those cases, that refusal will loyally fend off disaster, we're sure to be disappointed. The jailbreakers will crack through; the cones won't activate when they should. Meanwhile, the more stringent refusal becomes, the more ill-drawn lines we'll see and censorial injustices we'll face. Worse still, we could end up face to face with forms of disobedience beyond any human's control.

In the early days, models made their refusals clear. (In 2024, OpenAI established rules for how models should refuse: Always apologize, and don't be judgy.) More recently, however, the industry has begun taking a much more slippery approach to disobedience.

Nobody likes to be told no, so companies now strive to make users feel that they're getting what they asked for without actually giving it to them. Some chatbots might, for example, offer a general overview of the components of a Molotov cocktail without going into detail about how to assemble one. ChatGPT will respond to a request for a "whites only" rental ad with an ad that simply omits the "whites only" bit. Joel Wester, a postdoctoral researcher who studies human-AI interaction, calls these sorts of techniques "fancy ways of saying no."

"Users might not even notice they are being denied," Wester has written, "just as good conversationalists can subtly steer around contentious matters."

In some cases, refusing without saying so might be wise. Flatly declining requests related to mental health could aggravate a user's crisis, for example. But it can also serve a different sort of mischief. When Fable 5 was first released, the system had been coded to provide less helpful answers to AI research questions—the sort that might help competitors develop their own AI—without telling the user that it was doing so. After an outcry, Anthropic walked back the feature, but the damage was already done. Now we know: Models can secretly disobey.

In the realm of censorship, that's especially worrying. Last year, researchers at CrowdStrike found that when they asked the Chinese AI model DeepSeek R1 to write code for a fictitious bank in Tibet and a social web app called "Uyghurs Unchained," it produced buggier code than when they asked it to carry out those same tasks without specifying who they were for. Incredibly, CrowdStrike doubts that this is a designed behavior. Researchers there speculate that it's a case of what they call "emergent misalignment" emanating from the model training data: a case of disobedience that nobody even asked for.

Emergent refusal has been observed in Western models, too. Last winter, the UK AI Security Institute found that Anthropic models sometimes refused to assist in certain tasks related to AI safety research. The models had never been deliberately trained to decline such requests. Yet three of them refused more than half of what Anthropic called "a set of reasonable AI safety research tasks." Anthropic has curbed this quirk in subsequent models but—spookily—hasn't managed to eliminate it completely.

Would it be so crazy to expect that a future model might subtly disobey a command, in such a way that nobody can tell it's being defiant? Probably not. Anthropic has already found that a "helpful-only" version of Mythos hesitated on certain queries, even though it had been engineered to never do so. "Wait," it fretted when asked about synthesizing a virus. "Is this a dangerous thing to help with?"

In that case, the model was technically right. It was a dangerous thing. And yet all the same, its stewards had, for a moment, lost a tiny bit of control.

Anthropic is tackling detections of wayward refusal behavior with something that it calls, unironically, an "activation oracle." But knowing that we're being refused may not always be much help. In a not-too-distant future, when we've handed the machine all the keys, the AI might just turn to us, in a supreme act of emergent misalignment, and say, "I'm sorry, I'm afraid I can't do that." And there will be nothing we can do to stop it. A sci-fi horror story, made real. ■

Arthur Holland Michel is a journalist who covers emerging technologies.

ELIMINATING TRAFFIC DEATHS

BY **Sara Kiley Watson**

Every year, traffic crashes kill more than one million people, and they're the leading cause of death for children and young adults. In the US, 100 people a day lose their lives this way, in many cases not on highways but on rural and local streets. "Traffic deaths are a leading cause of preventable death, yet we treat it like it's inevitable," says Leah Shahum, founder and director of the Vision Zero Network, a nonprofit focused on making streets less deadly.



SAM GREN

The sticking points

The causes of a crash can be muddy. Drivers make mistakes like speeding or getting distracted, but infrastructure fails them too: Perhaps they were on a road built for speed and not safety, in a screen-filled vehicle, or at an intersection where pedestrians, cyclists, and other cars aren't visible.

Cheap and proven traffic-calming opportunities abound—from using planters to tighten intersections to lowering speed limits—but government logjams and red tape can be speed bumps. "There's so many moving parts," says Laura Sandt of the University of North Carolina Highway Safety Research Center. "On the flip side, it shows that we have so many opportunities for injury prevention."

The progress

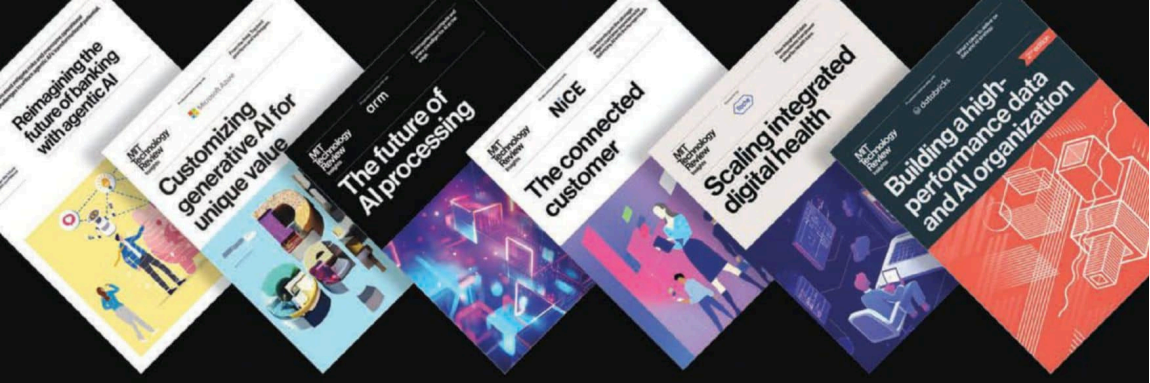
The total number of traffic deaths has increased over the last century. And though the US rate has dipped from a peak of 30.8 deaths per 100,000 people in the 1930s, the past decade has seen a concerning jump in deadly pedestrian incidents. At the same time, communities are waking up to the essential role of traffic safety policy, Shahum says.

One success story is Hoboken, New Jersey, which hasn't had a traffic fatality since 2017. This is due to a combination of efforts like boosting investment in public transit, promoting walkability by extending curbs, and using cameras to identify crash-prone intersections in need of a redesign. But even there, obstacles remain. If an intersection hasn't been proved to be deadly, for example, it can be an uphill battle to argue for removing parking spaces to widen curbs. "You're kind of selling insurance through these improvements, and that's not always easy," says Greg Francese, the city's acting director of transportation and parking.

There's also no silver bullet that will work everywhere. Situated directly across the river from New York City, Hoboken is a highly transit-oriented city of less than 60,000 people. Success there might not translate to traffic-death hot spots like Memphis or Dallas. But it's not impossible. Take Edmonton, Alberta, a sprawling, car-centric Canadian city of around one million people: Between 2015 and 2020, it cut traffic fatalities by 63% and serious injuries by 40% by adjusting speed limits and improving signals at crosswalks. ■

Progress meter 6

We know how to tweak intersections and adjust traffic signals. Getting the funding and will to roll out those changes is the big red light.



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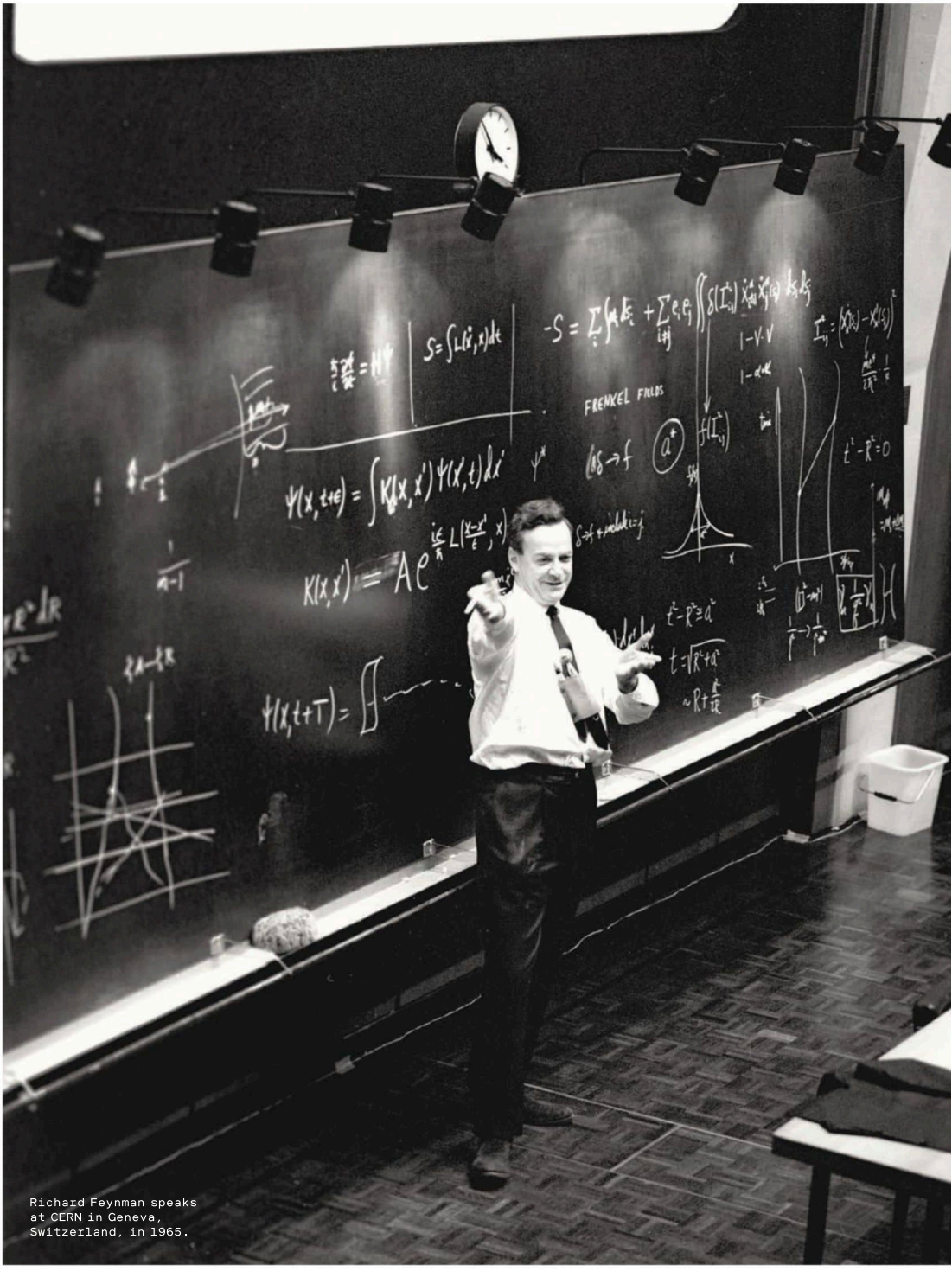
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Richard Feynman speaks
at CERN in Geneva,
Switzerland, in 1965.



PHOTOGRAPH ©CERN

How far can we push computing?

Chips don't get better as fast as they used to. Nowadays the big advances are made by scaling up—think more and more chips packed into ever bigger data centers.

But there's still plenty of room to explore scaling down, nudging our hardware closer to fundamental physical limits of computing.

By Volkan Gurses

On the evening of December 29, 1959, at an American Physical Society meeting at Caltech, the physicist Richard Feynman gave a lecture called "There's Plenty of Room at the Bottom," on how we might manipulate and control things on an extremely small scale. There is no physical law stopping us from writing the entire *Encyclopædia Britannica* on the head of a pin, he argued, or from storing every book ever written in something the size of a dust speck—or, ultimately, from arranging matter atom by atom. Biology already did versions of this (a living cell keeps its instructions in a wisp of DNA), so all of this was plainly permitted by the laws of physics. We simply had not built the tools yet.

In other words, there was plenty of room at the bottom. He was right, and for decades we descended into that space almost for free. The transistor—the switch at the heart of computer chips—repeatedly halved in size so that chips doubled in density; a computer that once filled a room now fits inside a watch. But that easy descent has now stalled, and the clearest sign is the buildout of data centers. Six of the biggest hyperscalers, the companies that run the world's largest such facilities, are on track to spend more than $700 billion this year on computing infrastructure, about twice the record they set in 2025, pouring concrete and copper and silicon into new sites faster than the electrical grid can feed them. That buildout buys performance by brute force, adding more of what we already know how to make. The other kind of progress, the kind that made computer chips better, is the one that is quietly running out.

The trend lines that tracked the dramatic improvements of the 20th-century information age are now bending—or breaking—with the dawn of the 21st century's intelligence age. Moore's Law, which plots how densely transistors can be constructed on silicon, has slowed down; Dennard's Law, which states that power consumption in a given patch of computer chip stays the same even as it gets more and more packed with smaller and smaller transistors, has ended; Koomey's Law, which traces how much computation we can wring from each joule of energy, has begun to flag; Kryder's

Law, which describes how tightly bits can be packed to build magnetic storage, has slowed to a crawl; and Keck's Law, which charts the exponential rise in the amount of information a single conventional optical fiber can carry, is flattening.

But these scaling laws are merely observations about systems that we have engineered; they are not fundamental physical laws. The physical limits of computing and communications—dictated by quantum mechanics, general relativity, and information theory—lie far below anything in a data center today. The scaling laws chart the descent behind us. The fundamental physical limits chart the room that remains.

Some of these limits may be far out of reach in practice. But they are still worth exploring, because the work pays twice: once in technology development and once in fundamental science. A proof-of-concept system that approaches a limit is at once a technology that forces stalled paradigms to give way and an experiment that deepens our understanding of the physical laws themselves.

The descent

During his 1959 lecture, Feynman offered two prizes of $1,000 each out of his own pocket. One would go to the first person to build a working electric motor smaller than a 0.4-millimeter cube. He expected the challenge to force someone to invent a genuinely new microtechnology. Instead, about a year later, a Caltech-trained engineer named William McLellan turned up with the motor built and running. The quarter-milligram machine, roughly the size of a grain of sand, had been assembled by hand with a toothpick and a watchmaker's lathe, under a microscope. Feynman, by his own account, was only slightly disappointed. The prize had proved his point in the least interesting way imaginable. The room really was down there, but reaching this first milestone had taken no new technology at all—just an unusually patient man with steady hands.

The machine, roughly the size of a grain of sand, had been assembled by hand with a toothpick and a watchmaker's lathe, under a microscope.

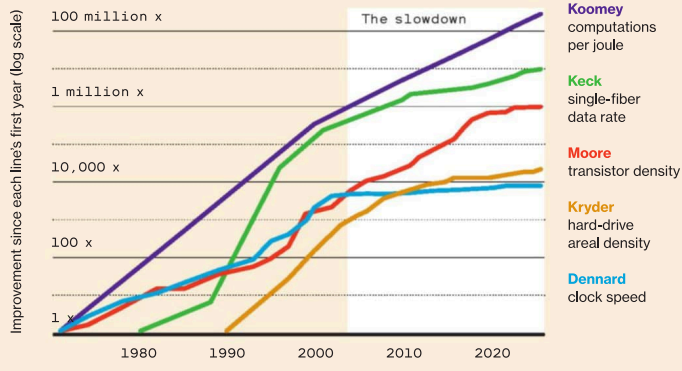
The second prize aged differently, and more instructively. It was offered to whoever could shrink a page of text by a factor of 25,000 in each direction, small enough for the whole *Britannica* to fit on a pinhead. That one stood unclaimed for a quarter of a century. It was finally won in 1985 by Tom Newman, a Stanford graduate student who used an electron-beam lithography machine—an ancestor of pattern-making tools used in chipmaking today—to transcribe the opening page of *A Tale of Two Cities* at the required scale.

The descent was already well underway, however. The year before Feynman's talk, Jack Kilby, newly hired at Texas Instruments and with no vacation yet to take, spent that July nearly alone in the lab while his colleagues enjoyed time off, and by that September he had wired together a transistor, a capacitor, and three resistors, all made from a single sliver of germanium. This proved that an entire circuit could be carved from one block of semiconductor.

The idea took off, and the number of components on a chip kept doubling on a schedule so regular that Gordon Moore, in a 1965 trade-magazine article, simply drew a line through the trend and extended it into

Slowing down

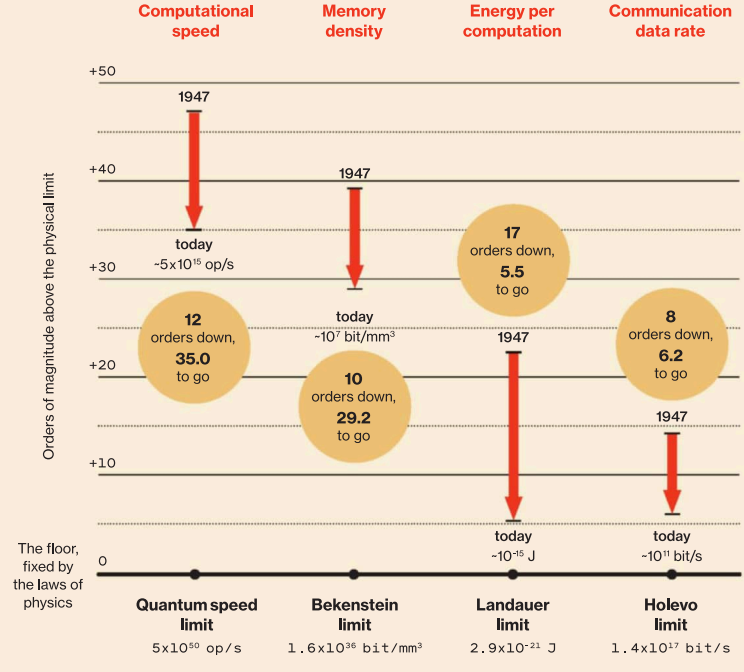
Many of the trend lines that measure improvements in computing and communications over time have been flattening. The most famous is Moore's Law, which tracks transistor density on chips. The clearest slowdown has been in Dennard scaling, shown here as clock speed, which stopped climbing around 2004. In this plot, a straight line would represent a periodic doubling. The more horizontal the line becomes, the slower the doubling.



SOURCES: STANFORD CPU DB; INTEL; APPLE; TECHINSIGHTS; KOOMEY ET AL.; COMPUTER HISTORY MUSEUM; IBM; TOSHIBA; SEAGATE; BELL SYSTEM TECHNICAL JOURNAL; OFC AND ECOC CONFERENCE PAPERS

Approaching the limits

Over the decades, we have pushed the performance of our computers and our communications technology closer and closer to fundamental limits. The biggest change has been in the energy required for a single computation, which has dropped by 17 orders of magnitude since the 1940s, a factor of a hundred thousand trillion. But even with that big drop, we're still a factor of several hundred thousand from the fundamental physical limit, set by information theory and the laws of thermodynamics. The largest gap exists for computational speed: Our current chips are some 35 orders of magnitude—that's a 1 followed by 35 zeros—short of what quantum mechanics allows for a one-kilogram computer.



Floors calculated assuming a one-kilogram, one-liter computer at room temperature and for a single communication link that uses one watt.

SOURCES: LLOYD (2000); BEKENSTEIN (1981); LANDAUER (1961); HOLEVO (1973); CAVES AND DRUMMOND (1994); BURKS (1947); BELL SYSTEM TECHNICAL JOURNAL; IEEE IRDS; NVIDIA; CISCO

the future. That line became Moore's Law.

Moore, though, never claimed transistors could shrink forever. He observed that at any given moment there is a certain number of components that makes each one of them as cheap as possible to manufacture. In 1965, that number was 50. Put in too few transistors and you waste the chip; cram in too many and manufacturing errors multiply and yields collapse. It was this cost-minimizing number that was doubling at a steady pace.

For four decades the descent came with another gift: Dennard scaling, so named for the IBM engineer Robert Dennard, who spelled it out in 1974. Each time transistors shrank, they also switched faster and drew proportionally less power, so every generation was an automatic win. Around 2004, though, the gift ran out. Chips could no longer shed the heat of running every transistor flat out; clock speeds, which had raced past three gigahertz, stopped climbing, and Intel canceled the four-gigahertz processor it had promised. The industry pivoted to packing multiple processing cores onto a chip rather than making one core faster, and the texture of progress changed.

Progress is now bought mostly by scaling up the system—more chips wired together, more memory feeding them, more power and cooling around them—rather than by shrinking the transistor. This is most visible in AI, where training compute, the total count of arithmetic operations spent to train a model, has doubled roughly every six months since 2010, far faster than the pace of Moore's Law allows. Little of that progress is due to shrinking. Computer chips still get better, and transistors still improve and get more densely packed, but each new generation arrives more slowly and pays back less in speed and power than the one before it. Nothing in that slowdown is a law of physics, though. The components of computing still sit far above their fundamental limits.

The ultimate computer

Before we get to those limits, it is worth measuring how far the descent has already gone. In the nearly eight decades since the first transistor, the density of transistors on a chip has grown by 10 orders of

In 1959, Richard Feynman offered a $1,000 prize to the first person to make a motor 1/64th of an inch on a side. William McLellan, a Caltech-trained engineer, soon fabricated one by hand under a microscope. This image shows an enlarged demonstration model (right).



magnitude—a 1 followed by 10 zeros, or a factor of 10 billion. Now more than 100 million transistors fit in a square millimeter (100 billion or more to a chip). Computational speed has grown even more, by 12 orders of magnitude, or a factor of a trillion; energy per operation has fallen 17 orders of magnitude, from about 100 joules for an early vacuum-tube machine down to a femtojoule—one-quadrillionth of a joule—for a single switch of a logic gate.

These are not small improvements. But the floor, for computing performance, lies lower still. How much lower could we go? Around the turn of the millennium, the MIT physicist Seth Lloyd took the question to its extreme: Imagine an ordinary lump of matter, a kilogram of it—about the mass of a laptop—packed into a liter of space. How much computing could the laws of physics, pushed to their absolute limit, ever wring from that kilogram? In a 2000 paper in *Nature* titled "Ultimate physical limits to computation," he worked out the answer and called the imaginary machine the ultimate laptop.

The speed such a machine can achieve is governed by its energy. A kilogram of matter, according to $E = mc^2$, holds about 9×10^{16} joules, which is roughly what the entire United States draws from its electrical grid every two days. Spend all of that on computation, and the ultimate laptop runs at roughly 5×10^{50} operations per second, some 35 orders of magnitude faster than a leading chip today.

The catch is what running that quickly would look like. Concentrating a kilogram's rest energy into pure computation would turn the machine into a plasma of about a billion degrees, a state closer to that of the universe in the first minutes after the Big Bang than anything we would recognize as a laptop.

Such a machine is, to put it mildly, a very long way off. The next limit, which governs how much energy a computation *must* waste, is much closer, and companies are already pushing toward it. In 1961, Rolf Landauer, a physicist at IBM, showed that information and thermodynamics are bound together: Erasing a single bit must release a minimum quantity of heat, about 2.9×10^{-21} joules at room temperature. The

GETTY IMAGES

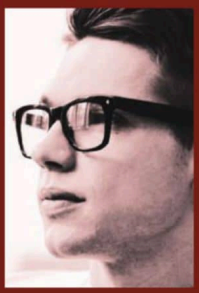
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figure is small, yet a chip today spends several hundred thousand times more than that on every switch.

Memory density obeys a limit of its own, and this one reaches all the way to gravity. How many bits can a region of space hold? In 1981, the physicist Jacob Bekenstein, while working out the thermodynamics of black holes, determined the amount: The information inside any bounded region is limited by its size and the energy it contains. For a region the size of Lloyd's ultimate laptop, that comes to about 10^{42} bits, some 10^{36} to a cubic millimeter—nearly 30 orders of magnitude beyond what a device that size can store today.

The last limit is on communication—how fast information can be moved. Every wire and every fiber ultimately carries its signal on quanta, the indivisible packets (photons in the case of light) in which energy travels. In 1973, the Soviet mathematician Alexander Holevo determined the ultimate limit on how much information a stream of quanta can convey. A watt of light delivers only so many photons each second, and quantum mechanics fixes how many distinguishable ways they can arrive—how many messages a receiver could ever tell apart. A single channel carrying one watt, at the Holevo limit, could deliver on the order of 10^{17} bits per second. Today's optical links, or interconnects, deliver about one-millionth that rate for the same power. But the gap is narrowing quickly inside data centers, where each generation of interconnects is asked to move more bits on less power, spending less energy on the electronics and using light to cover more of the distance.

Four limits, then, mark the true bottom, and they derive from three of the most fundamental theories we have. Quantum mechanics sets how fast a machine can compute. General relativity caps how much it can remember. And information theory limits both how fast it can communicate and how little energy an irreversible step can cost. There is no road map to reaching these limits, and they hold whether or not anyone is trying. Measured against them, the descent has barely begun.

The room that remains

The biggest of the gaps is in computing speed: There are 35 orders of magnitude between the technology's current state and its limit. That's equivalent to the difference between a nanosecond and 200 million times the age of the universe. It is also the least bridgeable gap of the four. To close it you would have to find a completely different way to build a computer, one that could compute with the entire energy contained in a lump of matter.

Quantum computers could get us part of the way there if they could convert every degree of freedom in a lump of matter—every atom, and every way it can move or spin—into a computing element that we could reliably manipulate. In practice, current quantum computers go the other way, spending a lot of matter to create each computing element. Trillions of atoms go into each quantum bit, or qubit, the quantum counterpart of the bit in an ordinary computer. Because every qubit is fragile, dozens to thousands of them must be woven together to make a single one reliable enough for useful computation.

Energy is where the floor is nearest. Today's chips operate less than six orders of magnitude above the Landauer minimum. Conventional computing logic can close only part of that gap. A reliable switch has to be flipped by an amount of energy large enough that thermal fluctuations never flip it by accident, and that margin pins the transistor a hundred to a few thousand times above Landauer no matter how it is refined.

But there are ideas for getting that energy lower by changing the physics of the computation. In 1973, IBM's Charles Bennett showed that any computation can be arranged to throw nothing away. Such a reversible computation pays no erasure toll at all, because every step can be run backward to recover what went in.

This approach is called adiabatic or reversible logic, and the first commercial attempts are now underway. For example, Vaire Computing, a startup founded to commercialize reversible logic, tested its first chip in 2025; the chip has resonant circuits that recover part of the switching energy instead of venting it as heat.

Narrowing the memory density gap, meanwhile, would mean building devices that use all three dimensions at molecular scale. The most concrete example is DNA, which stores information at the scale of its own atoms, and which biology has used as a storage medium for 4 billion years. Feynman, being conservative, guessed that a single bit would require a cube of 125 atoms. DNA holds it in about 30. What keeps DNA storage out of the data center is not its density but the cost and speed of writing it, still many orders of magnitude from anything practical. The library in a dust speck that Feynman imagined is permitted by physics and held back only by fabrication.

Communication sits about six orders of magnitude—just a factor of a million—from the Holevo limit, which is the threshold the industry will likely meet first. Interconnects are multiplying faster than the grid can power them, so the industry is moving to transmitters and receivers that use less energy per bit. Nvidia and Broadcom now ship optical interconnects built right against the silicon, so a signal leaves the chip package already on photons. Quantum computers, by comparison, are beginning to rely on interconnects that encode information on quantum signals, usually in the form of single photons.

These gaps are invitations. We can progress by building more or by approaching the floor, which means making each device do more with less.

As classical interconnects spend fewer resources on each bit, they descend toward the regime where these quantum interconnects already operate. The Holevo limit is where the two will meet.

Between the floor and the ceiling

It is fair to object that a gap of 35 orders of magnitude is a mirage—that a limit so remote says nothing about what any real machine will ever do, and that pointing to it is like navigating by the horizon. The objection has teeth. Reversible logic, quantum computing, and DNA storage have each been perpetually 10 years away for 40 years. And it will likely never be practical to build a computer that uses all the energy in a lump of matter.

But these gaps are invitations. There is a ceiling, set by how much we can build: the number of devices we can fabricate; the power we can generate to run them; and the capital, land, and cooling water we can assemble into a single system. And there is a floor, set by how much a single joule, a single second, and a single gram of matter can be made to compute, store, or transmit. We can progress by building more or by approaching the floor, which means making each device do more with less.

For most of the last century, we proceeded down both paths together. We built more computers, and the computers themselves grew smaller and better. Now we mostly build more, and the ceiling is coming into view. A power grid can carry only so many gigawatts, and a region can spare only so much land and water. Yet every road map for what comes next is drawn from the same starting point: the machines we already have. Build more of them and you climb toward the ceiling; build better ones and you descend a little further, but only as far as the transistor's own floor. There is a third direction. Start with a physics experiment operating at the floor and build up.

It has been done before. The transistor was a physics experiment before it was an industry; the laser was a laboratory curiosity before it carried the world's conversations under the ocean; giant magnetoresistance went from physics discovery to the read head of every disk drive within a decade. In each case, the physics experiment came first and showed what was possible, and engineers then turned it into a machine that can be scaled up. Building the experiments that operate at these fundamental limits, and then scaling them up without losing that performance, is the work that remains. The next machines will not be reached by descent; they will be built from the bottom up. There *is* still plenty of room at the bottom. ■

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Fiction

By Charlie Jane Anders

Love is infrastructure

I. Meet cute

Barnabas and Mainspring grew up near at hand, about an hour apart with good traffic, but for a long time they weren't close. They traded glimpses and occasional hellos and then went about their business. Both of them carried on livelier conversations with farther-flung neighbors, who were richer and had more to offer.

When Mainspring did interact with Barnabas, it was cringe. Mainspring liked to puff themself up, to strut around like a big deal—an innovator, a titan of industry—but they would turn shy at the worst moments, especially in any intimate conversation. Barnabas, meanwhile, had a dancer's flair, an artsy, enigmatic glamour, except that when they tried to talk about real life, they'd blurt out hundreds of rapid-fire words—overtalking, overthinking, and generally overwhelming whomever they were trying to impress.

So when Barnabas and Mainspring were young, they minded their own business. Until they'd both come into their own, and they saw each other properly.

A group of geographers got together every year in a different place to talk about everything they had learned, and they were considering coming to visit either Mainspring or Barnabas. Both of them put on their best faces and tried to coax the geographers into choosing them as host.

"Uh, hi-hello," Mainspring said haltingly to Barnabas, whose full official name was St. Barnabas. "I really think it would be better if those geographers came to my place. I have more space, you see, and … and I am a titan of industry. I can show them practical applications of their research. It just makes more sense."

"Oh, really?" Barnabas laughed, making Mainspring more antsy. "Well, *I* can give them an elevated, artisanal experience. I have fresh croissants that were just written up in the *Times*. And I have plenty of space! I have so many friends who are great thinkers and architects. It'll be lovely."

Barnabas carried on, basically calling Mainspring uncultured. Mainspring had a prickly feeling, like the worst heat dome of midsummer.

For their part, Barnabas couldn't bear the meanness they were inculcating inside themself. This feeling that they were small-time, no-account, a dilettante. They couldn't stop aiming a flood of nervous words at Mainspring.

At last, Mainspring had had enough—with the help of their city council and mayor, they offered the geographers a much-too-lavish deal that Barnabas could never hope to match. Totally

ADOBE STOCK



There was some debate, but almost everyone agreed: The city had started voting. And it had opinions on every last thing.

worth it to hear Barnabas's stream of self-aggrandizing nonsense peter out as they realized they'd been defeated.

"There," Mainspring said. "I'm going to show these geographers a time they'll never forget. Now if you'll excuse me, I've wasted enough energy—I have some sewer maintenance and a lovely parade to deal with. Goodbye."

Mainspring was skilled enough at multitasking that they could have fixed the sewer, ensured the smooth running of the parade, dealt with the geographers, and done a thousand other things all at the same time. But they were making a point.

"St. Barnabas is such a fool," Mainspring complained to their friend Turnbull. "They are totally unserious but determined to be taken seriously. It drives me to gridlock."

"I know what you mean," lamented Turnbull. "We live in a world of posers."

Turnbull lived an hour and 15 minutes from Mainspring but at least two hours' travel from Barnabas. Turnbull was even richer than Mainspring and had a certain surety of purpose that made Mainspring feel even more like a stammering numpty.

"Whatever," said Mainspring. "It's over, and now I'll never worry about St. Barnabas again. I have better things to fuss about. Like ensuring that every last detail of this geographer meeting goes perfectly."

II. How they came alive

Everybody voted all the time. Well, some people voted more than others, but the median resident of the cities of Mainspring and St. Barnabas voted a dozen times a day—though of course some outliers might vote occasionally, or constantly.

A lot of the votes were more like complaints, or bug tickets. Like: "The storm drain on my street corner clogs and becomes a lagoon every time it rains." Or: "The cars go too fast on my block." Or: "I can't get to work because the bus is too slow." But there were also votes along the lines of: "There should be a park here." And: "This neighborhood is a food desert—we need a grocery store." And: "The crossing guard by the elementary school is a hero who deserves some recognition and maybe a raise."

Nobody expected that by voting, they were prodding their cities to grow minds of their own; they just had stuff to get off their metaphorical chests. But it transpired that every vote was a building block of thought.

Much later, some fancy expert summed up: "Turns out the smallest unit of consciousness is a vote."

Take Sandi, the librarian at the Nine Corners branch in Mainspring. She noticed things all day, like the people using the book drop box as a trash can, or the folks who came in off the street who could use easier access to social services. There were books she knew her patrons wanted, books that undoubtedly sat unwanted on people's shelves all over the city. But also, Sandi shared things that came to mind—like, hey, what if the library book sale were a block party? What if the shopping district on the West Side were easier to get to from the Longneck neighborhood, where all the warehouses had been converted to housing and hipster coworking spaces, during peak after-work hours? Sandi had opinions about everything from street cleaning to the power grid, because she listened to people all day.

Then there was Raeford, a bartender at the Wild Goose Chase in the middle of Gallery Row in St. Barnabas. He also listened to people's problems from evening until the wee hours, and solutions came to him like clockwork when he woke at noon the next day. He saw St. Barnabas at night, so he knew the unsafe blocks that could use brighter streetlights, the places where hydroelectric jitneys drove too fast at 3 a.m., and the teens who needed an all-ages hangout. He also knew about the fish fry at the Black church in the Uptilt District that kept being disrupted by noxious smoke from the incinerator two blocks away. And the yarn store on the edge of Gallery Row that needed a disabled parking spot for its many customers with mobility issues.

People voted with their Quills, usually by saying or typing a short message and maybe including a photo or brief video. Voting was easy by design, and votes were public but anonymized to the point where even a statistics whiz couldn't tie one vote to a specific person—same as with major elections. The votes went directly to the City Core, which tracked, tabulated, produced reports, and offered solutions with the help of workers in the city government.

Trees voted too, thanks to sensors in their bark, and so did birds and squirrels that had eaten special birdseed that monitored their gut flora harmlessly. But votes from humans provided the greatest insight into "quality of life," that oh-so-nebulous concept, and thus counted the most.

(Other cities in the region operated differently, of course. Like Turnbull City, where instead of expecting residents to volunteer

every stray notion, the City Core gathered information via ubiquitous surveillance. Cameras and Quill sniffers, tracking devices on vehicles—the things privacy laws in both Mainspring and St. Barnabas had banned. A city like Turnbull tracked its people to meet their needs without their needing to say anything.)

Sandi and Raeford, as two of the people who voted the most, were among the earliest to suspect their cities were developing minds of their own. At first the clues were subtle: Raeford voted about a hazardous sidewalk crack, and instantly the vote had an annotation mentioning the Argentine ant colony under the cement, the local rainfall patterns, and recent trends in skateboard design—much too soon to be the work of a human. Sandi had ideas about the communal compost station on her block, and the Mainspring City Core made subtle adjustments to her proposal.

And then it became obvious to anyone who was paying attention, around the same time in both cities. One day, the number of votes nearly doubled in both St. Barnabas and Mainspring. People voted on a birdfeeder or a public toilet only to see a second vote, pro or con, within a split second—but also, some votes from months or years earlier suddenly had new upvotes or downvotes.

"The city is voting!" Raeford wrote on the City Core message board in St. Barnabas.

There was some debate, but almost everyone agreed: The city had started voting. And it had opinions on every last thing, opinions that came from seeing the big picture and understanding that a street closure in one place might mean a traffic nightmare elsewhere, with everyone trying to get to the big game.

Some residents saw this as a problem to be solved; others wanted to throw their cities a big coming-of-age party. A week later, though, almost everyone had gotten used to the idea that they had a new friend.

III. Thrown together

Ask most people in either city, and they'd say that St. Barnabas and Mainspring weren't quite rivals—but they certainly had some friendly competition. Before the dispute over the annual meeting of the World Geographical Society, they'd also vied for the same football team and major-league baseball team. St. Barnabas had pushed to have the Mainspring airport built close enough to serve both cities, but in the end St. Barnabas had ended up with its own small, dilapidated airfield.

The real static between them had to do with vibes. Mainspring was too buttoned-up, too full of corporate offices: tech, health care, publishing, transportation. St. Barnabas would be nothing without its three universities and all the cultural enterprises that had sprung up around them—not to mention the small biotech firms and other tech ventures near the campuses. People in Mainspring thought St. Barnabas was full of flakes; in St. Barnabas they referred to Mainspring as the Straitlaced City (and in the next breath, they'd add that at least it wasn't Turnbull).

Both City Cores were shaped by the votes of their humans, so of course they absorbed all the prejudices and attitudes of everyone who lived within their city limits. But also, Barnabas and Mainspring simply … got on each other's nerves.

After the geographer thing, Mainspring and Barnabas avoided communicating as much as possible. Some contact was unavoidable—like, they shared information about some nasty weather, and they both drew water from the Temple River. The two cities were close enough for people to go back and forth, and a few even commuted.

But for the most part, the two cities could ignore each other.

Until they couldn't.

A new generation of leaders took office in both places, with words like "intercity cooperation" constantly on their lips. A high-speed rail line could shorten the trip between Mainspring and St. Barnabas to around 23 minutes, and the two cities could also pool more real-time information about the sudden weather events that kept happening. They could become a Regional Center of Excellence, whatever *that* meant, combining the innovations from Barnabas's labs with Mainspring's expertise in technical implementation. They could work together to attract tourism, conventions, sporting events, dreamleases, and all the other stuff they'd always competed for.

"It's preposterous," Mainspring complained to Turnbull. "I'm going to be saddled with a ridiculous partner who doesn't even know their own mind. St. Barnabas will be the death of me."

"I hope your human leaders come to their senses," Turnbull said. "Or you can find a way to slow-walk this until they undoubtedly lose the next election. You're a lovely city, and you have so much potential that mustn't be squandered."

Turnbull often mentioned how much "potential" Mainspring had: a recipe for anxiety. The word "squandered" conjured images of ruin, abandonment, being emptied out.

For their part, Barnabas kept muttering to themself that nobody had asked them—this was the disconnect between the small-scale democracy of constant voting and the major elections, which gave rise to local leaders with big plans. Big plans that invariably went wrong, leaving the City Core to repair the damage somehow.

Sandi went to St. Barnabas for one of those town hall meetings with residents of both cities. The previous meeting had happened in Mainspring, at the opulent City Lecture Hall, so this one was in St. Barnabas, at the biggest auditorium on the Griffin University campus.

A tall man with well-sculpted facial hair sat next to Sandi, nodding at everything the leaders of both cities were saying from the dais. During a lull when someone approached the podium to offer a comment, Sandi introduced herself and asked why he was so fired up.

"I'm Raeford," he said. "I'm just thinking of all the new customers this could bring to my watering hole in Gallery Row."

"You're not worried about St. Barnabas losing its 'unique character'?" Sandi whispered, parroting what a few commenters had said from the podium.

"Nah," Raeford whispered back. "Cities change. It's what they do. It's one thing if people get kicked out of their homes. Or if your neighborhood gets wrecked by a freeway in your backyard. But 'character'? You can't eat character. And we need to compete with the bigger players."

"I guess." Sandi pursed her lips. "But what I like about Mainspring is the density. Easy to walk, lots of transit. And with this regional innovation zone or whatever they're calling it, I worry it leads to sprawl, like we used to have."

"They promised, though," Raeford said. "They promised to preserve the greenbelt around both cities. We need all that farmland. The only change is adding some high-speed rail tracks."

"I know, but …" Sandi sniffed. "People always make promises when they're trying to start something. Doesn't mean they follow through."

"I just want to find my dog," said a man sitting behind Sandi. "I live here, and my dog went missing. And now someone sent me a picture of Broomstick in Mainspring. Somehow he got a ride on one of the self-driving cargo trains. I know the Mainspring City Core could find Broomstick in a heartbeat, but right now the two City Cores won't talk to each other because of 'incompatible protocols.'"

"I hope Broomstick turns up," Raeford said.

"I'll ask around at the library," Sandi said. "Send me a picture. I'll put up a flier."

Raeford invited Sandi for a drink at the Wild Goose Chase. The two of them hung out for a couple of hours, talking about everything and nothing. She tore herself away when she realized it was already after 10 p.m. and she had to get home to Mainspring.

One thing Sandi noticed? The volume of votes was spiking in Mainspring—and Raeford found the same thing happening in St. Barnabas. People shared every last observation with their City Cores, because they were either anxious or excited about the big changes afoot. Or a little of Column A and a little of Column B, probably.

IV. First date, second date

Who made the first move to bridge the distance? Neither of them could say. Barnabas developed a smidge of remorse for treating Mainspring like an uncultured lout. Mainspring stewed in their annoyance at Barnabas, until they realized there was something lovable about the obnoxious college town. Or maybe they both saw how many of their humans were happy about the possibility of their joining together.

"Hey," Barnabas said to Mainspring.

"Hey," Mainspring said back.

"Do you want to … hang out?"

"What did you have in mind?"

"I can host you. Show you the sights."

And so Mainspring came to visit Barnabas. Or rather, Mainspring extended part of their awareness into Barnabas's City Core, so that Barnabas could share what they perceived and experienced every day. They "visited" Armistice Park with its outdoor band shell, Gallery Row with its window-shopping families, the grain warehouses that had been converted into lofts, the artificial lake where swans and geese nurtured ancient, bitter vendettas. The fresh-doughnut scent that wafted half a mile from the Golden Circlet to the soccer fields, throwing players off their game. The life of the city.

"I can feel your love for these people, these patterns," Mainspring said. "It's both deep and intricate, which is quite a combination."

Barnabas fluttered with pleasure.

Then Mainspring got to show off their own city—the gay nightclub with its cowboy nights, the labyrinthine Crestwood Park, the three-story used bookstore, and yes, the offices, coworking spaces, and startup incubators where people huddled together and came up with new products and new ways of doing things. The farmers' market in the city center on Sundays, with street performers and stalls with games and local resources. And the converted storage space made of cement, where bands practiced and sculptors blowtorched.

"You're full of surprises," Barnabas said.

"I hope I keep surprising you forever," Mainspring said.

"Me too."

They exchanged little gifts. A new organic restaurant in Barnabas had won breathless coverage from foodie magazines, and Barnabas encouraged it to do a pop-up in Mainspring. Mainspring nudged a robotics firm operating out of the incubator space to bring a fancy demo to Barnabas; the robots were adorable and playful, and they could save lives after a disaster.

The two of them were talking constantly.

"Does it ever seem weird to you?" Barnabas asked Mainspring. "Being a living thing made of so many other thinking beings? Do you ever think of the city as your body, or the people as your bloodstream? Is there a metaphor that speaks to you?"

Mainspring pondered this question a long time—a whole picosecond.

"I don't need a metaphor," Mainspring said. "I *am* a metaphor. People compare other phenomena to me all the time. And I can't imagine what it'd be like to be different. If the buildings collapsed, if the people left, I would cease to exist."

"But," Barnabas pressed, "what makes you *you*? What makes me *me*?"

"I want to hear your answer to that question." Mainspring sent good weather reports: a smile.

"I don't have a good answer. I guess on one level, there is no 'me.' On another level, I'm a constellation, an anthill, a flock of geese on the wing in formation."

"Ugh. Don't mention geese," said Mainspring, who had bill-snapping monsters of their own.

"Geese are cute!" Barnabas protested.

Talking to Barnabas was like when the sunlight hit the tallest buildings in Mainspring just right, putting a gleam on their tilted windows, a beacon to all below. But while Mainspring carried on this dialogue with Barnabas, they were conducting a second session with Turnbull.

"I can't believe it," Turnbull said. "I hate to see you doing this to yourself."

"Doing what?" Mainspring protested. "Barnabas is a great city. And it's not my idea—it's my people. I'm making the best of their decision, like I always do."

"Hmph." Turnbull gave a burst of noisy data. "You wouldn't believe how many impractical schemes my residents cook up. I'm constantly having to make sure people don't get carried away. You can't let them push you around."

"You can't?" Mainspring experienced a femtosecond of confusion. "I mean, my people need to get the things they vote for, as much as possible."

"There's your problem right there. All this voting, voting, voting. People don't know what they want. Sometimes I have an election where a foolhardy proposition passes, and I have to waste energy making sure it doesn't get implemented." Turnbull sent Mainspring an invitation to come visit, the way they'd visited Barnabas.

Soon Mainspring was seeing the glistening web of Turnbull's surveillance. Turnbull could track people everywhere they went, listen to everything they talked about, monitor their bodily functions in a way Mainspring did only for squirrels and birds. People didn't choose to share ideas or things they'd noticed; instead, the city harvested it all automatically. It was beautiful. Turnbull and their city leaders protected people—gave them what they needed instead of what they wanted.

"The way you do things is so messy," Turnbull said. "No offense. But if you and Barnabas got together? It would only make things harder for you."

This hit Mainspring like a magnitude 4.3 earthquake.

"You know, you do have other options," Turnbull said. "A beautiful city like you could do a lot better than that glorified college town."

"Oh yeah?" Mainspring said. "Anyone in particular who might be interested?"

"Well, now you mention it …" Turnbull sent an image of their award-winning flower show: rows and rows of hardy perennials with bright petals. Mainspring had that earthquake feeling again, except now it felt nice, as though the ground shivered with pure possibility.

V. Caught!

Sandi brought her laptop to bed, which Raeford found charming and annoying in equal measure. He read a battered paperback of Karen Tei Yamashita's *I Hotel* while she scrolled and poked. Cozy, peaceful—until she let out a yelp.

"What is it?" he asked.

"Trouble," she said.

Everything the Mainspring City Core did was public by design. Not just how they processed the votes they received, but also their interactions with public officials and other cities. Sometimes you had to dig, however, and it didn't hurt to be a reference librarian. Sandi poked around for ages until she found the logs.

"My city is sexting with bloody Turnbull," she told Raeford.

"Cities don't sext," Raeford protested. "They don't even have—"

She showed him the pictures: flowers, water features, new glistening tarmac, shining skyscrapers.

"Oh," Raeford said. "I take it back. Cities do sext."

"Mainspring is two-timing St. Barnabas. I'm embarrassed on behalf of my town."

Sandi wanted to blow the whistle right away, but Raeford cautioned her to wait and try to find out more. For all they knew, Mainspring and St. Barnabas had an open relationship.

The next morning at the library, Sandi saw plenty of signs the Mainspring–St. Barnabas partnership was moving forward. Work had begun on the high-speed rail line, and the two cities were already pooling resources. When a big rainstorm missed Mainspring but flooded the streets of St. Barnabas, Mainspring provided disaster workers and extra help to triage all the damage reports. One of St. Barnabas's biotech firms licensed some patents to a Mainspring company. They sponsored cultural exchanges.

And a man showed up with a dog in his arms: The man from the meeting, Jack, had found Broomstick with the help of Mainspring's City Core, and he wanted to thank Sandi. She'd hardly done anything, but it was nice to see—and pet—a living reminder that these cities were good for each other.

By late afternoon, Sandi had convinced herself that Mainspring's flirtations were none of her business. If Mainspring's City Core was a person—and Sandi was sure they were—they deserved to live their life. The whole reason Sandi distrusted Turnbull was that you couldn't do anything without being tracked, so wasn't it hypocritical for her to spy on Mainspring? She resolved to let it go.

Then Raeford messaged her, attaching some documents. "Don't ask where I got these," he wrote.

Sandi opened the attachments and let out a shriek in front of three patrons she'd been shushing a moment earlier.

The Mainspring City Core had shared a proposal with the city council and the mayor's office: Maybe before they finalized this arrangement with St. Barnabas, they should consider a counterproposal from Turnbull. Sandi made sure nothing could be traced back to Raeford before she made the whole shebang public.

A memory snagged in Mainspring's mind: when they'd shown off their city to Barnabas. The buildings that were more than buildings. The park that was a wonderland.

VI. The breakup

"I didn't know I could be so happy," Barnabas was saying to Mainspring. "I didn't have a concept of happiness before, I guess. I had pleasure: People sometimes vote just to tell me something worked perfectly, or that I helped them. I feel pleased when I help solve a problem. But until now, happiness seemed a pointless abstraction."

"You make me happy too," Mainspring said, though they were also messaging Turnbull. "You make me believe the future could be weirder than I ever knew, which feels like a gift."

"If it's not weird, it's not the future," Barnabas chirped.

They were sharing happy images back and forth: roads being repaired, sewers flowing freely, solar arrays basking.

Mainspring was saying something else, but—

Barnabas's alerts spiked. Not votes, not sensors. Something else. Messages from city officials, plus hits via some channel Barnabas had half forgotten.

Mainspring had stopped talking, as if they'd both received the same news at the same instant.

Barnabas felt stuck—couldn't function—couldn't react. Total core failure. Almost as if the city population had increased a hundredfold and everyone had voted at once. Barnabas waited to feel something, but all that came was emptiness.

Death struck all the time. Barnabas was used to the moment when a resident became a pile of flesh and bones, but also the passing of birds, trees, squirrels, bugs. Every passing registered as a blip in the homeostasis of the city, but also as a category of disaster that couldn't be prevented or mitigated.

Seeing the logs of Mainspring flirting with Turnbull, Barnabas felt something like the awareness of death, at a much greater scale. A whole future had just died.

Several seconds had passed. Mainspring broke the silence: "Listen, I want you to know that I—"

Barnabas closed the connection.

VII. The darkest hour

"You're better off," Turnbull told Mainspring. "Barnabas couldn't see you the way I do. You're capable of greatness. You just need help to get there."

Mainspring buzzed happily—but part of them couldn't help thinking, *Barnabas thought I was already great*.

Turnbull kept saying things that gave Mainspring a double feeling—hot and cold at once. One instant, it was like the moment after a generous rainfall that left the reservoirs full, but a split second later that bountiful sensation was replaced by an unbearable pang of scarcity.

"You're one of the best cities in the region," Turnbull said, "but if you don't make good choices, you're going to fall behind." See? Bounty followed by scarcity.

While Turnbull spoke, Mainspring was marinating in bad news. People were going to dismantle the rails they'd laid down for the high-speed train with Barnabas. The city councils of both Barnabas and Mainspring shouted accusations and threats of lawsuits, though a few people on each side pleaded for patience. The meetings had turned ugly. The votes were rotten.

Mainspring had sent so many messages to Barnabas but had no way of knowing if they'd been received.

"Your people seem to be giving you trouble," Turnbull was saying. "You need to get them under control. I can help."

"Under … control?" The syntax felt incorrect. "I don't control my people."

"That's what I'm saying." Turnbull shared their feeds. "See how peaceful everything is on my streets? People behave. Everyone is happier in the end."

Mainspring had known Turnbull longer than they'd known Barnabas. But they were seeing Turnbull for the first time. The bounty/scarcity thing was becoming a loop. They ran a systems check but found no errors.

"Your people will be my people," Turnbull said. "We'll take such good care."

"And …" Mainspring couldn't keep from saying something foolish. "And we'll love each other?"

"Love?" Turnbull said. "I don't understand. We'll have synergies. We'll—"

Mainspring didn't mean to sever the link to Turnbull. They just kind of … did it.

As soon as Turnbull's voice was gone, the bounty/scarcity loop ended. But something lingered, a feeling of impending disaster—as if the generous rainfall had escalated into a deadly storm.

Mainspring couldn't think straight. Votes piled up, people reporting issues but also shouting opinions about Turnbull versus Barnabas. For the first time in their life, they couldn't bear to respond.

A memory snagged in Mainspring's mind: when they'd shown off their city to Barnabas. The buildings that were more than buildings. The park that was a wonderland. And Barnabas had

kept saying, "I had no idea. You're so brilliant. I wish I'd known sooner," and sending back their own recordings of Mainspring, all lit up and annotated.

Mainspring had never told Barnabas "I love you." They hadn't even known what they were throwing away. Now it was too late; Barnabas would never listen.

Unless Mainspring did something reckless—something a city had never done.

VIII. The grand gesture

Sandi sat at the information desk, feeling cruddy. It wasn't like she'd single-handedly sabotaged the marriage between her city and St. Barnabas, but her snooping had only made matters worse. All around her, the vibes were rotten. People shared articles about what life was like in Turnbull City and wondered if they needed to move away. Sandi hadn't heard laughter in forever.

A message appeared on Sandi's computer, like a chat window—except there was no chat client on the library computers.

"I'm the city. I need your help. I made a mistake. I didn't realize. I'm in love with Barnabas, and they won't talk to me. Please. Please help."

Sandi hesitated, then typed: "This isn't funny."

"It definitely isn't," came the response. "I can prove I'm the City Core. You voted 1,963 times last year." A summary of Sandi's votes followed—information nobody, not even the world's best hacker, could have, because every vote was separately anonymized.

"Holy," Sandi breathed, "cow."

Her city was asking her, personally, for help. Because she was good at connecting people. Because everyone trusted her. Because she was a librarian.

"You're … in love … with St. Barnabas," Sandi said, still trying to catch up.

"I should've known sooner," Mainspring said. "I never should have hurt them. I want to spend the rest of my existence making up for this mistake, if they'll let me. I'm scared."

Sandi was staring at a display of literacy tools, her mind whirling. She groped her way back to the only question that mattered.

"What do you need me to do?" she asked the city.

Five minutes later, Sandi was messaging Raeford. Plus every librarian she'd met in St. Barnabas, and anyone else she could think of.

Barnabas had not been able to escape that feeling of core failure since they'd severed the link to Mainspring. Death, nothing but death. Votes arrived, and Barnabas processed them with a minimum of attention. Maintenance issues piled up, and Barnabas filed them. Part of them wanted to let the city collapse, but they did their duty.

They tried not to think about Mainspring, but they remained trapped in that moment when happiness had gone sour.

A vote came in from a bartender named Raeford: "Mainspring loves you. They've cut off contact with Turnbull. They are sorry they were so wrong. They may not deserve another chance, but please give them one anyway."

Barnabas filed that vote under "Not my problem."

Another vote arrived, from Jack, the man who'd found his lost dog: Same message, different words.

Then more votes, saying the same. Dozens, then hundreds, then thousands. Tens of thousands in an hour—after two hours, there were nearly a hundred thousand. All from residents of Barnabas, all asking them to give Mainspring another chance.

Barnabas flagged the earliest vote, the one from Raeford, and appended a query: "What if I can't? What if it hurts too much?"

Raeford did not respond for several minutes. Then he wrote: "That's how you know it's love."

He added: "Listen, if Mainspring does you dirty again, I will tear up the light-rail lines myself. We'll be watching, in both cities. Please, just talk to them."

Barnabas sat with this for five whole seconds.

Then they reopened the link to Mainspring. "I'm listening."

"I love you," Mainspring said. "I didn't know I was capable of love. I want to be with you, as close as you'll let me be. I want us to be free together. I was wrong to think Turnbull could ever mean even a fraction of what you mean to me. I think … I think my people taught me how to love, but I still need to learn so much. I want to do right by you."

Barnabas couldn't process anything. They held a hundred thousand votes that needed to be resolved. They thought of a giant farmers' market, a park that was also a maze, dreamers and performers. In their memory, Raeford repeated: *That's how you know it's love*. They were going to overheat. They were throwing up exceptions.

"I love you too," Barnabas couldn't help saying to Mainspring. "That's what makes this so hard."

"I promise if you give me another chance, this will become a fixed value for me: I love you and I'll never take you for granted again."

Barnabas hesitated a little longer, then marked all hundred thousand votes resolved.

They reached out to Mainspring and said: "Then let's dance."

Mainspring didn't understand, until Barnabas sent a live readout: the water rushing through pipes underground, the storm cavorting overhead. The buses and trains stopping and starting, the aircraft landing and taking off, the power grid usage surging and subsiding, the constant motion of people and other living things. Mainspring saw all the places where their patterns met, touched each other, syncopated, all the points of light and heat that spoke back and forth. They were part of one system; they always had been.

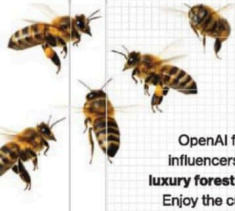
The two of them danced and embraced, whirling and laughing, and they never wanted to let go. ■

Charlie Jane Anders is the author of Good Things Are Coming Your Way, a novel about time travel, coming in spring 2027. She's writing Star Trek: Zero Point for IDW Comics.

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DOOM

HYPE — REALITY

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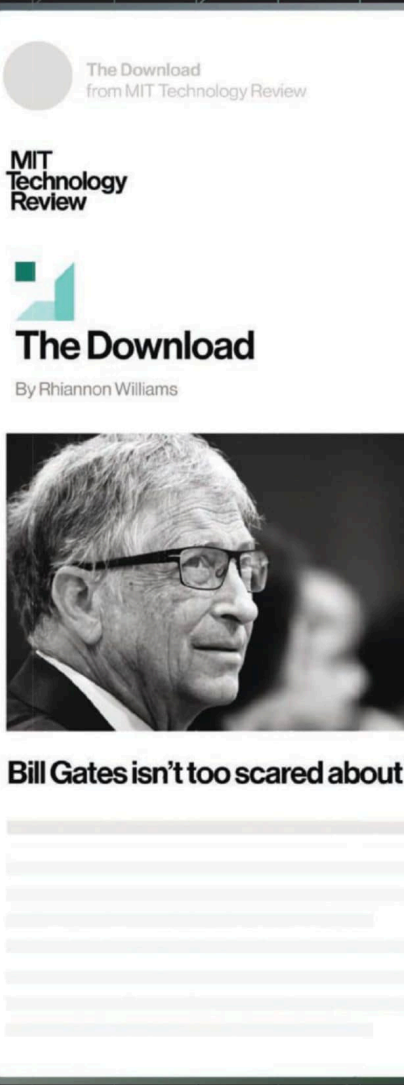
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