MIT Technology Review

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I think we are going to
drive the cost of
intelligence
down to so close to
zero
that it will be this
before-and-after
transformation
for society.”

– Sam Altman, CEO, OpenAI

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One of the formative memories of my youth took place on a camping trip at an Alabama state park. My dad's friend brought an at-the-time gee-whiz gadget, a portable television, and we used it to watch the very first space shuttle launch from under the loblolly pines. It was thrilling. And it was hard not to believe, watching that shuttle go up (and, a few days later, land), that we were entering an era when travel into the near reaches of space would become common.

But as it turns out, that's not the future we built.

This is our Build issue, and although it's certainly about creating the future we want, in many ways this issue is also about a future that never arrived. Interplanetary space stations. Friendly robots. Even (if you squint and accept a generous definition) terraforming an increasingly uninhabitable Earth.

Building is a popular tech industry motif—especially in Silicon Valley, where "Time to build" has become something of a call to arms following an influential essay by Marc Andreessen that lamented America's seeming inability to build just about anything. That essay was published four years ago, at the apex of the country's disastrous response to covid-19, when masks, PPE, and even hospital beds were in short supply. (As were basic necessities of day-to-day life like eggs, flour, and toilet paper.) It's an alluring argument.

Yet the future is built brick by brick from the imperfect decisions we make in the present. We don't often recognize that the seeming steps forward we are taking today could be seen as steps back in the years to come. This could very well be how we come to view some of the efforts we are making in terms of climate remediation. On page 34, Xander Peters (accompanied by some incredible photography from Virginia Hanusik) writes about Louisiana's attempts to protect communities against increased flooding—and wonders if perhaps a managed retreat might not be the better course of action.

Sometimes the things we don't do, or the steps we skip, have bigger implications than the actions we do take. For the space program, the decision to race to the moon rather than to first build a way station—as was originally envisioned by some of the pioneers of space travel—may have had the long-term effect of keeping us more earthbound than we might otherwise be. On page 44, David W. Brown looks at the fallout of those skipped steps and recounts the race to build a new, privately operated space station before the International Space Station comes plummeting back to Earth around 2030.

Other times, we're just held back because we haven't figured out how to do things yet. Simply put: the tech just isn't quite there. For our cover story on home robots (page 26), Melissa Heikkilä looks at how the intersection of robotics and artificial intelligence, and especially large language models, could at last be ushering in the era of helper robots that we've been dreaming of since the days of *The Jetsons*. It's such a fertile area of development, with action from both big industry incumbents like Google and highly specialized, sometimes secretive startups, that there is far more than we could get into in a single story.

ROBYN KESSLER

Mat Honan is editor in chief of MIT Technology Review.

"There was an entire interview with Meta that I didn't end up using," Melissa told me. "They have a team working on 'embodied AI,' which believes that true general intelligence needs a physical element to it, such as robots or glasses. They've built an entire mock apartment in one of their offices, including a full-size living room, kitchen, dining room, and so on, in which they conduct experiments with robots and virtual reality. It's pretty cool!"

Look for us to keep that reporting going at technologyreview.com.

And there's much more, too—including a zinger of a story from Annalee Newitz that takes on the history of brainwashing, a feature on building accountability into police body cameras, and a wild report on designing vegan cheese with generative AI. We hope you find something to take away and build on.

Thanks for reading,

Mat Honan

We unplugged a mainframe to plug in digital excellence into banking operations.

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Infosys cobalt

"All of a sudden, Henry turns to me and says, **'Why can't that robot be an extension of my body?'"**
–p. 26

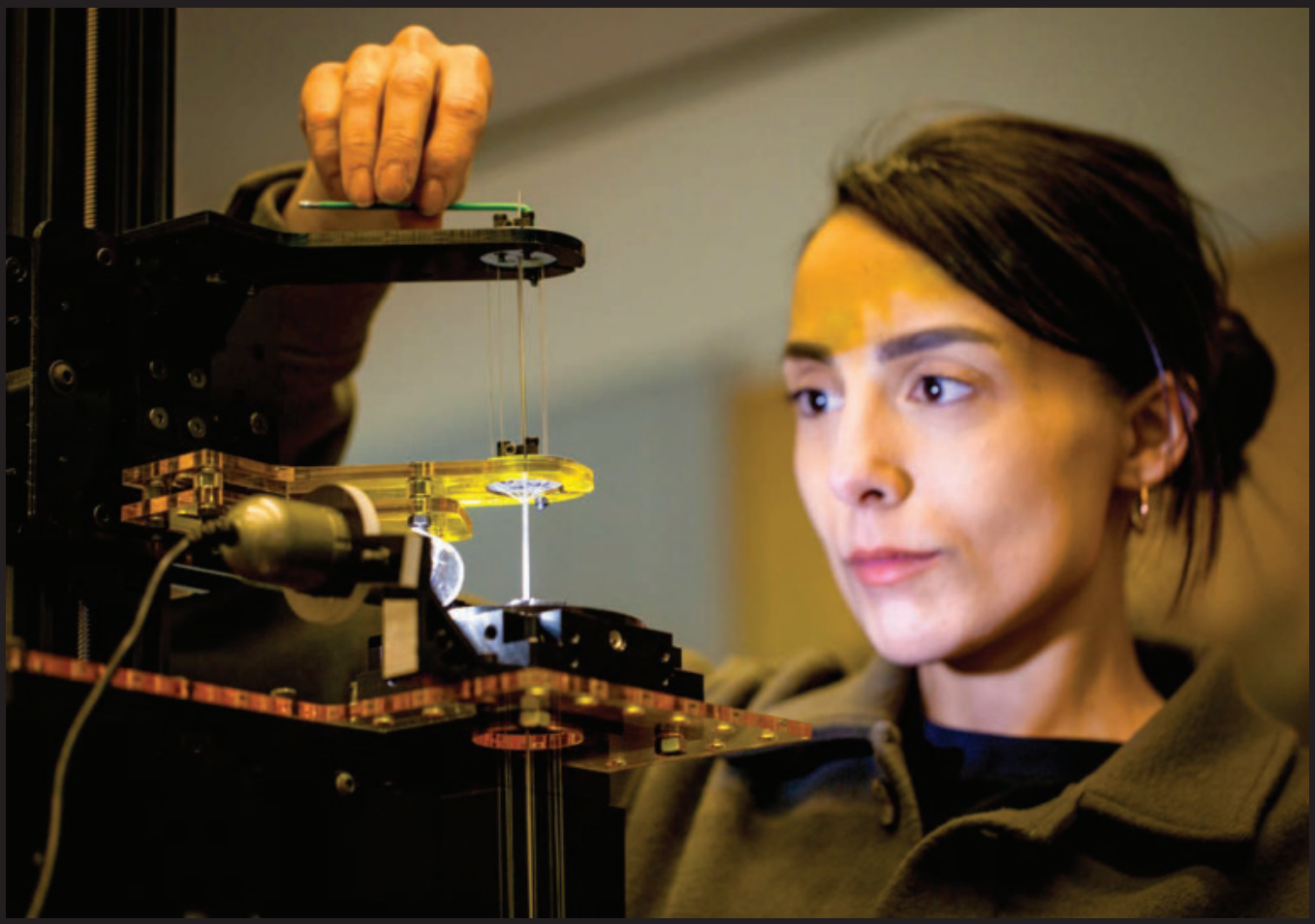
Front

ON THE COVER
Illustration by R. Kikuo Johnson

Build

Back

Imagine what we can become.



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Corrections to our March/April 2024 issue:

The article "A journey to the edge of particle physics" misstates how long particle physicists have been using machine learning. It has been since the early 1990s.

The article "Europa ho!" misstates that Europa receives one-fifth as much sunlight as Earth. The amount is less than 5%.

The article "Revealing a river" misspells the name of the founder of Viaje al Microcosmos, Lizeth Ovalle. We regret the errors.

The Download

Designing cheese with AI

Machine learning can help formulate novel foods, like vegan brie that's actually delicious.

By Andrew Rosenblum

As Climax Foods CEO Oliver Zahn serves up a plate of vegan brie, feta, and blue cheese in his offices in Emeryville, California, I'm keeping my expectations modest. Most vegan cheese falls into an edible uncanny valley full of discomforting not-quite-right versions of the real thing. But the brie I taste today is smooth, rich, and velvety—and delicious. I could easily believe it was made from cow's milk, but it is made entirely from plants. And it couldn't have come into existence, says Zahn, without the use of machine learning.

Climax Foods is one of several startups, also including Shiru of Alameda, California, and NotCo of Chile, that have used artificial intelligence to design plant-based foods. The companies train algorithms on datasets of ingredients with desirable traits like flavor, scent, or stretchability. Then they use AI to comb troves of data to develop new combinations of those ingredients that perform similarly.

"Traditional ingredient discovery can take years and tens of millions of dollars, and what results are ingredients only incrementally better than the previous generation," says Shiru CEO Jasmin Hume, who wrote her PhD thesis on protein engineering. "[Now] we can go from scratch, meaning what nature has to offer; pick out the proteins that will function best; and prototype and test them in about three months."

Not everyone in the industry is bullish about AI-assisted ingredient discovery. Jonathan McIntyre, a food consultant who formerly headed R&D teams in both beverages and snacks at ▸

JOHN F. MALTA

Pepsi, thinks the technology is "significantly" overhyped as a tool for his field. "AI is only as good as the data you feed it," he says. And given how jealously food companies guard formulas and proprietary information, he adds, there won't necessarily be sufficient data to yield productive results. McIntyre has a cautionary tale: during his stint at Pepsi, the company attempted to use IBM's Watson to create a better soda. "It formulated the worst-tasting thing ever," he says.

Climax Foods circumvented the data scarcity problem by creating its own training sets to essentially reverse-engineer why cheese tastes so good. "When we started, there was very little data on why an animal product tastes the way it does—animal cheddar, blue, brie, mozzarella—because it is what it is," says Zahn, who was most recently head of data science at Google. "There [was] no commercial reason to understand it."

In the food science lab on the ground floor of the Climax offices, on the site of an old chocolate factory, Zahn shows off some of the instruments his team used to build its data trove. There's a machine that uses ion chromatography to show the precise balance of different acids after bacterial strains break down lactose. A mass spectrometer acts like an "electronic nose" to reveal which volatile compounds generate our olfactory response to food. A device called a rheometer tracks how a cheese responds to physical deformation; part of our response to cheese is based on how it reacts to slicing or chewing. The cheese data creates target baselines of performance that an AI can try to reach with different combinations of plant ingredients.

Using educated guesswork about which plants might perform well as substitutes, Climax food scientists have created more than 5,000 cheese prototypes in the past four years. With the same lab instruments employed on animal cheese, the Climax team performs an analysis that includes roughly 50 different assays for texture and flavor, generating millions of data points in the process. The AI is trained on these prototypes, and the algorithm then suggests mixtures that might perform even better. The team tries them out and keeps iterating. "You vary all

Ready, set, grow: These are the biotech plants you can buy now

For $73, I bought genetically modified tomato seeds and a glowing petunia.

By Antonio Regalado

This spring I am looking forward to growing some biotech in my backyard for the first time. It's possible because of startups that have started selling genetically engineered plants directly to consumers, including a bright-purple tomato and a petunia that glows in the dark. So this past February, for $73, I ordered both by pressing a few buttons online.

Biotech seeds have been a huge business for a while. In fact, by sheer mass, GMOs are probably the most significant product of genetic engineering ever. Except most of us aren't planting cotton or corn that can resist worms or survive a spritz of Roundup, the big gene-splicing innovations that companies like Monsanto and Pioneer Hi-Bred introduced in the 1990s.

Purple tomatoes developed by Norfolk Healthy Produce.

the input knobs, you measure the outputs, and then you try to squeeze the difference between the output and your animal target to be as small as possible," Zahn says. Including small-scale "micro-prototypes," he estimates, Climax has analyzed roughly 100,000 plant ingredient combinations.

Tasting and subtly adjusting the ingredient blends in so many prototypes by hand would take several thousand years, Zahn says. But starting from zero in early 2020, he and his AI-aided team were able to formulate their first cheese and bring it to market in April 2023.

The plant constituents of that product, a vegan blue cheese, are hardly exotic. The top four ingredients are pumpkin seeds, coconut oil, lima beans, and hemp protein powder. And yet Dominique Crenn, a Michelin-starred chef, described it as "soft, buttery, and surprisingly rich—beyond imagination for a vegan cheese."

Bel Group, the maker of Laughing Cow, has an agreement to license the company's products, and a second large producer that Zahn cannot yet publicly name has also signed on. He is currently beating the venture capital bushes for a funding round and hopes to begin selling the brie and feta later this year.

Unlike Watson's ill-fated attempt to formulate a better Pepsi, the Climax algorithms can pull together ingredients in new ways that seem like alchemy. "There is an interaction of one component with another component that triggers a flavor or sensation that you didn't expect," Zahn says. "It's not like just the sum of the two components—it's something completely different."

One reason to develop alternatives to dairy-based cheese is its environmental cost: by weight, cheese has a higher carbon footprint than either chicken or pork, and humans eat roughly 22 million tons of it each year. For Zahn, the answer is not asking consumers to settle for a rubbery, bland substitute—but offering a plant-based version that tastes as good or better and could cost much less to make. ■

Andrew Rosenblum's writing has appeared in New Scientist*,* Popular Science*,* Wired*, and many other places.*

COURTESY OF NORFOLK HEALTH PRODUCE

What makes these new plants different is that you can buy them directly from their creators and then plant them in the yard, on a balcony, or just in a pot.

Purple tomato

Starting off my biotech shopping spree, I first spent $20 to order 10 tomato seeds from Norfolk Healthy Produce, a small company in Davis, California, that created what it calls the Purple Tomato. The seeds have a gene introduced from a snapdragon flower, which adds a nutrient, anthocyanin, that also gives the fruits their striking color.

According to Channa S. Prakash, a geneticist and dean at Tuskegee University, the tomato is "the first-of-its-kind GMO food crop marketed directly to home gardeners."

The CEO of the company, Nathan Pumplin, was packing seeds when I reached him by phone. He claimed that anthocyanin has health benefits—it's an antioxidant—but he agreed that the color is a useful sales pitch.

"I don't need to make a label that says this red tomato is better for you than the other red tomato," says Pumplin. "We can simply put out the purple tomato, and people say, 'Oh my gosh, this tomato is purple.' Its beauty is a distinguishing characteristic that people can just immediately see and understand."

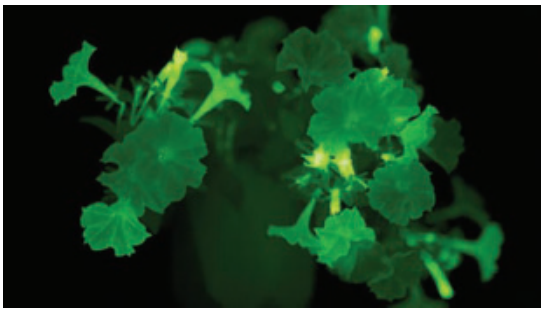
There is a plan to mass-produce the purple tomatoes for sale in supermarkets. But Pumplin says the company couldn't ignore thousands of requests from regular gardeners. "It's not the main focus of our business, but we are very interested in having people grow these at home," he says. And "if home gardeners want to save the seed and replant it in their gardens for their own use, that is okay."

Glowing flower

I next decided to shell out for the "firefly petunia," so called because the plant is supposed to glow in the dark. It's sold by Light Bio, a startup backed by the venture capital firm NFX. The plant is such a novelty that it was being sold in a preorder, with promises they would arrive by May. One petunia plant costs $29 plus $24 for shipping. The company's marketing promises that your plant will unveil "mesmerizing luminescence after dusk" and that "its soothing light is produced from living energy, cultivating a deeper connection with the inner life of the plant."

It joins a short list of ornamental plants with gene modifications. Another is an orange petunia, approved in the US in 2021, that got its unusual color from a corn gene. (When some copies got loose prior to approval, officials in the US and Europe demanded its eradication in what became known as "the petunia carnage.")

Karen Sarkisyan, a synthetic biologist at the MRC Laboratory of Medical Sciences in the UK, is one of the petunia's creators, and also the chief scientist of Light Bio. His lab is interested in using bioluminescence as a reporter system—a plant could reveal, for instance, how it responds to a toxin or viral infection in lab experiments. "In general, we're trying to make ▸



Light Bio's firefly petunia.

useful things, so this is more of an exception," he says of the firefly petunia. "The motivation was more about merging biology and art, rather than utility."

Like a lot of things in biotech, making a glowing petunia was not easy to do—it's the seemingly sudden result of decades of research into the chemistry that permits certain plants and animals to glow faintly.

Imposing those genetic circuits on plants did not work too well at first. Several years ago, for instance, a Kickstarter project that raised nearly $500,000 to make glowing roses failed to deliver on its promises after the project proved too difficult. "It was fairly obvious … that there was no good technology at that time," says Sarkisyan, who later played a role in discovering genes from a glowing fungus which, after being added to a petunia, made it shine brightly enough to work as a novelty item.

That work continues. Sarkisyan says the company is working on "increasing the brightness and making more colors." It's also working on making other types of plants glow, although which ones remains a secret. "I cannot really comment on specific species we're working on," he says, although he did show me a photo of a spectacular glowing chrysanthemum.

Sarkisyan told me he sometimes likes to have a meditative experience among the glowing plants. Ironically, he can only do that in the lab and not at home, since he lives in the UK. The country, which takes a strict view on GMOs, has not approved the plants for sale (neither has Europe).

But he thinks the petunia could win over critics. "Especially with all the talk and concerns about the GM stuff, this is the first time there can be a safe, friendly, pleasant GM houseplant in every home," he says. "We think it's a very interesting project because it is one of the first in consumer biotech. I do think we will see more and more in the future." ■

Antonio Regalado is the senior editor for biomedicine at MIT Technology Review.

I used generative AI to turn my story into a comic—and you can too

By pulling together several different generative models into an easy-to-use package controlled with the push of a button, Lore Machine heralds the arrival of one-click AI.

By Will Douglas Heaven

Thirteen years ago, as an assignment for a journalism class, I wrote a stupid short story about a man who eats luxury cat food. This morning, I sat and watched as a generative AI platform called Lore Machine brought my words to life.

I fed my story into a text box and got this message: "We are identifying scenes, locations, and characters as well as vibes. This process can take up to 2 minutes." Lore Machine analyzed the text, extracted descriptions of the characters and locations mentioned, and then handed those bits of information off to an image generation model. An illustrated storyboard popped up on the screen. As I clicked through vivid comic-book renderings of my half-forgotten characters, my heart was pounding.

After more than a year in development, Lore Machine is now available to the public for the first time. For $10 a month, you can upload 100,000 words of text (up to 30,000 words at a time) and generate 80 images for short stories, scripts, podcast transcripts, and more. There are price points for power users too, including an enterprise plan costing $160 a month that covers 2.24 million words and 1,792 images. The illustrations come in a range of preset styles, from manga to watercolor to pulp '80s TV show.

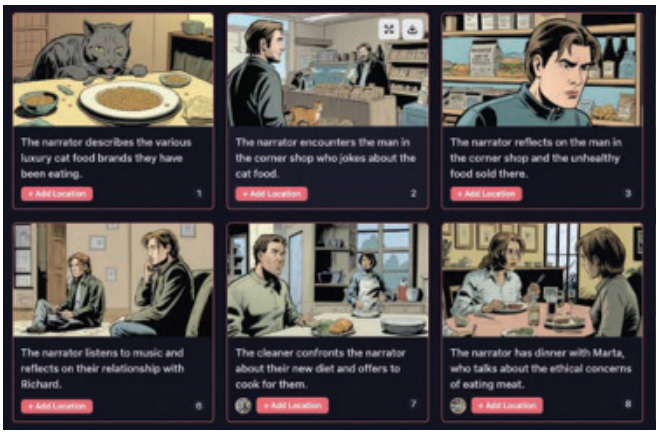
Zac Ryder, founder of the creative agency Modern Arts, has been using an early-access version of the tool since Lore Machine founder Thobey Campion first showed him what it could do. Ryder sent over a script for a short film, and Campion used Lore Machine to turn it into a 16-page graphic novel overnight.

"I remember Thobey sharing his screen. All of us were just completely floored," says Ryder. "It wasn't so much the image generation aspect of it. It was the level of the storytelling. From the flow of the narrative to the emotion of the characters, it was spot on right out of the gate."

Modern Arts is now using Lore Machine to develop a fictional universe for a manga series based on text written by the creator of Netflix's *Love, Death & Robots*.

Under the hood, Lore Machine is built from familiar parts. A large language model scans your text, identifying descriptions of people and places as well as its overall sentiment. A version of

COURTESY OF LIGHT BIO



Stable Diffusion generates the images. What sets it apart is how easy it is to use. Between uploading my story and downloading its storyboard, I clicked maybe half a dozen times.

That makes it one of a new wave of user-friendly tools that hide the stunning power of generative models behind a one-click web interface. "It's a lot of work to stay current with new AI tools, and the interface and workflow for each tool is different," says Ben Palmer, CEO of the New Computer Corporation, a content creation firm. "Using a mega-tool with one consistent UI is very compelling. I feel like this is where the industry will land."

Look! No prompts!

Campion set up the company behind Lore Machine two years ago to work on a blockchain version of Wikipedia. But when he saw how people took to generative models, he switched direction. Campion used the free-to-use text-to-image model Midjourney to make a comic-book version of Samuel Taylor Coleridge's *The Rime of the Ancient Mariner*. It went viral, he says, but it was no fun to make.

"My wife hated that project," says Campion. "I was up to four in the morning, every night, just hammering away, trying to get these images right." The problem was that text-to-image models like Midjourney generate images one by one. That makes it hard to maintain consistency between different images of the same characters. Even locking in a specific style across multiple images can be hard. "I ended up veering toward a trippier, abstract expression," he says.

The experience made him see that this tech needed to be a lot easier to use. Campion won't say exactly how Lore Machine manages to keep its images and style consistent across a series of illustrations. It's pretty good, but not perfect: in one scene from my story a short-haired character has grown bangs; in another, the same character appears twice.

The illustrations can start to feel generic, too. I was disappointed that my descriptions of one character as having "teeth like pinto beans" and another as having "hands like slices of bleached white bread" didn't translate to their portraits. But compared with doing this by hand, prompt by prompt, Lore Machine is a huge step up.

"The consistency is great," says Ryder. It's given Modern Arts the confidence to use Lore Machine in a project with one of its clients. "Had we constantly needed to go back and fix consistency issues, there's no way we would have been able to deliver on time," he says.

Like all generative models, the tech behind Lore Machine will spit out toxic content on demand. Campion says they have stopped it from generating images depicting violence or hateful stereotypes. But otherwise, he is unwilling to curb artists' creative expression. Generating illustrations for celebrity fan fiction is fair game, for example.

Much of the initial interest in Lore Machine has come from marketing agencies. But Campion hopes the public release will encourage a wider range of users to try it out. Six months ago, he says, he got a call from the principal of a school in Manhattan for kids with learning disabilities. The principal wanted to run his textbooks through the tool so that his kids could have images to look at. "I hadn't even thought of that," says Campion. "I was too stuck in a Hollywood mindset." ■

Will Douglas Heaven is senior editor of AI at MIT Technology Review.

The narrator encounters the man in the corner shop who jokes about the cat food.

The narrator sits on the floor and eats breakfast with the cats.

LORE MACHINE/WILL DOUGLAS HEAVEN

Beautiful data: FAA aviation maps

In all the visual information published by the US government, there may be no product with a higher information density than the Federal Aviation Administration's maps for pilots.

By Jon Keegan

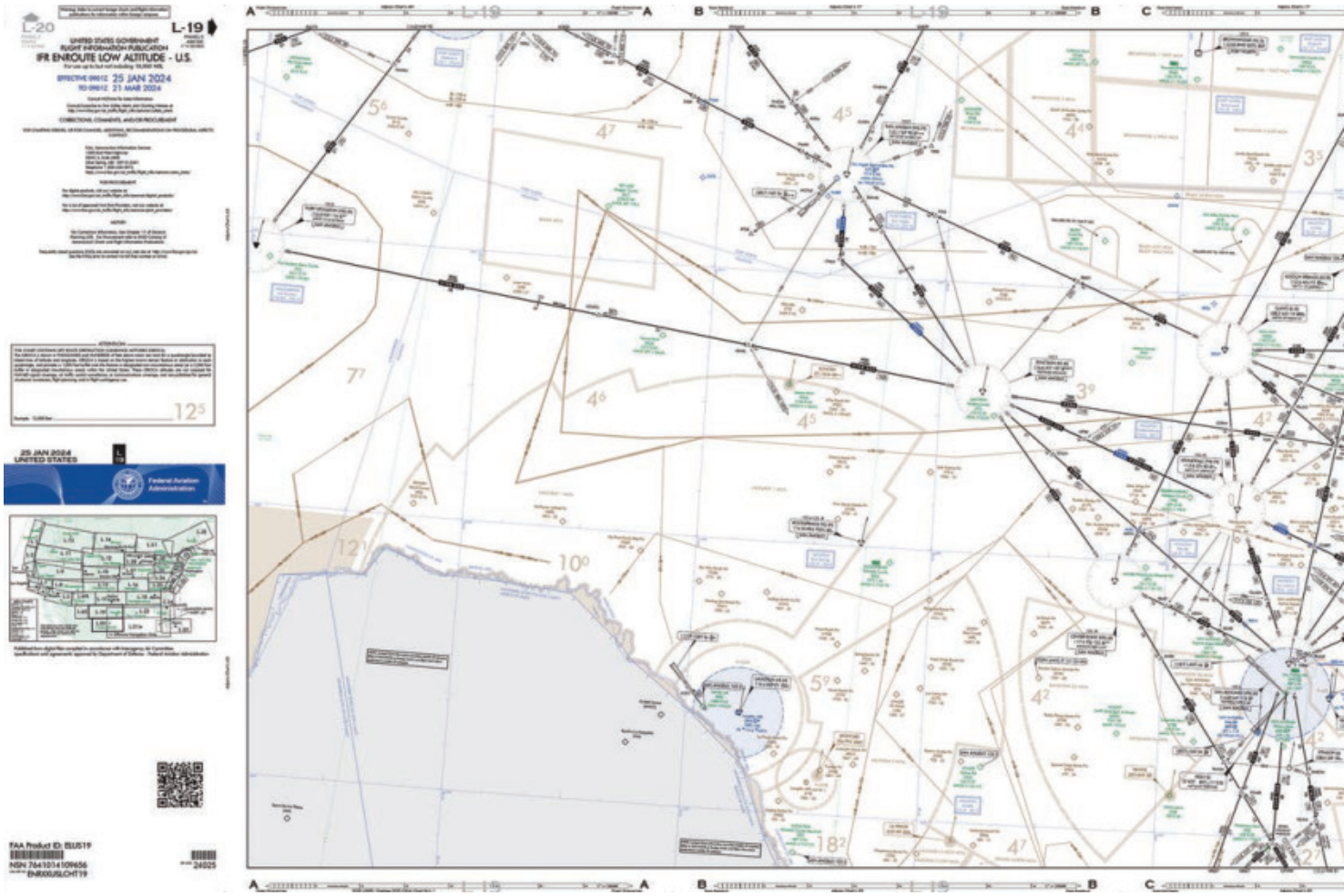
A detail of a low-altitude IFR map for the Houston area. Source: FAA.

The FAA publishes free detailed maps—or, as pilots prefer, "charts"—covering the entirety of the US airspace. The density of the critical information layered on these maps is staggering, yet pilots can decipher them at a glance.

There are several categories of aviation maps that the FAA makes available.

Terminal Procedures Publications

The Terminal Procedures Publications (TPP) offer instructions for arriving at or departing airports large and small across the US. These maps are published in 25 regional editions. The complete set is published every 56 days, and digital versions are updated every 28 days. Because they are meant to give pilots the most relevant information about the airport they are navigating to, they are mostly black and white. Detailed diagrams of each airport, along with adjacent geographical features such as lakes and rivers, runways, and nearby navigational waypoints, help pilots set their radios to the correct frequency, approach from the right direction, and take off and land along safe flight paths.



VFR vs. IFR

Visual flight rules (VFR) apply when conditions are clear and the pilot can see features on the ground. For this type of flying, the FAA's colorful and information-dense VFR maps can be used to locate important ground features as well as special airspace zones with flight restrictions. These zones include military training areas and sensitive sites related to national security, such as the area surrounding Camp David, the presidential retreat in Maryland. VFR maps have a base layer of natural features such as rivers, lakes, and mountains and include potential obstacles such as stadiums, windmills, and power lines. For each airport, the name, the orientation of the runways, and the control towers' radio frequencies are noted.

When conditions obscure features on the ground, pilots must instead follow instrument flight rules (IFR). While the VFR maps emphasize the visible features on the ground, IFR maps place the focus on radio navigation. Unlike the colorful VFR maps, these maps have less background information, containing mostly white space so that important ground-based radio beacons and navigation waypoints are clearly legible without any distractions.

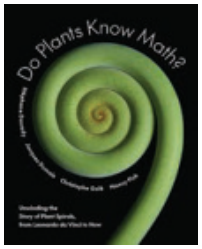
Those waypoints, which represent points of latitude and longitude, are a notable detail of the IFR maps, serving as invisible signposts allowing flights to follow a point-to-point path. The points have five-letter names that are meant to be understood when spoken over noisy radio transmissions.

Waypoints' names are created with input from each airport's ground controllers, and they are quite colorful. Atlanta's Hartsfield-Jackson International has *Lord of the Rings*–themed waypoints: HOBTT, FRDDO, BLLBO, and GNDLF. The skies around this airport are also filled with several *Star Wars* waypoints: SKWKR, JJEDI, CHWEE, and XWNNG.

In 2016, the FAA renamed some Florida waypoints that were named after a popular TV show personality but had become controversial. The waypoints were DONLD, TRMMP, and UFIRD. ■

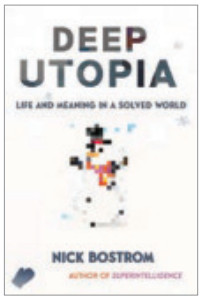
A version of this story appeared in Beautiful Public Data *(beautifulpublicdata.com), a newsletter curated by Jon Keegan.*

Book reviews



Do Plants Know Math? Unwinding the Story of Plant Spirals, from Leonardo da Vinci to Now
By Stéphane Douady, et al. (Princeton University Press, 2024)

Charles Darwin was driven to distraction by plant spirals, growing so exasperated that he once begged a friend to explain the mystery "if you wish to save me from a miserable death." Leonardo da Vinci and Alan Turing, among others, shared his obsession. This book shows how the beauty of both math and plants unfurls before our very eyes.



Deep Utopia: Life and Meaning in a Solved World
By Nick Bostrom (IdeaPress, 2024)

What does the director of the Future of Humanity Institute have to say about the future of artificial intelligence? Nick Bostrom, a philosopher, wonders here what the outcome might be if we develop superintelligence safely, govern it well, and make good use of it.

Frostbite: How Refrigeration Changed Our Food, Our Planet, and Ourselves By Nicola Twilley (Penguin, 2024)

The introduction of artificial refrigeration, argues *New Yorker* contributor Nicola Twilley, overturned millennia of dietary history, launching a new chapter in human nutrition. The ability to better preserve food has had its benefits, to be sure, but the costs are catching up to us, she argues. Refrigeration is a major contributor to climate change; it's also redefined what "fresh" means. (Tomatoes in January? Don't do it.)

Jobs of the future: AI prompt engineer

This increasingly ubiquitous role helps to guide generative artificial intelligence.

By Charlie Metcalfe

The role of AI prompt engineer attracted attention for its high-six-figure salaries when it emerged in early 2023. Companies define it in different ways, but its principal aim is to help a company integrate AI into its operations.

Danai Myrtzani of Sleed, a digital marketing agency in Greece, describes herself as more prompter than engineer. She joined the company in March 2023 as one of two experts on its new experimental-AI team.

Go-to AI experts: Since joining Sleed, Myrtzani has helped develop a tool that generates personalized LinkedIn posts for clients. The tool works with OpenAI's ChatGPT platform, which automates the writing process using sets of built-in prompts. Myrtzani's job is to ensure that users get the results they are looking for. She also teaches other employees how to use generative AI tools, hosts workshops, and writes an internal newsletter dedicated to AI. Her employers "want pretty much everyone to be able to use AI," she says, because these tools have the potential to automate trivial tasks, making more time for work that requires creative thinking. She refers to her department as "the support team for AI."

An education in language: Myrtzani came to Sleed with experience experimenting with generative AI tools as well as a university education in social anthropology. Those studies gave her an expertise in human language systems that the company thought would be especially valuable in the job. "The more qualified you are at using language, the easier it is to create prompts," she says.

More than prompt writers: Many writers have been concerned that generative AI could make their jobs obsolete. Prompt engineers are especially vulnerable: demand for their services could disappear if the software becomes better at understanding users' prompts. But Myrtzani says her own position demands much more than just prompt writing, including identifying and integrating AI-based solutions for business challenges. "The higher tiers of prompt engineering are where the enduring and evolving aspects of the role lie," she says. ■

COURTESY OF THE PUBLISHERS; COURTESY OF DANAI MYRTZANI

Op-Ed

The coming materials transformation

What's possible in a world powered by clean, abundant renewable energy.

By Deb Chachra

In 1856, Napoleon III commissioned a baby rattle for his newborn son, to be made from one of the most precious metals known at the time: light, silvery, and corrosion-resistant aluminum. Despite its abundance—it's the third most common element in Earth's crust—the metal wasn't isolated until 1824, and the complexity and cost of the process made the rattle a gift fit for a prince. It wasn't until 1886 that two young researchers, on opposite sides of the Atlantic, developed the method that is still used for refining aluminum commercially. The Hall-Héroult process is extraordinarily energy intensive: the chemically modified ore is dissolved into a high-temperature bath of molten minerals, and an electrical current is passed through it to separate the metallic aluminum. It's also *intrinsically* energy intensive: part of the reason the metal was isolated only relatively recently is because aluminum atoms bind so tightly to oxygen. No amount of clever engineering will change that physical reality. The astronomical growth in worldwide aluminum production over the last century was made possible by the build-out of the energy infrastructure necessary to power commercial refineries, and to do so in a way that was economically viable. In the US, that was facilitated by the massive hydroelectricity projects built by the federal government as part of Franklin D. Roosevelt's New Deal, closely followed by World War II and the immense mobilization of resources it entailed: aluminum was the material of choice for the thousands and thousands of aircraft that rolled off wartime assembly lines as fast as others were shot down. Within a century, the metal went from precious and rare to ubiquitous and literally disposable.

Just as much as technological breakthroughs, it's that availability of energy that has shaped our material world. The exponential rise in fossil-fuel usage over the past century and a half has powered novel, energy-intensive modes of extracting, processing, and consuming matter, at unprecedented scale. But now, the cumulative environmental, health, and social impacts—in economics terms, the negative externalities—of this approach have become unignorable. We can see them nearly everywhere we look, from the health effects of living near highways or oil refineries to the ever-growing issue of plastic, textile, and electronic waste.

We're accustomed to thinking about the energy transition as a way of solving the environmental problem of climate change. We need energy to meet human needs—for protection from the elements (whether as warmth or cooling), fuel for cooking, artificial light, social needs like mobility and communication, and more. Decarbonizing our energy systems means meeting these needs without burning fossil fuels and releasing greenhouse gases into the atmosphere. Largely as a result of public investment in clean-energy research and development, a world powered by electricity from abundant, renewable, nonpolluting sources is now within reach.

What is much less appreciated is that this shift also has the potential to power a transformation in our relationship with matter and materials, enabling us to address the environmental problem of pollution and waste. That won't happen by accident, any more than the growth of these industries in the 20th century was an accident. In order to reach this future, we need to understand, research, invest in, and build it. Every joule of electricity that comes from fossil fuels means paying for what's burned to produce it. In fact, because of the inefficiency of thermal generation, it means paying for many more joules of heat.

Just as much as technological breakthroughs, it's the availability of energy that has shaped our material world.

Energy generation from renewable sources has capital and operating costs, of course, but minimal, incremental ones. That's because the input energy arrives as wind or sunlight, not as boxcars of coal. In the big picture, this means that in a fully decarbonized

world, all energy will be closer to hydroelectricity in its economics: while it may never quite be "too cheap to meter," it may indeed be too cheap to reliably generate a profit on an open energy market. This is a problem for investor-owned energy infrastructure, but it's potentially transformative for community-owned systems (including public utilities, nonprofit electricity cooperatives, or local microgrids), where cheaper and more abundant energy can power a just transition and a new economy.

Twentieth-century investments in energy infrastructure, like the New Deal's Rural Electrification Act of 1936 and its counterparts worldwide, formed the basis for the global industrial economy. If we can achieve a similar scale of commitment to renewable energy—prioritizing abundance and access over profit—it will lead to another jump in what's possible in the material world, where what was previously unthinkably expensive becomes quotidian reality. For example, just like refining aluminum, desalinating seawater is intrinsically energy intensive. But in a world with cheap, clean electricity, residents of coastal cities could get a reliable supply of drinking water from oceanside water treatment plants instead of contested freshwater sources.

Desalination is not the only energy-intensive process that would become viable. Aluminum, glass, and steel are among the most recycled materials in part because so much energy is needed to make them from their raw precursors that recovery is economically worthwhile. In contrast, plastics—in their near infinite variety—don't lend themselves to mechanical recycling except in a handful of cases. Effectively recycling plastics means breaking them down into their chemical building blocks, ready to be put together into new forms. And since most plastics will burn to produce heat, going in the opposite direction—reassembling those carbon atoms into new plastics—requires a significant input of energy. It's always been easier, cheaper, and more profitable to just dump the waste into landfills and make new plastics out of freshly extracted oil and gas. But if the energy came from inexpensive renewables, the whole economic equation of making plastics could change. Carbon dioxide could be pulled from the air and transformed into useful polymers using energy from the sun, with the waste plastic decomposed into raw materials so the process could begin again.

If this sounds familiar, it's because it's how plants work. But, just like Hall and Héroult's breakthrough for aluminum, new processes would require both energy and technological innovation. Decades of research have gone into creating new kinds of plastics from fossil fuels, and only a proportionally tiny amount into what happens to those plastics at the end of their lives. But now numerous companies, including Twelve, are building on new research to do just this kind of transformation, using renewably sourced energy to turn water and atmospheric carbon dioxide back into hydrocarbons, in the form of fuel and materials.

Prioritizing abundance and access over profit will lead to another jump in what's possible.

Finally, it's not just about plastic. If we succeed in building a world of even cheaper and more abundant energy but we again use it to supercharge extraction, consumption, and disposal, then we might "solve" the pressing crisis around energy while worsening the multiple environmental crises posed by pollution. Instead, we can think about community-led investments in energy infrastructure as spinning up a new industrial system in which clean, inexpensive renewable energy makes it possible to recover a broad range of materials. That would cut out the enormous costs of primary extraction and disposal, including environmental depredation and geopolitical conflict.

Building momentum as fast as we can will limit the materials bill for the huge changes that decarbonization will entail, like replacing combustion-powered vehicles with their electric equivalents. This is already happening with companies like Ascend Elements, currently building a facility in Hopkinsville, Kentucky, to produce materials for new batteries from recycled lithium batteries. It's financed by more than half a billion dollars of recent private investment that builds on $480 million in Department of Energy grants, and the work is based on fundamental research that was supported by the National Science Foundation. As more and more clean, renewable energy comes online, we need to continue with policies that support research and development on the new technologies required to recover all kinds of materials—together with regulations that account for the true costs of extraction and disposal. This will facilitate not just an energy transition but also a *matter* transition, ensuring that the industrial sector aligns with the health of our planet. ■

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Everything you need to know about artificial wombs

Artificial wombs are nearing human trials. But the goal is to save the littlest preemies, not replace the uterus.

By Cassandra Willyard

Illustration by Amrita Marino

Last year, US Food and Drug Administration advisors met to discuss how to move research on artificial wombs from animals into humans. These medical devices are designed to give extremely premature infants a bit more time to develop in a womblike environment before entering the outside world. They have been tested with hundreds of lambs (and some piglets), but animal models can't fully predict how the technology will work for humans.

"The most challenging question to answer is how much unknown is acceptable," said An Massaro, the FDA's lead neonatologist in the Office of Pediatric Therapeutics, at the committee meeting. That's a question regulators will have to grapple with as this research moves out of the lab and into first-in-human trials.

What is an artificial womb?

An artificial womb is an experimental medical device intended to sustain and shelter extremely premature infants. In most of the technologies, the infant would float in a clear "biobag," surrounded by fluid. The idea is that preemies could spend a few weeks continuing to develop in this device after birth, so that "when they're transitioned from the device, they're more capable of surviving and having fewer complications with conventional treatment," says George Mychaliska, a pediatric surgeon at the University of Michigan.

One of the main limiting factors for survival in extremely premature babies is lung development. Rather than breathing air, babies in an artificial womb would have their lungs filled with lab-made amniotic fluid, mimicking the fluid that would have served this function in utero. Neonatologists would insert tubes into blood vessels in the umbilical cord so that the infant's blood could cycle through an artificial lung to pick up oxygen.

The device closest to being ready to be tested in humans, called the EXTrauterine Environment for Newborn Development, or EXTEND, encases the baby in a container filled with lab-made amniotic fluid, while scientists in Australia and Japan are working on a similar system. In Europe, the Perinatal Life Support project is working on its own technology. And in Canada, researchers have been testing their version of an artificial womb on piglets.

When will this technology be tested in humans?

The technology used in the EXTEND system has been tested on lamb fetuses—about 300 so far—with good results. The lambs can survive and develop inside it for three or even four weeks.

To move forward with human testing, the company needs an investigational-device exemption from the FDA. To greenlight a trial, FDA officials need to be convinced that babies who try EXTEND are likely to benefit from the system, and that they'll fare at least as well as babies who receive the current standard of care.

What would the first human tests look like?

The procedure requires a carefully choreographed transfer. First, the baby must be delivered via cesarean section and immediately have tubes inserted into the

umbilical cord before being transferred into the fluid-filled container.

The technology would likely be used first on infants born at 22 or 23 weeks, who don't have many other options. At 22 weeks of gestation, babies are tiny, often weighing less than a pound. And their lungs are still developing. When researchers looked at babies born between 2013 and 2018, survival among those who were resuscitated at 22 weeks was 30%. That number rose to nearly 56% at 23 weeks. And babies born at that stage who do survive have an increased risk of neurodevelopmental problems, cerebral palsy, mobility problems, hearing impairments, and other disabilities.

Selecting the right participants will be tricky. Some experts argue that gestational age shouldn't be the only criterion. One complicating factor is that prognosis varies widely from center to center, and it's improving as hospitals learn how best to treat these preemies. At the University of Iowa Stead Family Children's Hospital, for example, survival rates are much higher than average: 64% for babies born at 22 weeks. They've even managed to keep a handful of infants born at 21 weeks alive. "These babies are not a hopeless case," says Brady Thomas, a neonatologist at Stead. "Are you really going to make that much of a bigger impact by adding in this technology, and what risks might exist to those patients as you're starting to trial it?"

What are the risks?

One ever-present concern in the tiniest babies is brain bleeds, a risk that is partly down to their brain immaturity. Babies in an artificial womb would need to be on a blood thinner to prevent clots from forming where the tubes enter the body, which could increase that risk.

So if it works, could babies be grown entirely outside the womb?

Not anytime soon. Maybe not ever. The problem is twofold. First, fetal development is a carefully choreographed process that relies on chemical communication between the pregnant parent's body and the fetus. Even if researchers understood all the factors that contribute to fetal development—and they don't—there's no guarantee they could re-create those conditions.

The second issue is size. The artificial womb systems being developed require doctors to insert a small tube into the infant's umbilical cord to deliver oxygenated blood. The smaller the umbilical cord, the more difficult this becomes.

What are the ethical concerns?

In the near term, there are concerns about how to ensure that researchers are obtaining proper informed consent from parents who may be desperate to save their babies. "This is an issue that comes up with lots of last-chance therapies," says Vardit Ravitsky, a bioethicist and president of the Hastings Center, a bioethics research institute.

If the artificial wombs work, more significant questions will come up. When these devices are used to save infants born too soon, "this is obviously potentially a wonderful technology," Ravitsky says. But as with any technology, other uses might arise. Imagine that a woman wants to terminate a pregnancy at 21 or 22 weeks and this technology is available. How would that affect a woman's right to choose whether to carry a pregnancy to term?

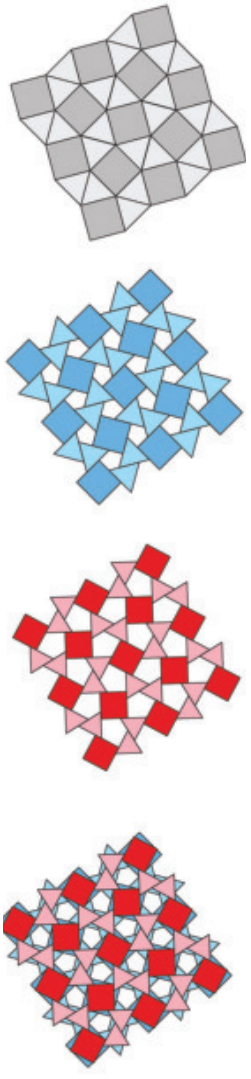
The advent of an artificial womb raises all kinds of questions, Ravitsky says: "What's a fetus, what's a baby, what's a newborn, what's birth, what's viability?" These questions have ethical implications, but also legal ones. "If we don't start thinking about it now, we're going to have lots of blind spots," she says. ■

Cassandra Willyard is a freelance science writer in Wisconsin. She specializes in medicine, energy, and the environment.

Taking shape

This architect starts with paper and scissors to find better ways to build. By Sofi Thanhauser

Portrait by Brooke Bierhaus



As a child, Emily Baker loved to make paper versions of things: cameras, a spaceship cockpit, buildings for a town in outer space.

It was a habit that stuck. Years later, studying architecture in graduate school at the Cranbrook Academy of Art in Michigan, she was playing around with some paper and scissors. It was 2010, and the school was about to buy a CNC router, a computer-controlled machine capable of cutting lines into sheets of steel. As she thought about how she might experiment with it, she made a striking discovery.

By making a series of cuts and folds in a sheet of paper, Baker found she could produce two planes connected by a complex set of thin strips. Without the need for any adhesive like glue or tape, this pattern created a surface that was thick but lightweight. Baker named her creation Spin-Valence. Structural tests later showed that an individual tile made this way, and rendered in steel, can bear more than a thousand times its own weight.

In chemistry, spin valence is a theory dealing with molecular behavior. Baker didn't know of the existing term when she named her own invention—"It was a total accident," she says. But diagrams related to chemical spin valence theory, she says, do "seem to have a network of patterns that are very similar to the tilings I'm working with."

Soon, Baker began experimenting with linking individual tiles together to produce a larger plane. There are perhaps thousands of geometric cutting patterns that can create these multiplane structures, and she has so far discovered only some of them. Certain patterns are stronger than others, and some are better at making curved planes.

Baker uses software to explore each pattern type but continues to work with cut paper to model possibilities. The Form Finding Lab at Princeton is now testing various tiles under tension and compression loads, and the results have already proved incredibly strong.

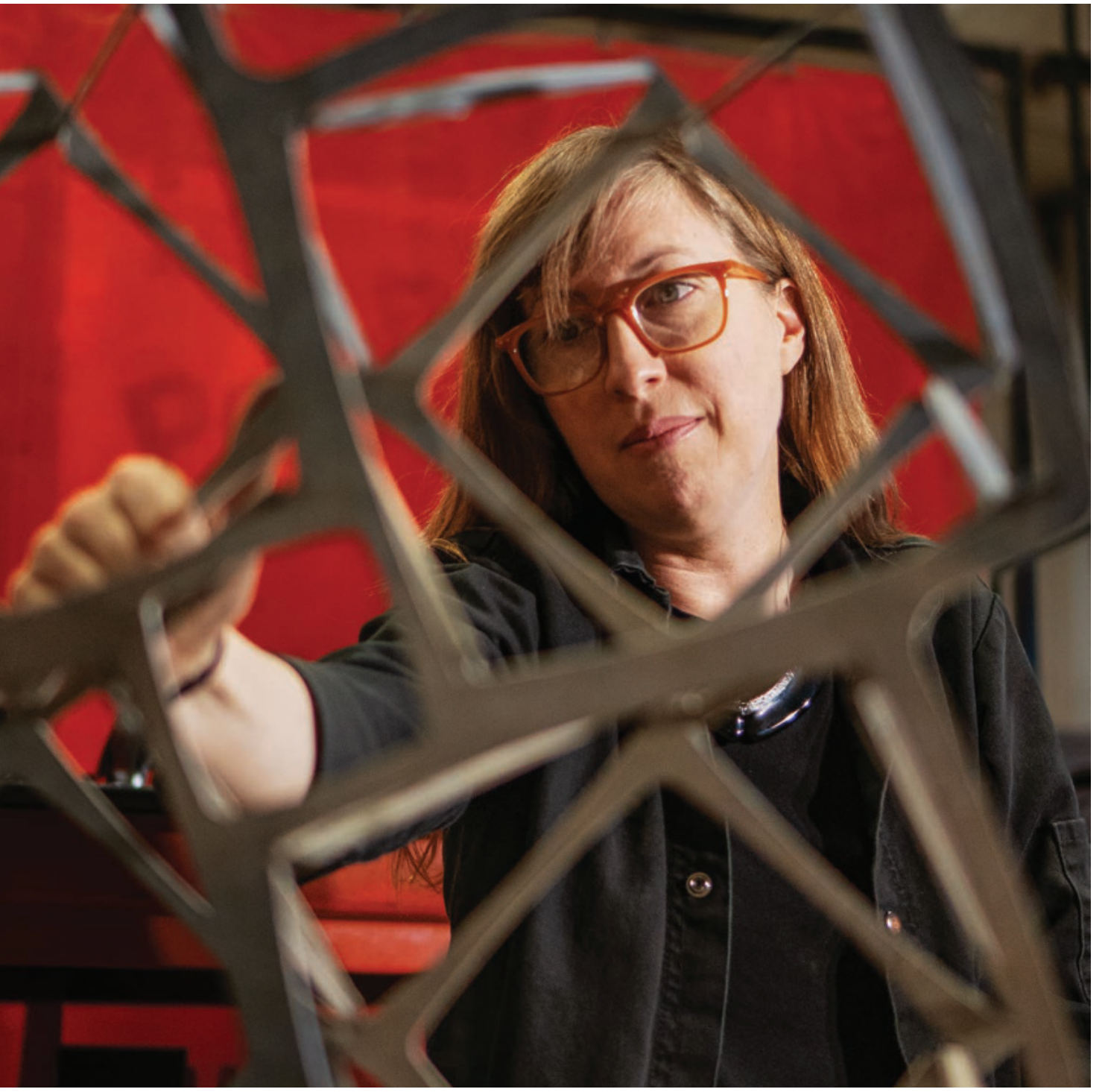
Baker is also exploring ways to use Spin-Valence in architecture and design. She envisions using the technique to make shelters or bridges that are easier to transport and assemble following a natural disaster, or to create lightweight structures that could be packed with supplies for missions to outer space. (Closer to home, her mother has begun passing along ideas to her quilting group; the designs bear a strong resemblance to quilt patterns.)

"What I find most exciting about the system is the way it adds stiffness to something that was previously very flexible," says Isabel Moreira de Oliveira, a PhD candidate in civil engineering at Princeton, who is writing her dissertation on Spin-Valence and testing which shapes work best for specific applications. "It entirely changes the behavior of something without adding material to it." Plus, she adds, "you can ship this flat. The assembly information is embedded in how it's cut." This could help reduce transportation costs and lower carbon emissions generated from shipping.

Baker grew up in Alabama and Arkansas, the daughter of a librarian and a chemical engineer at the camera company Eastman Kodak. Everybody in the family made things by hand—her mother taught her how to sew, and her father taught her how to work with wood. In high school, she took some classes in the school's agricultural program, including welding, where she had a particularly supportive teacher. "I'll tell you who the best two welders in the class are gonna be right now," she recalls him saying, as he pointed at her and the only other female student. And, she says, "it was true. We picked it up a little faster than the guys. It was really empowering."

Left: To develop Spin-Valence, a novel structural system, Emily Baker created prototypes by making cuts and folds in sheets of paper before shifting to digitally cut steel.

Opposite: Baker in her fabrication lab at the University of Arkansas.

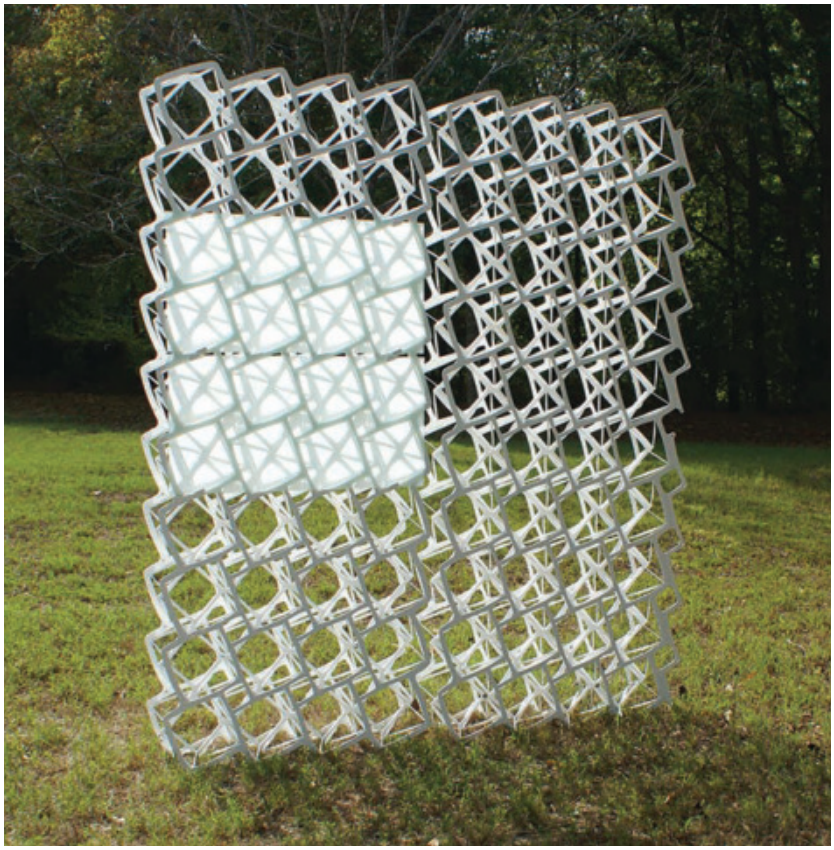


Baker went on to study chemical engineering at the University of Arkansas in Fayetteville before she switched to architecture, drawn to the more tactile work. After five years at a small architecture firm in Jackson, Mississippi, she enrolled at Cranbrook, where she sensed she would have the space and tools to experiment. She now teaches in the architecture program at the University of Arkansas.

No doubt her experience in high school welding class aided in a more recent collaboration. Together with her UA colleague Edmund Harriss, an assistant math professor, she has developed Zip-Form—a system for welding and bending two sheets of steel together to make complex 3D shapes using low-cost tools and easily learned skills.

As a process, it is "a physical manifestation of integrating differential properties of the curve," Harriss says. "The way the mathematical theory links to manufacturing process in Zip-Form is incredibly clean and elegant." He explains that Baker's willingness to engage seriously with the mathematics sets her apart from other architects he has worked with: "I think often people get intimidated by the mathematics and try to fall back on their expertise to say where the mathematics *isn't* working." Baker wasn't like that.

Like Spin-Valence, Zip-Form has potential applications in construction. Shortly after developing the technique, Baker met Mohamed Ismail, now an assistant professor of architecture at the University of Virginia, who was then a PhD student at MIT. He was working on low-cost, low-carbon structural systems for housing in developing countries. When Ismail learned that Baker and Harris had found a way to make complex 3D structures out of flat sheets, his mind immediately went to concrete. A system like this, he says, is "exactly the kind of thing that is necessary when you're trying to build complex concrete formwork [molds to pour the concrete into] in places where you don't have a robotic arm or 3D printer."



In a project they worked on together, Baker and Ismail used Zip-Form to create a mold for a 16-foot prototype curved beam that's more environmentally sustainable than a traditional beam, reducing the total carbon emissions associated with resource extraction, production, transport and other stages in the typical life cycle of a beam by 40%.

While most concrete buildings use vastly more material than is structurally necessary, curved beams save concrete by using material only where it is needed to bear a structural load. Concrete is responsible for approximately 8% of total global carbon emissions, but it is also desperately needed to build housing, especially in places like India and Africa, where the population is forecast to grow rapidly in the next 20 years. Zip-Form demands more labor than more automated processes, but the equipment it uses is more affordable.

Ismail and Baker are now working with a fabrication company in Kenya to demonstrate to real estate developers and an African housing nonprofit that this technology is competitive on price with traditional methods, and thus has a key role to play in affordable construction. The construction industry

Above: Baker began exploring digital fabrication as a graduate student at the Cranbrook Academy of Art, a path that has resulted in steel prototypes like this one.

Right: Baker and Edmund Harriss, a mathematician, developed Zip-Form, a system for welding and bending two sheets of steel together to make complex 3D shapes.

Below: Baker's foldable system has applications for everything from self-supporting architectural façades and deployable bridges to compact, shippable structures for use in outer space.

in the US can be mind-numbingly slow to adopt new techniques, Baker and Ismail both say, but they believe Zip-Form can easily be brought into building projects, using tools and materials that are already available.

Zip-Form has creative potential, too. Danielle Hatch, an artist known for large-scale fabric installations, is using the system to make a public sculpture in Arkansas inspired by the movement of ribbons on the dancers she saw at a Hispanic cultural festival. "How could I evoke that sense of lightness and play, with metal?" she wondered. Zip-Form allowed her to make steel that she describes as "lyrical."

Baker has been inspired by the work of R. Buckminster Fuller, the polymath known for popularizing the geodesic dome—and for turning his mind to everything from affordable housing and transportation to renewable energy. She has studied his story closely, especially reflecting on the gaps between the broad scope of his thought—which often sought to revolutionize entire systems—and the limited real-world changes that resulted from his ideas. "Is there something I should have learned from his life and experience?" she wonders.

Like Fuller, whose work extended far beyond architecture to consider the ways people relate to one another and to materials, Baker doesn't think just about physical forms but about how people build, live, and manufacture—and the hierarchies that determine who does what. She thinks of architecture as always being in conversation with the body of the builder. A brick, she points out, is an excellent example because it's the perfect size for a worker to hold while slathering it with mortar. Baker wants the tools she creates to be just as practical. ■

Sofi Thanhauser is a writer, artist, and musician based in Brooklyn, New York, and the author of Worn: A People's History of Clothing.

THE ROBOTS WE'VE ALWAYS WANTED

More data, better AI, and cheaper hardware are helping researchers take a step closer to the dream of useful household robots.

By Melissa Heikkilä

Silent. Rigid. Clumsy.

Henry and Jane Evans are used to awkward houseguests. For more than a decade, the couple, who live in Los Altos Hills, California, have hosted a slew of robots in their home.

In 2002, at age 40, Henry had a massive stroke, which left him with quadriplegia and an inability to speak. Since then, he's learned how to communicate by moving his eyes over a letter board, but he is highly reliant on caregivers and his wife, Jane.

Henry got a glimmer of a different kind of life when he saw Charlie Kemp on CNN in 2010. Kemp, a robotics professor at Georgia Tech, was on TV talking about PR2, a robot developed by the company Willow Garage. PR2 was a massive two-armed machine on wheels that looked like a crude metal butler. Kemp was demonstrating how the robot worked, and talking about his research on how health-care robots could help people. He showed how the PR2 robot could hand some medicine to the television host.

"All of a sudden, Henry turns to me and says, 'Why can't that robot be an extension of my body?' And I said, 'Why not?'" Jane says.

There was a solid reason why not. While engineers have made great progress in getting robots to work in tightly controlled environments like labs and factories, the home has proved difficult to design for. Out in the real, messy world, furniture and floor plans differ wildly; children and pets can jump in a robot's way; and clothes that need folding come in different shapes, colors, and sizes. Managing such unpredictable settings and varied conditions has been beyond the capabilities of even the most advanced robot prototypes.

That seems to finally be changing, in large part thanks to artificial intelligence. For decades, roboticists have more or less focused on controlling robots' "bodies"—their arms, legs, levers, wheels, and the like—via purpose-driven software. But a new generation of scientists and inventors believes that the previously missing ingredient of AI can give robots the ability to learn new skills and adapt to new environments faster than ever before. This new approach, just maybe, can finally bring robots out of the factory and into our homes.

Progress won't happen overnight, though, as the Evanses know far too well from their many years of using various robot prototypes.

PR2 was the first robot they brought in, and it opened entirely new skills for Henry. It would hold a beard shaver and Henry would move his face against it, allowing him to shave and scratch an itch by himself for the first time in a decade. But at 450 pounds (200 kilograms) or so and $400,000, the robot was difficult to have around. "It could easily take out a wall in your house," Jane says. "I wasn't a big fan."

More recently, the Evanses have been testing out a smaller robot called Stretch, which Kemp developed through his startup Hello Robot. The first iteration launched during the pandemic with a much more reasonable price tag of around $18,000.

Stretch weighs about 50 pounds. It has a small mobile base, a stick with a camera dangling off it, and an adjustable arm featuring a gripper with suction cups at the ends. It can be controlled with a console controller. Henry controls Stretch using a laptop, with a tool that that tracks his head movements to move a cursor around. He is able to move his thumb and index finger enough to click a computer mouse. Last summer, Stretch was with the couple for more than a month, and Henry says it gave him a whole new level of autonomy. "It was practical, and I could see using it every day," he says.

Using his laptop, he could get the robot to brush his hair and have it hold fruit kebabs for him to snack on. It also opened up Henry's relationship with his granddaughter Teddie. Before, they barely interacted. "She didn't hug him at all goodbye. Nothing like that," Jane says. But "Papa Wheelie" and Teddie used Stretch to play, engaging in relay races, bowling, and magnetic fishing.

Stretch doesn't have much in the way of smarts: it comes with some preinstalled software, such as the web interface that Henry uses to control it, and other capabilities such as AI-enabled navigation. The main benefit of Stretch is that people can

In a video from 1957, a man operates two large robotic arms and uses the machine to apply a woman's lipstick. Robots have come a long way since.

PREVIOUS SPREAD AND OPPOSITE: PETER ADAMS; BELOW: FROM "LIGHTER SIDE OF THE NEWS – ATOMIC ROBOT A HANDY GUY" (1957) VIA YOUTUBE

Henry Evans used the Stretch robot to brush his hair, eat, and even play with his granddaughter.

plug in their own AI models and use them to do experiments. But it offers a glimpse of what a world with useful home robots could look like. Robots that can do many of the things humans do in the home—tasks such as folding laundry, cooking meals, and cleaning—have been a dream of robotics research since the inception of the field in the 1950s. For a long time, it's been just that: "Robotics is full of dreamers," says Kemp.

But the field is at an inflection point, says Ken Goldberg, a robotics professor at the University of California, Berkeley. Previous efforts to build a useful home robot, he says, have emphatically failed to meet the expectations set by popular culture—think the robotic maid from *The Jetsons*. Now things are very different. Thanks to cheap hardware like Stretch, along with efforts to collect and share data and advances in generative AI, robots are getting more competent and helpful faster than ever before. "We're at a point where we're very close to getting capability that is really going to be useful," Goldberg says.

Folding laundry, cooking shrimp, wiping surfaces, unloading shopping baskets—today's AI-powered robots are learning to do tasks that for their predecessors would have been extremely difficult.

Missing pieces

There's a well-known observation among roboticists: What is hard for humans is easy for machines, and what is easy for humans is hard for machines. Called Moravec's paradox, it was first articulated in the 1980s by Hans Moravec, then a roboticist at the Robotics Institute of Carnegie Mellon University. A robot can play chess or hold an object still for hours on end with no problem. Tying a shoelace, catching a ball, or having a conversation is another matter.

There are three reasons for this, says Goldberg. First, robots lack precise control and coordination. Second, their understanding of the surrounding world is limited because they are reliant on cameras and sensors to perceive it. Third, they lack an innate sense of practical physics.

"Pick up a hammer, and it will probably fall out of your gripper, unless you grab it near the heavy part. But you don't know that if you just look at it, unless you know how hammers work," Goldberg says.

On top of these basic considerations, there are many other technical things that need to be just right, from motors to cameras to Wi-Fi connections, and hardware can be prohibitively expensive.

Mechanically, we've been able to do fairly complex things for a while. In a video from 1957, two large robotic arms are dexterous enough to pinch a cigarette, place it in the mouth of a woman at a typewriter, and reapply her lipstick. But the intelligence and the spatial awareness of that robot came from the person who was operating it.

"The missing piece is: How do we get software to do [these things] automatically?" says Deepak Pathak, an assistant professor of computer science at Carnegie Mellon.

Researchers training robots have traditionally approached this problem by planning everything the robot does in excruciating detail. Robotics giant Boston Dynamics used this approach when it developed its boogying and parkouring humanoid robot Atlas. Cameras and computer vision are used to identify objects and scenes. Researchers then use that data to make models that can be used to predict with extreme precision what will happen

if a robot moves a certain way. Using these models, roboticists plan the motions of their machines by writing a very specific list of actions for them to take. The engineers then test these motions in the laboratory many times and tweak them to perfection.

This approach has its limits. Robots trained like this are strictly choreographed to work in one specific setting. Take them out of the laboratory and into an unfamiliar location, and they are likely to topple over.

Compared with other fields, such as computer vision, robotics has been in the dark ages, Pathak says. But that might not be the case for much longer, because the field is seeing a big shake-up. Thanks to the AI boom, he says, the focus is now shifting from feats of physical dexterity to building "general-purpose robot brains" in the form of neural networks. Much as the human brain is adaptable and can control different aspects of the human body, these networks can be adapted to work in different robots and different scenarios. Early signs of this work show promising results.

Robots, meet AI

For a long time, robotics research was an unforgiving field, plagued by slow progress. At the robotics institute at Carnegie Mellon, where Pathak works, he says, "there used to be a saying that if you touch a robot, you add one year to your PhD." Now, he says, students get exposure to many robots and see results in a matter of weeks.

What separates this new crop of robots is their software. Instead of the traditional painstaking planning and training, roboticists have started using deep learning and neural networks to create systems that learn from their environment on the go and adjust their behavior accordingly. At the same time, new, cheaper hardware, such as off-the-shelf components and robots like Stretch, is making this sort of experimentation more accessible.

Broadly speaking, there are two popular ways researchers are using AI to train robots. Pathak has been using reinforcement learning, an AI technique that allows systems to improve through trial and error, to get robots to adapt their movements in new environments. This is a technique that Boston Dynamics has also started using in its robot "dogs" called Spot.

Deepak Pathak's team at Carnegie Mellon has used an AI technique called reinforcement learning to create a robotic dog that can do extreme parkour with minimal pre-programming.

In 2022, Pathak's team used this method to create four-legged robot "dogs" capable of scrambling up steps and navigating tricky terrain. The robots were first trained to move around in a general way in a simulator. Then they were set loose in the real world, with a single built-in camera and computer vision software to guide them. Other similar robots rely on tightly prescribed internal maps of the world and cannot navigate beyond them.

Pathak says the team's approach was inspired by human navigation. Humans receive information about the surrounding world from their eyes, and this helps them instinctively place one foot in front of the other to get around in an appropriate way. Humans don't typically look down at the ground under their feet when they walk, but a few steps ahead, at a spot where they want to go. Pathak's team trained its robots to take a similar approach to walking: each one used the camera to look ahead. The robot was then able to memorize what was in front of it for long enough to guide its leg placement. The robots learned about the world in real time, without internal maps, and adjusted their behavior accordingly. At the time, experts told *MIT Technology Review* the technique was a "breakthrough in robot learning and autonomy" and could allow researchers to build legged robots capable of being deployed in the wild.

Pathak's robot dogs have since leveled up. The team's latest algorithm allows a quadruped robot to do extreme parkour. The robot was again trained to move around in a general way in a simulation. But using reinforcement learning, it was then able to teach itself new skills on the go, such as how to jump long distances, walk on its front legs, and clamber up tall boxes twice its height. These behaviors were not something the researchers programmed. Instead, the robot learned through trial and error and visual input from its front camera. "I didn't believe it was possible three years ago," Pathak says.

In the other popular technique, called

"EXTREME PARKOUR WITH LEGGED ROBOTS," XUXIN CHENG, ET AL.

imitation learning, models learn to perform tasks by, for example, imitating the actions of a human teleoperating a robot or using a VR headset to collect data on a robot. It's a technique that has gone in and out of fashion over decades but has recently become more popular with robots that do manipulation tasks, says Russ Tedrake, vice president of robotics research at the Toyota Research Institute and an MIT professor.

By pairing this technique with generative AI, researchers at the Toyota Research Institute, Columbia University, and MIT have been able to quickly teach robots to do many new tasks. They believe they have found a way to extend the technology propelling generative AI from the realm of text, images, and videos into the domain of robot movements.

The idea is to start with a human, who manually controls the robot to demonstrate behaviors such as whisking eggs or picking up plates. Using a technique called diffusion policy, the robot is then able to use the data fed into it to learn skills. The researchers have taught robots more than 200 skills, such as peeling vegetables and pouring liquids, and say they are working toward teaching 1,000 skills by the end of the year.

Many others have taken advantage of generative AI as well. Covariant, a robotics startup that spun off from OpenAI's now-shuttered robotics research unit, has built a multimodal model called RFM-1. It can accept prompts in the form of text, image, video, robot instructions, or measurements. Generative AI allows the robot to both understand instructions and generate images or videos relating to those tasks.

The Toyota Research Institute team hopes this will one day lead to "large behavior models," which are analogous to large language models, says Tedrake. "A lot of people think behavior cloning is going to get us to a ChatGPT moment for robotics," he says.

In a similar demonstration, earlier this year a team at Stanford managed to use a relatively cheap off-the-shelf robot costing $32,000 to do complex manipulation tasks such as cooking shrimp and cleaning stains. It learned those new skills quickly with AI.

Called Mobile ALOHA (a loose acronym for "a low-cost open-source hardware teleoperation system"), the robot learned to cook shrimp with the help of just 20 human demonstrations and data from other tasks, such as tearing off a paper towel or piece of tape. The Stanford researchers found that AI can help robots acquire transferable skills: training on one task can improve its performance for others.

While the current generation of generative AI works with images and language, researchers at the Toyota Research Institute, Columbia University, and MIT believe the approach can extend to the domain of robot motion.

This is all laying the groundwork for robots that can be useful in homes. Human needs change over time, and teaching robots to reliably do a wide range of tasks is important, as it will help them adapt to us. That is also crucial to commercialization—first-generation home robots will come with a hefty price tag, and the robots need to have enough useful skills for regular consumers to want to invest in them.

For a long time, a lot of the robotics community was very skeptical of these kinds of approaches, says Chelsea Finn, an assistant professor of computer science and electrical engineering at Stanford University and an advisor for the Mobile ALOHA project. Finn says that nearly a decade ago, learning-based approaches were rare at robotics conferences and disparaged in the robotics community. "The [natural-language-processing] boom has been convincing more of the community that this approach is really, really powerful," she says.

There is one catch, however. In order to imitate new behaviors, the AI models need plenty of data.

More is more

Unlike chatbots, which can be trained by using billions of data points hoovered from the internet, robots need data specifically created for robots. They need physical demonstrations of how washing machines and fridges are opened, dishes picked up, or laundry folded, says Lerrel Pinto, an assistant professor of computer science at New York University. Right now that data is very scarce, and it takes a long time for humans to collect.

Some researchers are trying to use existing videos of humans doing things to train robots, hoping the machines will be

RT-2, a recent model for robotic control, was trained on online text and images as well as interactions with the real world.

KELSEY MCCLELLAN

able to copy the actions without the need for physical demonstrations.

Pinto's lab has also developed a neat, cheap data collection approach that connects robotic movements to desired actions. Researchers took a reacher-grabber stick, similar to ones used to pick up trash, and attached an iPhone to it. Human volunteers can use this system to film themselves doing household chores, mimicking the robot's view of the end of its robotic arm. Using this stand-in for Stretch's robotic arm and an open-source system called DOBB-E, Pinto's team was able to get a Stretch robot to learn tasks such as pouring from a cup and opening shower curtains with just 20 minutes of iPhone data.

But for more complex tasks, robots would need even more data and more demonstrations.

The requisite scale would be hard to reach with DOBB-E, says Pinto, because you'd basically need to persuade every human on Earth to buy the reacher-grabber system, collect data, and upload it to the internet.

A new initiative kick-started by Google DeepMind, called the Open X-Embodiment Collaboration, aims to change that. Last year, the company partnered with 34 research labs and about 150 researchers to collect data from 22 different robots, including Hello Robot's Stretch. The resulting data set, which was published in October 2023, consists of robots demonstrating 527 skills, such as picking, pushing, and moving.

Sergey Levine, a computer scientist at UC Berkeley who participated in the project, says the goal was to create a "robot internet" by collecting data from labs around the world. This would give researchers access to bigger, more scalable, and more diverse data sets. The deep-learning revolution that led to the generative AI of today started in 2012 with the rise of ImageNet, a vast online data set of images. The Open X-Embodiment Collaboration is an attempt by the robotics community to do something similar for robot data.

Early signs show that more data is leading to smarter robots. The researchers built two versions of a model for robots, called RT-X, that could be either run locally on individual labs' computers or accessed via the web. The larger, web-accessible model was pretrained with internet data to develop a "visual common sense," or a baseline understanding of the world, from the large language and image models.

When the researchers ran the RT-X model on many different robots, they discovered that the robots were able to learn skills 50% more successfully than in the systems each individual lab was developing.

"I don't think anybody saw that coming," says Vincent Vanhoucke, Google DeepMind's head of robotics. "Suddenly there is a path to basically leveraging all these other sources of data to bring about very intelligent behaviors in robotics."

Many roboticists think that large vision-language models, which are able to analyze image and language data, might offer robots important hints as to how the surrounding world works, Vanhoucke says. They offer semantic clues about the world and could help robots with

reasoning, deducing things, and learning by interpreting images. To test this, researchers took a robot that had been trained on the larger model and asked it to point to a picture of Taylor Swift. The researchers had not shown the robot pictures of Swift, but it was still able to identify the pop star because it had a web-scale understanding of who she was even without photos of her in its dataset, says Vanhoucke.

Vanhoucke says Google DeepMind is increasingly using techniques similar to those it would use for machine translation to translate from English to robotics. Last summer, Google introduced a vision-language-action model called RT-2. This model gets its general understanding of the world from online text and images it has been trained on, as well as its own interactions in the real world. It translates that data into robotic actions. Each robot has a slightly different way of translating English into action, he adds.

"We increasingly feel like a robot is essentially a chatbot that speaks robotese," Vanhoucke says.

Baby steps

Despite the fast pace of development, robots still face many challenges before they can be released into the real world. They are still way too clumsy for regular consumers to justify spending tens of thousands of dollars on them. Robots also still lack the sort of common sense that would allow them to multitask. And they need to move from just picking things up and placing them somewhere to putting things together, says Goldberg—for example, putting a deck of cards or a board game back in its box and then into the games cupboard.

But to judge from the early results of integrating AI into robots, roboticists are not wasting their time, says Pinto.

"I feel fairly confident that we will see some semblance of a general-purpose home robot. Now, will it be accessible to the general public? I don't think so," he says. "But in terms of raw intelligence, we are already seeing signs right now."

Building the next generation of robots might not just assist humans in their everyday chores or help people like Henry Evans live a more independent life. For researchers like Pinto, there is an even bigger goal in sight.

Home robotics offers one of the best benchmarks for human-level machine intelligence, he says. The fact that a human can operate intelligently in the home environment, he adds, means we know this is a level of intelligence that can be reached.

"It's something which we can potentially solve. We just don't know how to solve it," he says.

For Henry and Jane Evans, a big win would be to get a robot that simply works reliably. The Stretch robot that the Evanses experimented with is still too buggy to use without researchers present to troubleshoot, and their home doesn't always have the dependable Wi-Fi connectivity Henry needs in order to communicate with Stretch using a laptop.

Even so, Henry says, one of the greatest benefits of his experiment with robots has been independence: "All I do is lay in bed, and now I can do things for myself that involve manipulating my physical environment."

Thanks to Stretch, for the first time in two decades, Henry was able to hold his own playing cards during a match.

"I kicked everyone's butt several times," he says.

"Okay, let's not talk too big here," Jane says, and laughs. ■

Thanks to Stretch, Henry Evans was able to hold his own playing cards for the first time in two decades.

Lerrel Pinto's lab outfitted a reacher-grabber stick with an iPhone in order to inexpensively collect data that can guide robotic movements.

"ON BRINGING ROBOTS HOME," NUR MUHAMMAD (MAHI) SHAFIULLAH, ET AL.; VY NGUYEN (CARD GAME)

Melissa Heikkilä is a senior reporter at MIT Technology Review, where she covers artificial intelligence and how it is changing our society.

Louisiana's southwestern coastline faces some of the most severe climate predictions in the US. Can a government-led project build the area up and out of crisis?

By XANDER PETERS | Photographs by Virginia Hanusik

How to stop the sinking

THERE IS MORE THAN ONE WAY TO RAISE A HOUSE.

Many of the mobile homes, Creole cottages, and other dwellings that have been flagged for flood risk along Louisiana's low-lying coastline can be separated from their foundations and slowly raised into the sky on hydraulic jacks. While a home is held aloft by temporary support beams, a new, elevated floor is built underneath or the foundation extended upward—think of the pilings you might see supporting a beach house.

But for homes like Christa and Alex Bell's, which consists of two stories and a two-car garage sitting on a concrete slab, the house-jacking process is more complex.

Slab homes depend on the concrete foundation underneath for flooring and for most, if not all, of their structural support. It's ideal, though difficult, to raise the house and the slab together and build a new foundation underneath; the other option is to separate the two and build a new, elevated floor. From there, homeowners could extend the foundation walls up and construct a new bottom space they could use for storage or parking. Or they could remove the roof, raise the exterior walls up an entire story, replace the roof, and write off the house's bottom floor as storage space.

No matter the approach, residents usually need to relocate for 60 to 90 days, after which their homes stand several feet higher in the air.

None of these details were on the Bells' minds a decade ago when they moved from Alabama to Lake Charles, an oil refinery and casino town of 81,000 near the Gulf Coast and Texas border.

But in May 2021, more than a foot of rain came down on the region in just 24 hours, causing flash floods. Even as Christa Bell watched Bayou Contraband—one of the region's many small, slow-moving rivers—rise until it spilled over and into their backyard, she wasn't concerned her house might flood. Only a single corner of the 1,900-square-foot home was in a floodplain, according to federal flood maps when they bought the house in

2017. Yet that day, the bayou kept rising, and by evening, floodwaters stood shin deep in the living room. “Everything in the garage was just floating,” she says.

Every home on the block required at least partial gutting. Weeks passed; couches, mattresses, carpet, and other flood debris collected in heaps near the street, mildewed and rotting.

It was a scene mirrored across much of southwest Louisiana, and not for the first time. In a 10-month span in 2020–2021, the area saw five climate-related disasters, including two destructive hurricanes and the impacts of a tropical storm’s outer bands. More storms are coming, and many areas are not prepared: a 2021 study from First Street Foundation, a nonprofit focused on climate risk data, estimates that nearly 40% of Lake Charles residential properties and more than half the city’s infrastructure are at risk of future flooding.

Some people aren’t waiting around to experience that uncertain future. In the months after the 2020 hurricanes, Christa Bell says, she noticed more friends making home improvements before placing their houses on the market. “We had five disasters in a row. That hastened the departure for a lot of people,” she says. “If it flooded again, we would seriously think about it.”

But some government officials and state engineers are hoping there is an alternative: elevation. The $6.8 billion Southwest Coastal Louisiana Project is betting that raising residences by an average of three to five feet and nonresidential buildings by three to six, coupled with extensive work to restore coastal boundary lands, will keep Louisianans in their communities and a local economy that helps power the country’s oil industry running. The project, a collaboration between the US Army Corps of Engineers and the Louisiana Coastal Protection and Restoration Authority (CPRA), is focused on roughly 4,700 square miles of land in three parishes in the southwestern corner of the state: Cameron, Vermilion, and Calcasieu, where Lake Charles is the parish seat. More than 3,000 homes have been identified as being at risk of imminent flooding, and therefore as candidates for elevation funding.

Ultimately, it’s something of a last-ditch effort to preserve this slice of coastline, even as some locals pick up and move inland and as formal plans for managed retreat—or government funding for community relocation—become more popular in climate-vulnerable areas across the country and the rest of the world.

Now, after eight years of surveys, paperwork, and waiting for cash, the pilot phase of the project is finally moving forward and raising 21 homes. As it does so, project staff and locals alike will be forced to grapple with a looming existential question: Can a region facing some of the nation’s most alarming climate predictions build its way out of an accelerating crisis?

Darrel Broussard, the project’s senior manager, sees its work as the region’s best chance at reducing damage over the next 50 years and safeguarding the roots residents have put down over generations. “This is Louisiana. This is where everyone lives. This is where we work. This is where the economy comes from,” he

Since 1932, Louisiana has lost some 1.2 million acres of coast to erosion—an area nearly twice the size of Rhode Island.

About the artwork:
Virginia Hanusik is an award-winning artist, author, and environmental advocate based in New Orleans, Louisiana. The photographs accompanying this story are part of an ongoing series exploring the relationship between landscape, culture, and the built environment. Her book *Into the Quiet and the Light: Water, Life, and Land Loss in South Louisiana* is available from Columbia University Press.

says. “There are models out there trying to predict the future. They’re just models. Right now, we currently have communities, neighbors, all living there.”

At the same time, some environmental experts worry that this may be too rosy an outlook, with time and nature conspiring against lasting success. “The sooner we can shift our mindset towards managed retreat, the better,” says Torbjörn Törnqvist, a geology professor at Tulane University. “This is a very tough issue. This is a part of the country that’s just going to disappear.”

IT DIDN’T TAKE LONG FOR THE BELLS TO FEEL AT HOME in Lake Charles, the biggest city in what Louisiana officials call the state’s “working coastline.” The economy here thrives on commercial fishing and agriculture, though petroleum services have long been at its heart; roughly 30% of Louisiana’s refining capacity is based in the region, and the state accounts for nearly one-sixth of the country’s refining capacity, according to the US Energy Information Administration.

But what appealed most to Christa Bell, a public relations professor at McNeese State University, was locals’ hospitality and cuisine—proud reflections of Louisiana’s friendly charm. She loved the warm aesthetic of historic Ryan Street’s red brick buildings, which stand in stark contrast to the city’s casinos and refineries and its single skyscraper, the former Capital One Tower.

The building has sat vacant since a hurricane damaged it nearly four years ago—and over that time it has become a symbol of the strain created by severe weather in an area where waterways flow like veins and where flooding occurs often.

When Congress first authorized the Southwest Coastal Louisiana Project in 2016, local and federal officials celebrated it as a step toward shoring up the region’s resiliency after catastrophic storms like 2005’s Hurricane Rita: $5.2 billion would go toward shoreline and marshland restoration, while $1.6 billion would elevate local structures to heights based on 100-year-flood levels predicted for 2075. (These levels are both a complex idea and a moving target. They refer to the type of flooding that has a 1-in-100 or 1% chance of happening in any given year, but what was considered a 100-year flood even a decade ago now occurs much more frequently, and the storms are more severe.)

The Corps completed a feasibility study that identified 3,462 homes and about 500 nonresidential structures and warehouses eligible for elevation. To meet the feasibility study’s criteria, houses had to be in the current 25-year floodplain (meaning there’s a 1-in-25 chance the property will flood in a given year)—a stipulation the agency says offers the “greatest rate of return.” For final inclusion in the project, homes will need to be able to structurally withstand the elevation process. They must also be free of hazardous materials like asbestos and have clear property titles. All structures will need to meet state and local building codes.

But with the federal government on the hook to cover 65% of project costs, work was effectively on hold until 2022, when Congress finally approved the first round of funding for building and land restoration: nearly $300 million through the Infrastructure Investment and Jobs Act. (The remaining 35% will come mostly through Louisiana’s Coastal Master Plan—a 50-year, $50 billion guide to coastal restoration and storm risk reduction that’s updated every four years—and its funding allocated by the state.)

The Southwest Coastal Louisiana Project’s pilot program has been able to move forward on an initial round of agreements with 21 homeowners, though this batch of funding will ultimately cover 800 to 1,000 elevations over the next three to five years. Priority is being given to homes “that would flood the most,” Broussard says, meaning those with the lowest first floors, as well as houses in low- and moderate-income neighborhoods. Officials estimate that each residential elevation will cost between $100,000 and $200,000; homeowners will pay nearly nothing out of pocket for the elevation but will cover any costs to make their homes eligible and for temporary housing during construction. (Relocation expenses for renters are covered under the federal Uniform Relocation Act.)

“Our benefits come from getting structures out of the floodplain, and the damage is avoided,” Broussard says. Once homes are elevated above 100-year flood levels, “we shouldn’t have to touch them for at least 50 years.”

But some experts remain skeptical of this kind of certainty, particularly since the way we measure 100-year floods is changing as the climate warms. As recent research from First Street notes, such flood estimates are typically based on outdated data

that do not reflect current rainfall or rising temperatures, among other factors. After adjusting the data to reflect a hotter, more humid atmosphere, its researchers estimate that a majority of Americans will experience what was previously considered a 100-year event every 20 years.

Törnqvist warns that the 100-year flood predictions underpinning the project are essentially a gamble—and as in gambling, odds can change.

But it's a bet coastal officials say they are willing to take.

While the project's flood-risk modeling was conducted in 2016, Broussard says it considered future factors like increasingly powerful storms and sea-level rise. Since then, Broussard contends, "nothing has changed," adding that the Corps does not intend to update models of future storm risk "at this time."

But even under its most optimistic estimates, the project won't finish raising structures until the early 2040s. By that time, decades will have passed since the project made the flood-level predictions that provide its foundation.

RAISING HOMES WON'T MEAN MUCH IN THE LONG term if the project can't preserve or rebuild land that has long acted as a natural barrier and protector for the coast's residents. Broussard says the entire effort is like a complicated, very large puzzle: for one piece to fit, the correct piece must come before it; to protect inland Louisiana communities, you must protect the coast first. Without intervention, the state could spend up to $15 billion in disaster damage annually by midcentury, according to the CPRA.

Bren Haase, the CPRA's chair and former executive director, says that "the landscape, the beaches, the cheniers, the ridges, and the vast areas of marshes are the protection for that portion of the coast" near Lake Charles. The marshlands have been particularly important in absorbing or temporarily storing excess storm surges, while cheniers—the coastal ridges running parallel to the gulf's shoreline—have acted as natural levees, slowing down those same storm surges and providing a home to holly oak trees whose roots kept shorelines intact.

But since 1932, Louisiana has lost some 1.2 million acres of coast to erosion—an area nearly twice the size of Rhode Island. State officials estimate that parts of southwest Louisiana lose up to 30 feet of coast each year. Altogether, by 2050, Louisiana could see some 500,000 acres of additional land loss.

The CPRA estimates that Cameron Parish—most of which is wetlands—would be hit hardest among the coastal parishes, with up to 40% of its existing land likely to disappear by 2050. Without its marshlands, local flood depths could increase more than 15 feet.

"In the future, [Cameron Parish] is not going to be there," Törnqvist says. "It's going to be one of the first larger parish-level areas in Louisiana to go."

Part of the problem is sea-level rise; another is an increase in the sheer amount of rain hitting the region. A significant contributor, though, is human activity, counterintuitively including past flood-control practices, like constructing dams upriver and levees to control the state's numerous waterways. In southeast Louisiana's Mississippi River Basin, a recent *Nature Sustainability* study estimates, the installation of these types of structures has led to a loss of roughly 1,700 acres annually. Then there was the dredging of transportation channels for the oil and gas industry, which redirected the plain's primary sediment sources away from its marshland and allowed the land to disintegrate. Jetty systems have meanwhile disrupted sediment patterns that built the chenier ridges over about 7,000 years. Such activity has also allowed salt water to flow inland, which has in turn killed freshwater wetlands where roots held the soil together.

Projected land loss over 50 years

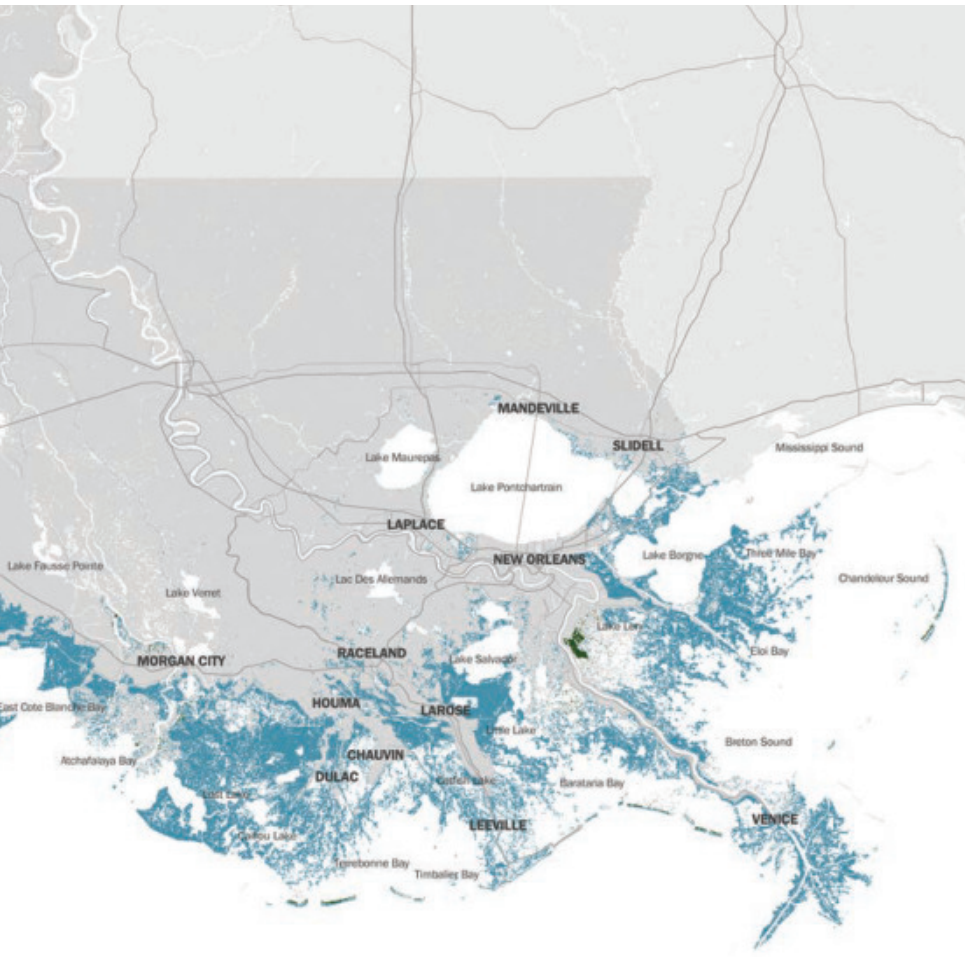
Continuing coastal change, sea-level rise, and other environmental processes will lead to additional land loss (shown in blue) in coastal Louisiana over 50 years. Projects included in the 2023 Coastal Master Plan attempt to mitigate this loss.

SOURCE: LOUISIANA'S 2023 COASTAL MASTER PLAN, LOUISIANA CPRA

In this context, elevating local structures is the easy part of the project. It will be much harder to undo a century of damage to coastal buffers that required millennia to develop.

The Southwest Coastal Project is planning to move millions of tons of dredged mud, rocks, oyster shells, and other materials to replace eroded land or guard vulnerable shoreline. More than 5 million cubic yards of dredged sediment from the Calcasieu Ship Channel, for instance, will be used to convert about 600 acres of open water near Calcasieu Parish's Black Lake back into marshland that had been lost to erosion. Meanwhile, more than 860,000 tons of rock will be strategically piled across a nearly nine-mile stretch that will extend existing breakwaters—artificial reefs that can reduce the impact of waves and lessen coastal erosion—at Cameron Parish's Holly Beach.

In total, the project aims to preserve nearly 22,000 net acres through ecosystem restoration.



Fortunately, it won't be working in isolation. Beyond Louisiana's Coastal Master Plan, various other CPRA schemes in Cameron Parish have already protected more than seven miles of shoreline and restored more than 3,800 acres of marsh, building more than 159,000 linear feet of earthen terraces to reduce wave erosion.

Still, officials like Haase are clear that future land loss is inevitable: "Even with our best and most aggressive efforts, the coast is going to continue to change."

FOR ALL THIS TO WORK, A LOT NEEDS TO GO RIGHT, and go right quickly.

Unfortunately, the pilot program is already behind initial time estimates: after funding was allocated, the Corps said it hoped the first structures would be elevated by early 2023. Nothing has yet been elevated. (The Corps says that "determining structure eligibility" and making multiple assessments at every location "has taken longer than expected.")

Meanwhile, state support may also be at risk since a new Republican governor—former state attorney general Jeff Landry—has taken over from Democrat John Bel Edwards. Landry called climate change a hoax in 2017, and weeks after his January inauguration he issued an executive order calling for the potential merger of the CPRA and the state's Department of Energy and Natural Resources, meaning the agency permitting petroleum industries would also oversee efforts to remediate their environmental fallout. (The governor's office did not respond to a request for comment.)

While plans drag, storm systems will inevitably keep roaring ashore, and sea levels will continue to rise. Someday, homes elevated four to five feet above their current level won't really be safe. And no matter how high homes go, cities like Lake Charles will still require local infrastructure upgrades, like bridges and sewer systems, that constitute a whole other set of vulnerabilities for residents. On top of that, storm winds have the power to cause severe structural damage, especially for homes at higher elevations; in 2020, Hurricane Laura's wind speeds peaked at about 150 miles per hour.

Craig Colten, a former Louisiana State University geography professor and a community researcher, is similarly skeptical of the Southwest Coastal Project's long-term success. "This notion that you can restore the coast—that might have been an ambitious and worthwhile goal in the 1990s, when people first started talking about it," he says. "But now, as we're seeing how this is playing out and realities of the pace of sea-level rise, I think most of the science community is saying maybe the restoration plan isn't going to really rebuild the coast."

Across the gulf, experts like Jim Blackburn, a professor of environmental law at Rice University in Houston, are calling for managed retreat instead. "Our mindset is wrong," he says. "We're more concerned about selling houses than telling the truth."

Indeed, managed retreat is a strategy that is being applied globally, notes Jim Elliott, a Rice University sociologist researching natural disasters' long-term community impacts. The option has been deployed in every US state and about 500 municipalities nationwide, he says.

Yet Elliott explains that only small communities (like the Oakwood Beach neighborhood of Staten Island, New York, which was severely damaged during Hurricane Sandy in 2012) and communities already disappearing as a result of coastal erosion (like Isle de Jean Charles, Louisiana, and Newtok, Alaska) have seen success in acquiring mixtures of state and federal funding to relocate most of their households.

The effort to move the mostly Indigenous residents from Isle de Jean Charles is in fact the only time Louisiana has funded large-scale community relocation. By 2016, when state legislators allocated that funding, the rural island had lost almost 98% of its land and was barely habitable. Colten, who helped advise the state on the relocation process, called it "incredibly complex"; issues included disagreements among residents and construction delays on a new planned community off island. The price tag was also staggering: roughly $1 million was spent to relocate each household, for a total of about $45 million to move 40 families.

"The costs are absolutely frightening for government officials to think about," he says. "Although the state very clearly touted

the Isle de Jean Charles relocation as a model for guiding other relocation efforts, I don't think that position is going to be made in the future."

For these reasons, Colten believes, the government will attempt to avoid managed retreat until it's the only option remaining, and only for those who can't afford to relocate on their own.

Jennifer Cobian, Calcasieu Parish's grants coordinator and assistant director of planning and development, says her parish has considered only small-scale managed retreat measures, like buyouts for individual homes in the city's most flood-prone areas.

A buyout "is always a painful thought to have—that this whole area right here should be abandoned, or folks should move elsewhere," Cobian says. Instead of "just abandoning properties or letting the property value go down," she hopes the Southwest Coastal Project will "elevate them and [allow] the individual to stay in their home."

Through those means, she believes, the community and economy can stay "vibrant, thriving."

COBIAN'S VISION FEELS FAR OFF FOR LOCALS LIKE Sheila Ramsey, who has lived in Lake Charles her entire life. The only time she, her granddaughter, and her son, who uses a wheelchair, have lived elsewhere was after the 2020 hurricanes damaged their home and forced them to temporarily relocate.

When Ramsey and her family eventually returned to Lake Charles, they learned their home insurance company had declared bankruptcy; the policy she had paid into was null and void.

Without that assistance, Ramsey has not been able to repair their home to livability. She also couldn't afford to move, even if she wanted to. So she's forced to choose between paying her monthly mortgage and fixing the house. The family lives in a rented camper on the front lawn.

"I'm just praying and believing to God that something's gonna come through," Ramsey says.

Stories like hers reflect the severe challenges facing southwest Louisiana. But while she and her family are essentially stuck waiting for help, others are leaving the area for good.

Migrating away from coastal threats is not exactly a new phenomenon in the region. Small-scale inland migration, or "moving up the bayou," in some ways defines its history of survival, Colten says: "You stay within reach of your relatives and occupation by moving five, 10 miles up the bayou. It moves you out of harm's way but keeps you in your cultural milieu."

But movement over the past several years has been vastly accelerated. Since Hurricane Rita's 18 feet of storm surge in 2005, Cameron Parish's rural population has dwindled from roughly 10,000 to just about 5,000 today. And after the 2020 hurricanes, Lake Charles experienced the nation's largest population exodus that year, according to US Postal Service change-of-address data.

This makes life even more difficult for the people who stay, Colten says. Communities are "losing their ability to support the basic parish services and pay the personnel who need to be there to administer emergency management and basic fire and police services—the basics."

Despite these challenges and the skepticism from experts, local officials like Calcasieu Parish's Cobian and Haase, the CPRA chair, remain hopeful they have found a way build a future here.

Haase believes "with all [his] heart and mind" in southwest Louisiana's survival. CPRA's mission is "to provide for a sustainable coast into the future," he says. "It's not to provide necessarily for the same coast we have today, or the coast that we had 10 or 20 or 100 years ago, but it is to provide a sustainable footprint that's livable."

Christa Bell, meanwhile, is unsure if her family will stay or leave. She understands that elevating their home could be complicated, and she and her husband haven't yet been contacted about the possibility. But if someone did reach out, she says, "we'd be willing to discuss if they could convince us they could do it without destroying the house, or costing an arm and a leg."

Anything to avoid flooding, she adds. Even if that means leaving southwest Louisiana altogether. ■

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MOM'S
DREAM
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L-300

Stations

As the International Space Station reaches the end of its life, the private sector is looking to step in and build a permanent presence in low Earth orbit. By DAVID W. BROWN

in the sky

The International Space Station was designed to fly for 20 years. It has lasted six years longer than that. Plans are now underway to safely destroy the craft around 2030.

1973

Skylab, the first US space station, was launched by NASA on May 14, 1973, on the final flight of the agency's Saturn V rocket. Skylab followed an experimental Soviet station launched in 1971 and was occupied until February 1974, by three successive astronaut crews.

1986

The Soviet Union and later Russia operated **Mir** from 1986 to 2001. Mir was assembled in orbit over the course of about 10 years. During its life, the station played host to American astronauts and set records for long-duration spaceflights, with visits lasting hundreds of days.

Washington, DC, was hot and humid on June 23, 1993, but no one was sweating more than Daniel Goldin, the administrator of NASA. Standing outside the House chamber, he watched nervously as votes registered on the electronic tally board. The space station wasn't going to make it. The United States had spent more than $11 billion on it by then, with thousands of pounds of paperwork to show for it—but zero pounds of flight hardware. Whether there would ever be a station came down, now, to a cancellation vote on the House floor.

Politically, the space station was something of a wayward orphan. It was a nine-year-old Reagan administration initiative, expanded by George H.W. Bush as the centerpiece of a would-be return to the moon and an attempt to reach Mars. When voters replaced Bush with Bill Clinton, Goldin persuaded the new president to keep the station by pitching it as a post-Soviet reconstruction effort. The Russians were great at building stations, which would save NASA a fortune in R&D. In turn, NASA's funding would keep Russian rocket scientists employed—and less likely to freelance for hostile foreign powers. Still, dissatisfaction with NASA was a bipartisan affair: everyone seemed to agree that the agency was bloated and ossified. Representative Tim Roemer, a Democrat from Indiana, wanted to make some big changes, and he introduced an amendment to the NASA authorization bill to kill the station once and for all.

Goldin had made more than 100 phone calls in the day and a half before the vote, hoping to sway lawmakers to endorse the station, which he saw as critical for studying biomedicine, electronics, materials engineering, and the human body in a completely alien environment: microgravity. Things down to the molecular level behave profoundly differently in space, and flying experiments a week at a time on the shuttle wasn't enough to learn much. Real research required a permanent presence in space, and that meant a space station.

Supporters of the space station had gone into the vote expecting to win. Not by much—20 votes, maybe. But the longer the vote went on, the closer it got. Each side began cheering as it pulled ahead. The 110 new members of Congress, none of whom had ever before cast a vote involving the station, revealed themselves to be less reliable than expected.

Finally, the tally reached 215–215, with one vote remaining: Representative John Lewis of Georgia, a civil rights legend. As Lewis walked down the hall toward the legislative chamber, Goldin's legislative aide, Jeff Lawrence, told the administrator to say something—anything—to win him over. As Lewis walked by, Goldin had only one second, maybe two, and the best he could get out was a raw, honest, "Congressman Lewis, the future of the space program depends on you." He added: "The nation is counting on you. How will you vote?"

Lewis smiled as he walked by. He said, "I ain't telling you."

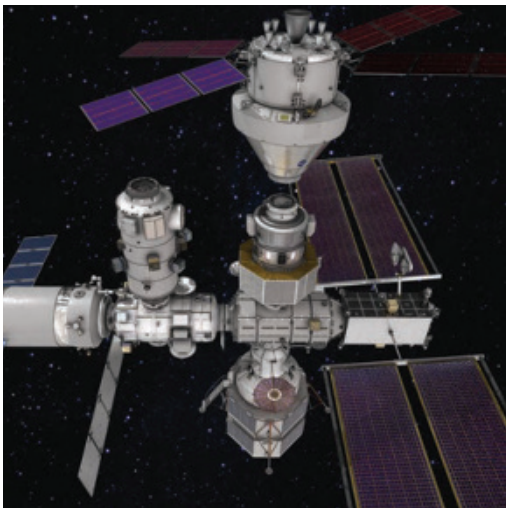
The station, later named the International Space Station, survived by his single vote, 216–215. Five years later, Russia launched the first module from Kazakhstan, and since November 2000, not a single day has elapsed without a human being in space.

NASA designed the International Space Station to fly for 20 years. It has lasted six years longer than that, though it is showing its age, and NASA is currently studying how to safely destroy the space laboratory by around 2030. This will involve a "deorbit vehicle" docking with the ISS, which is the size of a football field (including end zones), and firing

ABOVE AND PREVIOUS SPREAD: NASA

2021

Like Mir, China's **Tiangong space station** was assembled in space. Its first module launched in April 2021, and its third and final module docked in November 2022. China is excluded from participation in the International Space Station and so has gone it alone in low Earth orbit.



2025 (planned)

As part of a return to the moon, NASA is working with international partners to build **Gateway**, an outpost in lunar orbit. The station will be used for research and to support exploration of the lunar surface and places beyond. Launches to assemble it will begin no earlier than 2025.

thrusters so that the station, which circles the Earth at five miles per second, slams down squarely in the middle of the Pacific Ocean, avoiding land, injury, and the loss of human life.

As the scorched remains of the station sink to the bottom of the sea, however, the story of America in low Earth orbit (LEO) will continue. The ISS never really became what some had hoped: a launching point for an expanding human presence in the solar system. But it did enable fundamental research on materials and medicine, and it helped us start to understand how space affects the human body. To build on that work, NASA has partnered with private companies to develop new, commercial space stations for research, manufacturing, and tourism. If they are successful, these companies will bring about a new era of space exploration: private rockets flying to private destinations. They will also demonstrate a new model in which NASA builds infrastructure and the private sector takes it from there, freeing the agency to explore deeper and deeper into space, where the process can be repeated. They're already planning to do it around the moon. One day, Mars could follow.

From the dawn of the space age, space stations were envisioned as essential to leaving Earth.

In 1952, Wernher von Braun, the primary architect of the American space program, called them "as inevitable as the rising of the sun" and said they'd be integral to any sustainable exploration program, mitigating cost and complexity. Indeed, he proposed building a space station before a moon or Mars program, so that expeditions would have a logistical way station for resupply and refueling.

"Going into the 1960s, there's a lot of consensus and momentum around the idea that space is going to be a three-step process," says historian David Hitt, coauthor of *Homesteading Space: The Skylab Story*. Step one, he told me, is transportation. You've got to leave Earth somehow, which means developing the infrastructure to build human-safe rockets and launching them. Step two is habitation. You need a place to live once you are in space—for its own sake as a science laboratory, and also as a logistical waypoint between Earth and other celestial objects. "Once you have transportation and habitation," he says, "you can take your next step, which is exploration."

The mindset changed after the Soviet Union beat the United States to orbit, first with its Sputnik I satellite in 1957 and again when cosmonaut Yuri Gagarin became the first man in space in 1961. President John F. Kennedy committed the nation to landing a man on the moon and returning him safely to Earth "before this decade is out." It was an outrageously ambitious goal, given that NASA had only managed to launch a human to space three weeks earlier. "It required moving quickly, and the way you do that is to take the three-step plan and get rid of step two," Hitt told me. "As it turned out, if you skip the habitation stage, it works—the US got to the moon, but did so in a way that did not lay the groundwork for the long-term sustainability of the program."

We are still working on that. Two years after the final Apollo mission, NASA launched the first American space station, Skylab. Adapted from the second stage of a Saturn V moon rocket, it was enormous: 99 feet (30 meters) long and by far the heaviest spacecraft ever launched. NASA would eventually launch three missions of three astronauts each to the station, where they would perform more than a hundred experiments.

GETTY IMAGES (TIANGONG); NASA

"In a very real way, Skylab was the first American space mission," Hitt says. "Before Skylab, we were flying moon missions—even going back to the Mercury program, the goal was always the moon. Skylab is the first time that space itself became the destination." Its goals were foundational to what would later come. "The big thing that Skylab taught us is that human beings can, in fact, live and work long durations in a space environment. If we're serious about going to Mars, you [may] spend way longer in space than you're going to spend on the Martian surface."

Skylab remains the only space station built and launched solely by the United States. In 1986, the Soviet Union launched the first module of Mir, a modular space station built like Lego blocks, one segment at a time. Because NASA had discontinued the Saturn V rocket, the agency necessarily adopted the same modular station model, eventually partnering with Russia and other countries to build the ISS. Today it shares the skies with Tiangong, China's permanent space station, the first module of which launched in 2021. None of these stations have acted as moon or Mars way stations in the von Braun mold; to satisfy that requirement, NASA is developing a future station called Gateway that is intended to orbit the moon. Its first module could launch next year.

Although they never became transportation hubs, each space station has advanced the critical cause of learning what long stretches of space do to the human body. (Russian cosmonaut Valeri Polyakov, who flew on Mir, holds the all-time record for continuous spaceflight, with 437 days.) Researchers still have a relative paucity of knowledge about how the body responds to space. On Earth, we have the collective experience of more than 100 billion human beings across 300,000 years, and still much about the human body remains a mystery. Why do we yawn? What should we eat? Fewer than a thousand people in 63 years have ever been to space. Such studies can only occur on permanent space stations.

"During the shuttle program, we were studying the effects of just a shorter-duration spaceflight—a couple weeks—on the human body," Steven Platts, chief scientist of NASA's Human Research Program, told me. Among the problems was "orthostatic intolerance," which is the body's inability to regulate blood pressure. It affected about a quarter of crew members who returned from space. Once NASA and Russia launched the ISS and spaceflight durations increased from weeks to months, that number leaped to 80%. "We spent a lot of time trying to tease out that mechanism. And we eventually came up with countermeasures so that that risk is now considered closed," he says.

Other challenges include spaceflight-associated neuro-ocular syndrome, which is a change in the structure and function of the eye, something researchers identified about 10 years ago. "We didn't really see it with the shuttle, but as we started doing more and more station missions, we saw it," Platts says. They have also identified small, structural changes in the brain but have yet to figure out what that means in the long term: "That's a relatively new risk that we didn't know about before the space station."

Overall, he says, the ability of the human body to regulate its function in space is "amazing." His group is working on about 30 risks to humans posed by space exploration, which it classifies in a color-coding scheme. Green issues are well controlled. Yellow risks are of moderate concern, and red ones must be solved before missions are possible. "Right now, for low Earth orbit there are no red. Everything is yellow and green. We understand it pretty well and we can deal with it. But as we get to lunar, we see more yellow and some red, and as we get to Mars, we see more red yet," Platts says. "There are things that we know right now are a problem, and we're working hard to try and figure them out, either from a research standpoint or an engineering standpoint."

Some problems can only be studied as we venture farther into space—the long-term effects of Mars dust on the human body, for example. Others, such as the unanticipated development of psychiatric disorders, can be studied closer to home.

"Even going back to the Mercury program, the goal was always the moon. Skylab is the first time that space itself became the destination."

Michael Baine, the chief technology officer of Axiom Space, began his career at NASA Johnson Space Center.

ANTHONY RATHBUN

NASA and other institutions are currently studying all this on the ISS and will need to continue such research long beyond the space station's retirement—one reason why it is imperative that someone else launch a successor space station, and soon. To that end, just as it did with SpaceX from 2006 through 2011, the agency has seeded several companies with small investments, promising to lease space on emergent space stations. And right now, the soonest likely to launch is being led out of a sprawling former Fry's Electronics retail store in a shopping center complex in Texas.

I met Michael Baine, the chief technology officer of Axiom Space, on a gray, drizzly January morning at the entrance to its Space Station Development Facility in Houston. Baine began his career at NASA Johnson Space Center just down the road, where he worked on everything from the shuttle and station to experimental lunar landers. Later, he left the agency to join Intuitive Machines as its chief of engineering. In February, that company's Nova-C spacecraft, Odysseus, became the first US spacecraft to land successfully on the moon since the end of the Apollo program in 1972, making Intuitive Machines the first private company to land successfully on a celestial object beyond Earth. Baine has worked at Axiom Space since 2016. The startup's long-term goal is to build the first private commercial space station. It has successfully organized and managed three private missions to the International Space Station, in large part to study firsthand how humans work and live in space, so that they might design a more user-friendly product.

Axiom is not the only company interested in launching private space stations. Most notably, Blue Origin announced in 2021 that in partnership with the aerospace outfit Sierra Nevada, it would build Orbital Reef, a "mixed-use business park" capable of supporting up to 10 people simultaneously in low Earth orbit. In January, Sierra Nevada successfully stress-tested a one-third-scale test article of its habitat module, with the intention of launching a station into orbit on a Blue Origin New Glenn rocket in 2027. Other companies, such as Lockheed Martin, have made moves into the market, though their progress is less clear.

Axiom plans to build its own orbital facility much differently, Baine told me as we entered the facility. Suspended from the wall above, large, low-fidelity models of spacecraft hung from the ceiling, including the X-38 (an experimental emergency return vehicle for space station crew) and Zvezda, the Russian module of the ISS, which today is plagued by age-induced stress fractures and consequent leaks. Crew vehicles no longer dock with it.

"It's very difficult to build a full, self-sustaining space station and launch it in one shot," Baine said as we walked past an open-concept cube farm beneath the models, where about 500 men and women are designing a space station to replace Zvezda and the rest of the ISS. "What you want to do is assemble it in

Above: A mock-up of Axiom's Habitat One (Hab One), which will include crew quarters and manufacturing capabilities.

Right: A mock-up of the interior of the module.

space in a piecemeal fashion. The easiest way to do that is to start with something that is already there."

That "something" is the International Space Station itself. In 2026, Baine expects to launch Axiom Hab One, a cylindrical module with crew quarters and manufacturing capabilities that will plug into an open port on the ISS. Later, Axiom plans to launch Hab Two, expanding habitation, scientific, and manufacturing services. Then it hopes to launch a research and manufacturing facility, complete with a spacious, fully glassed cupola to give Axiom astronauts and visitors on the station access to a complete view of planet Earth, as well as the length of the station. Finally, the company intends to launch a "power thermal module" with massive solar panels, expanded life support capabilities, and payload capacity.

Each new segment is designed to plug into the preceding Axiom segment. This isn't aspirational; there is a hard deadline in effect. Unless the ISS gets a new lease on life, everything must be launched and assembled by 2030. Once NASA officially declares the ISS mission completed, the Lego-like Axiom Station will detach from the ISS as its own integrated and fully self-sustaining space station. Afterward, the deorbit vehicle will do its job and push the ISS into the ocean.

"It's a big risk reduction for us to be able to use ISS as a staging point to build up our capability one element at a time," Baine explains. That plan also offers a huge commercial advantage. There is already a robust, global user base of companies and researchers sending projects to the ISS. "In order to court those users to migrate to a commercial solution, it just becomes easier if you're already at a location where they're at," he says. Everything from technical interfaces to the way Axiom Station will handle the outgassing of materials will be compatible with existing ISS hardware: "We have to meet the same standards that NASA does."

A lot of people are betting that there are fortunes to be made in LEO, and because of that, the US taxpayer is not paying for Axiom Station. Though NASA intends to eventually rent space on Hab One, and has already awarded tens of millions of dollars to kick off early development, the commercial station is being built by hundreds of millions of private dollars. The cultivation of commercial research and manufacturing is ongoing, which was NASA's aim going all the way back to Dan Goldin's tenure as administrator.

"We wanted to turn over the keys to the shuttle, the station—all that—to the private sector," says Lori Garver, a former deputy administrator of NASA and author of *Escaping Gravity*. "Dan believed if we could hand over low-Earth-orbit infrastructure, NASA could go farther into space, and I really bought into that." Garver would later pioneer the commercial spaceflight model that led SpaceX and other companies to take over launch services, saving the agency tens of billions of dollars while simultaneously speeding launch cadence—the same model that led to Axiom's space station work.

"After launching the first module in 1998, we announced that space was open for business," Garver told me. The first person to reach out was Fisk Johnson, of S.C. Johnson & Son. He wanted to work with NASA to develop a bioreactor to help create new pharmaceuticals for liver disease in a microgravity environment. "I worked with him for probably three years at NASA," Garver says. "Unfortunately, their flight mission was *Columbia*, and we lost the experiment in the tragedy."

In the decades to follow, commercial research and development would increase, with limitations. NASA, Russia, and the other partner nations did not design the ISS specifically as a large-scale research and manufacturing facility, and one reason no company has elected to simply buy the station outright is that refurbishing it would be more complex and expensive than either building a new station, as Axiom has elected to do, or renting space on a modern successor.

As we came upon a stunning, full-scale mock-up of Hab One at the far end of the building, I asked Baine if starting with the technical solutions already developed by

"We wanted to turn over the keys to the shuttle, the station—all that—to the private sector."

ANTHONY RATHBUN

NASA—the way environmental systems work, for example—makes Axiom Station easier from an engineering perspective.

"You would think so," he replied, "but these are very demanding standards, and they require a lot of attention to detail." The voluminous testing and analyses to prove that you meet the requirements necessary to interface with ISS generate a lot of work, "but you end up with a structure or a component that is extremely reliable. The chances that a failure could propagate to a loss of crew is very, very remote."

Only looking at the mock-up did I realize the immensity of the spacecraft. It is 15 feet (4.6 meters) at its widest, and 36 feet long. Once docked with the ISS, Hab One, which weighs 30 metric tons on Earth and can support four astronauts, will be the longest element on the station.

Here at the Space Station Development Facility, the entire mock-up is made of CNC-machined wood. But the module is much further along than the existence of a "mock-up stage" would suggest. Its pressure vessel (that is, its primary shell, which holds air and maintains an Earth-like pressure environment in the vacuum of space) and its hatches are essentially completed and will soon be shipped from Italy by the same contractor that built many modules of the ISS. Baine walked me through a partitioned facility where Axiom Station's avionics, propulsion, life support systems, communications, and other subsystems are well into development. Befitting the former Fry's Electronics building in which we stood, there was a home-brew element to the systems, many of which were strewn across tables—an elaborate web of wires, tubes, circuit boards, and chips. The station will run on Linux.

Axiom built the mock-up to solve an almost comically fundamental challenge that any project such as this faces: turning the pressure shell and the myriad subsystems and components into a human-safe spacefaring vehicle. You can't just drill holes in the pressure shell, any more than you can punch a hole in a balloon and expect it to keep its shape. Axiom must build the module inside and around it. "It is a spaceship-in-the-bottle problem," Baine said. "You basically have to feed all your systems through a 50-inch hatch and integrate them into the element." He calls it one of the hardest problems in the business, because it's about more than assembling systems inside a pressure shell in Houston—it's also about making the station user friendly for servicing in orbit, if ever a technical issue arises.

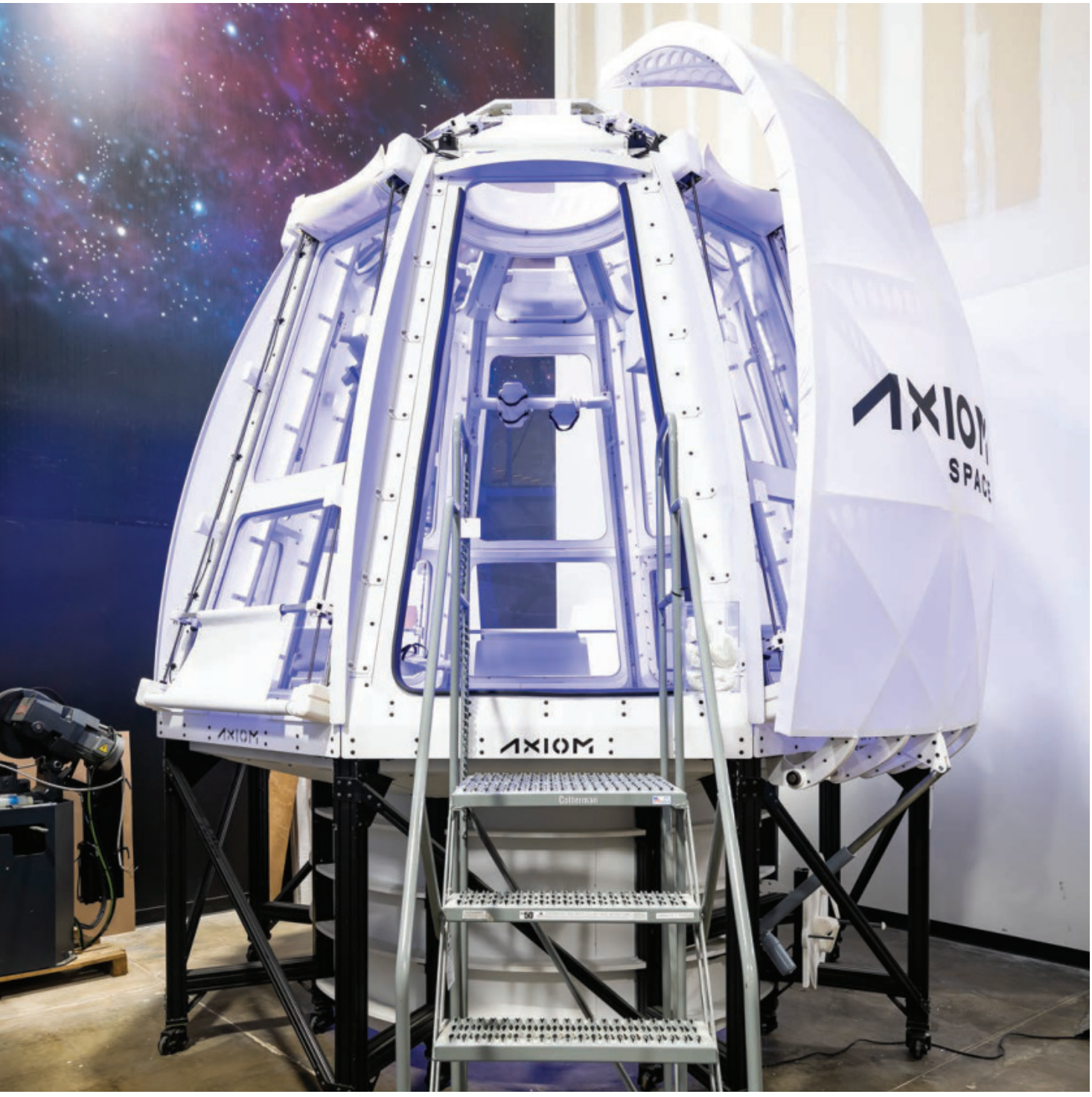
Today, tourism and research are probably the best-known uses of private spaceflight. But Axiom has other functions in mind for the station, including serving as a destination for countries that have yet to get involved in sending humans to space. Last year, the company announced the Axiom Space Access Program, which Tejpaul Bhatia, the company's chief revenue officer, described as a "space program in a box" for countries around the world. Axiom says the program is evolving, but that it is a pathway for space participation. Azerbaijan was the first country to sign on.

But one of the most promising business prospects for the immediate future is manufacturing. Low Earth orbit is an especially good environment for making things in three areas: pharmaceuticals, metallurgy, and optics. Microgravity eliminates a number of physical phenomena that can interfere with sensitive steps in manufacturing processes, yielding more consistent material properties and structures. Axiom and Blue Origin are betting that modern space stations built around the insights gleaned from decades of ISS experimentation (but freed of its 1980s and 1990s technology) will pay dividends.

As part of its push to encourage companies to develop their own space stations, NASA has committed to leasing space on those that meet the agency's stringent human-spaceflight requirements. Just as with a major shopping center, an "anchor tenant" can offer financial stability and attract more tenants. To help this along, a US national laboratory based in Melbourne, Florida, is specifically funding and supporting non-aerospace companies that might benefit from microgravity research.

"It is a spaceship-in-the-bottle problem. You basically have to feed all your systems through a 50-inch hatch."

ANTHONY RATHBUN



Left: Axiom's R&D facility is housed in a sprawling former Fry's Electronics retail store in a shopping center complex.

Above: The Axiom Station Earth Observatory module will allow astronauts a 360-degree view of their surroundings.

Biomedicine in particular has yielded perhaps the best results with the nearest-term impact, as best represented by LambdaVision, a company established in 2009 by molecular biologists Nicole Wagner and Robert Birge. What makes it the most compelling glimpse of LEO's promise is that LambdaVision was not founded as an aerospace company. Rather, Wagner and Birge were building a traditional, Earth-based company atop their research on a protein called bacteriorhodopsin and its potential to restore neural function. BR is a "proton pump," which is just what it sounds like. It pumps a proton from one side of a cell to the other.

They focused on the problems of retinitis pigmentosa and macular degeneration. In a healthy eye, photoreceptor cells—rods and cones—take in light and convert it into a signal that goes to bipolar and ganglion cells, and then to the optic nerve. In both diseases, the rods and cones start to die, and once they are gone, there is nothing to take in light and turn it into a signal that can be sent to the brain. Retinitis pigmentosa, which afflicts 1.5 million people around the world, begins by affecting peripheral vision and encroaches inward, leading to severe tunnel vision before causing complete blindness. Macular degeneration works the opposite way, first affecting central vision and then spreading outward. About 30 million people around the world suffer from it. Treatments exist for both diseases, but even the best can only slow their progression. In the end, blindness wins, and once it does, there is no treatment.

Wagner, Birge, and their team at LambdaVision had an idea for something that might help: a simple, flexible implant about as big as the circle stamped out by a hole punch and the thickness of a piece of construction paper that could replace the damaged light-sensing cells and restore full vision. In principle, physicians could install the patch in the back of the eye, the same way they treat detached retinas, so it would not even require specialized training.

The problem was making this artificial retina. The implant requires using a scaffold—essentially a tightly woven porous material similar to gauze—and binding a polymer to it. Atop that, the researchers begin applying alternating layers of BR protein and polymers. With enough layers, the protein can absorb enough light and pump protons—hydrogen ions, specifically—toward the bipolar and ganglion cells, which take it from there, restoring vision in high definition.

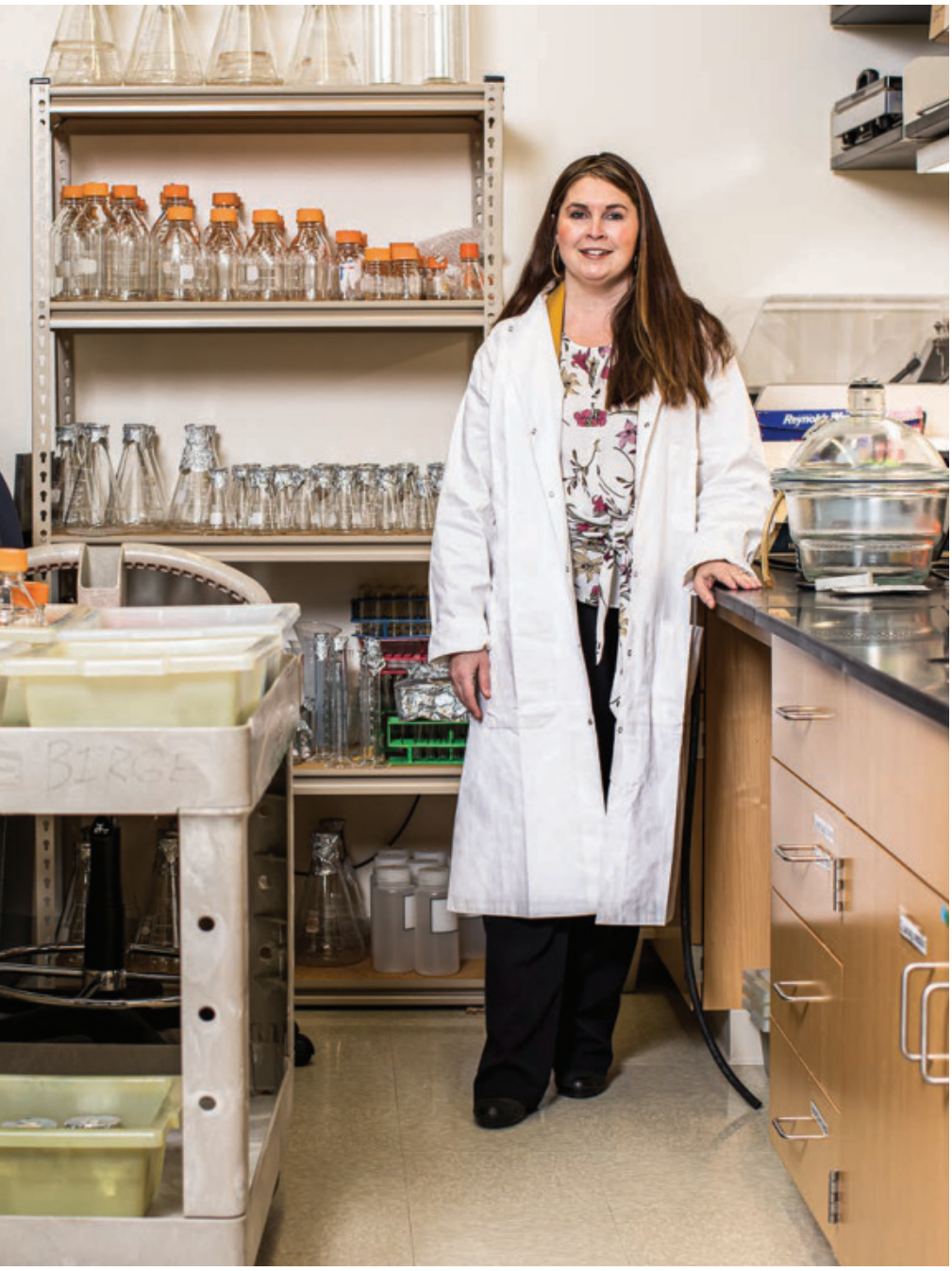
To apply multiple layers, scientists float the scaffold on a solution in multiple beakers, moving from one to the next and repeating the process. The problem is that fluid solutions are never perfect—things float, they sink, they settle, they form sediment, they evaporate, there is convection, there are surface-tension variations—and every variation and imperfection can lead to a flawed layer.

If an implant requires 200 layers, an imperfection at layer 50 compounds massively by the end. The process is simply inefficient, and rife with irregular protein deposition. Early trials revealed that this issue negatively affected the artificial retina's performance.

It was the sort of thing LambdaVision was hoping to work through as part of MassChallenge, a business incubation program in Boston. Wagner was working in the business accelerator's co-working space one day in 2017. It had a "Google-y" feel, she felt, with an open-concept office and smart people all around, and she was at the desk they'd assigned her when somebody dropped by to say that the International Space Station National Laboratory was holding a lunch presentation down the hall, and there was free pizza.

Why not, Wagner thought. It would be pretty cool to hear people from NASA talk about the moon and Mars. When she got there, though, it turned out that it wasn't that sort of presentation at all. Instead, representatives from CASIS—the Center for the Advancement of Science in Space, a nonprofit that operates the ISS National Lab—gave a talk on how they are using microgravity to help people on Earth.

"I never envisioned doing anything in space—I didn't know how to get there, or how it worked. Before that moment, it all sounded like science fiction."



Nicole Wagner is co-founder of LambdaVision, a biotech startup that is working on making artificial retinas in low Earth orbit.

JULIE BIDWELL

The US segment of the International Space Station, like Los Alamos, Oak Ridge, and Brookhaven, is a national laboratory dedicated to scientific and technological research. The office simply has a better view. About half the science conducted on the US segment is managed by the ISS National Laboratory out of Florida, with the remainder overseen by NASA. This division of resources allows for a wide range of scientific investigations on the station. Where NASA's research typically focuses on exploration, space technology, and fundamental science to support future deep-space missions, the ISS National Laboratory aims to develop a sustainable low-Earth-orbit economy, encompassing fields like materials science, biology, pharmaceutical research, and technology development.

Research being conducted on the station touches on metallurgy and fiber optics. Alloys like nitinol (nickel-titanium) can withstand huge temperature swings and are superelastic, with extraordinary potential for medical devices, aerospace, and robotics. Think artificial muscles. The problem is that nitinol is extremely hard to make on Earth because materials settle out and heat can get distributed unevenly during manufacturing, which yields an unreliable product. The same liabilities degrade the quality of fiber optics manufactured on Earth.

The solution to both is to go to space: in microgravity, heat distributes more uniformly and sedimentation does not occur. Crystallization, the process of forming and growing crystals, is consistent across long distances with minimal degradation (meaning pristine fiber-optic signals even as you grow across vast stretches). More broadly, however, space-based crystallography has applications in almost every field of electronics and biomedicine.

As Wagner learned, researchers have found immediate gains on the space station today in everything from development of more effective vaccines (gravity on Earth harms the interaction of antigens and adjuvants) to higher-grade drug formulations and nanoparticle suspensions. One such drug, made by Taiho Pharmaceutical, is used to treat muscular dystrophy and has reached final-stage trials.

"They were talking at that time about things like bioprinting on orbit, and future missions they were planning," Wagner told me. "It hit me immediately that we could do this—actually leverage microgravity to manufacture an artificial retina. I never envisioned doing anything in space—I didn't know how to get there, or how it worked. Before that moment, it all sounded like science fiction."

After the meeting, she immediately called her team. "There's a prize that I think we can win," she said. It was the CASIS-Boeing Technology in Space Prize, which funds research that might benefit from space-station access. "We're gonna do it."

Her team was immediately skeptical. In truth, she had her doubts as well. She was running a small startup. How were they going to build a small, automated science laboratory, put it on the International

LambdaVision's artificial retina (above) can be manufatured inside a small box (left), without need of astronaut intervention.

Right: A mock-up of NASA's Habitation and Logistics Outpost (HALO) module, the first component of a planned moon-orbiting Gateway station.

Space Station, have communication with it on the ground—how would they afford that? She pulled up a web browser and typed in "raspberry pi communication with space station." She thought: *What am I getting into?*

"It was my super-naïve vision of what space was at the time," she told me. The proper term that now described her company, she soon learned, was "space adjacent": a business that is not specifically in the aerospace industry but could benefit from—even work better by—leaving planet Earth.

She was relieved when she found out that LambdaVision didn't have to develop its own mission control and space infrastructure. It already existed, and there were partner companies that specialized in space-adjacent businesses. Her company linked up with Space Tango, which focuses on building underlying health and technology products in space, to develop its hardware. They managed to condense their open beaker system to an automated experiment the size of a shoebox. And she was right about one thing: they did win the prize.

The team flew its first mission at the end of 2018, and it showed promising results. In the years since, the company has secured additional funding and flown a total of nine times to the ISS, most recently launching on January 30. With each mission, they have gradually improved their manufacturing hardware, system automation and imaging, and orbital processes. "We're seeing much more evenly coated films in microgravity and overcome other challenges we see in a gravity environment," Wagner says. "There's much less waste."

The system works autonomously, without need of astronaut intervention. Essentially, the team assembles it in a small box, astronauts plug it into power on the ISS, and when it has manufactured the sheets of artificial retinas, an astronaut unplugs it and ships it back to Earth.

"At first, we just wanted to demonstrate that it's feasible to do this in space," says Wagner. "We don't worry about that now—we are thinking hard now about scaling the system up. To support our early clinical trials, we don't need millions of artificial retinas. We need hundreds, maybe thousands, to start. And that gives us time to determine how we are going to scale that up as we transition from the ISS—a public space station—to private, commercial space stations in low Earth orbit."

So far, LambdaVision has performed small-animal studies in rats and advanced to large-animal studies in pigs, successfully installing the implants and demonstrating their tolerability. The company is continuing preclinical development to support clinical trials—doing such things as testing the artificial retinas for efficacy and safety—with a goal of beginning human trials as soon as early 2027.

"When I think about doing it in space and talking about cost and efficiency, I don't think about it any differently than if somebody said, 'Hey I'm gonna go do this in China' or 'I'm gonna go do this in California,'" Wagner says. "A space station is actually closer. It's only 250 miles in the sky, versus 3,000 miles to California."

If LambdaVision is successful, that alone would practically justify the vote cast by John Lewis 31 years ago. It is hard to think of an achievement more profound than curing blindness for millions. But even more than delivering such sweeping and life-changing results, one of the most significant accomplishments of the ISS might be proving that such results can even be achieved in the first place.

PHOTOS COURTESY OF LAMBDAVISION

NASA

So far, no major medicines born on the space station have been brought to market. No mass-produced technologies have yet emerged from low Earth orbit. Research has been iterative, and in-space manufacturing remains in the early stages. But according to Ariel Ekblaw, CEO of the Aurelia Institute, a nonprofit space research center dedicated to working on "critical path" infrastructure for space architectures, NASA's groundwork for the ISS has made a next generation of more product-focused work possible.

"Maybe Dan Goldin was ahead of his time in thinking that such work was going to be achieved within the time span of humanity's first-ever truly large-scale international space station," she told me, "and what we see now is not just basic science, but entities like biotech companies actually taking what we learned from NASA and the National Lab over the last 20-plus years, and envision putting mass-produced products or mass-produced infrastructure in space."

If indeed the handoff of low Earth orbit from NASA-led to commercial operations succeeds, it would be a promising glimpse of the future of the lunar economy. There, as in LEO, NASA is methodically building infrastructure and solving fundamental problems of exploration. The moon-orbiting Gateway station—a NASA-led international effort—is deep into development, with the Habitation and Logistics Outpost (HALO) module set to launch as early as next year. That station will serve as the "second step" of a sustainable moon strategy that was excised from the Apollo program 60 years ago. From there, NASA hopes to cultivate a presence on the lunar surface.

If the LEO model holds, the agency could one day transfer moon-base operations to the private sector and turn to Mars. There might be a lot of money to be made simply in harvesting water on the moon, to say nothing of rare earth elements that lend themselves to manufacturing as well.

One of the harshest restraints on progress in space has been, ironically, space. "Right now, on a good day, only 11 people fit in orbit on ISS and Tiangong," says Ekblaw. The age of private space stations is going to be fundamentally transformative if only because there will be more room for dedicated researchers.

Axiom's goal is to double its infrastructure in space every five years. This means doubling the number of people in orbit, the number of hosted payloads, and the amount of manufacturing they are capable of doing.

"Within two to three years, I could send a graduate student to space with Axiom," Ekblaw says. "It requires a little creative fundraising, but I think that that is opening up a realm of possibility." In the past, she explains, a doctoral researcher would be unbelievably fortunate to have research fly as part of a single flight mission. Today, however, researchers even in a master's program can fly experiments repeatedly because of the increased opportunities afforded by commercial spaceflight. In the future, rather than relying on career NASA astronauts—who have myriad responsibilities in orbit and spend a good amount of time as guinea pigs themselves—scientists could go up personally to run their own research projects in greater depth.

"And that," she says, "is a future that is very, very near." ■

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

The space race grabbed headlines, but the mind-control race changed America forever.

By Annalee Newitz
Illustration by Shirley Chong

Changing our minds

On an early spring day in 1959, Edward Hunter testified before a US Senate subcommittee investigating "the effect of Red China Communes on the United States." It was the kind of opportunity he relished. A war correspondent who had spent considerable time in Asia, Hunter had achieved brief media stardom in 1951 after his book *Brain-Washing in Red China* introduced a new concept to the American public: a supposedly scientific system for changing people's minds, even making them love things they once hated.

But Hunter wasn't just a reporter, objectively chronicling conditions in China. As he told the assembled senators, he was also an anticommunist activist who served as a propagandist for the OSS, or Office of Strategic Services—something that was considered normal and patriotic at the time. His reporting blurred the line between fact and political mythology.

When a senator asked about Hunter's work for the OSS, the operative boasted that he was the first to "discover the technique of mind-attack" in mainland China, the first to use the word "brainwashing" in writing in any language, and "the first, except for the Chinese, to use the word in speech in any language."

None of this was true. Other operatives associated with the OSS had used the word in reports before Hunter published articles about it. More important, as the University of Hong Kong legal scholar Ryan Mitchell has pointed out, the Chinese word Hunter used at the hearing—*xinao* (洗腦), translated as "wash brain"—has a long history going back to scientifically minded Chinese philosophers of the late 19th century, who used it to mean something more akin to enlightenment.

Yet Hunter's sensational tales still became an important part of the disinformation and pseudoscience that fueled a "mind-control race" during the Cold War, much like the space race. Inspired by new studies on brain function, the US military and intelligence communities prepared themselves for a psychic war with the Soviet Union and China by spending millions of dollars on research into manipulating the human brain. But while the science never exactly panned out, residual beliefs fostered by this bizarre conflict continue to play a role in ideological and scientific debates to this day.

Coercive persuasion and pseudoscience

Ironically, "brainwashing" was not a widely used term among communists in China. The word *xinao*, Mitchell told me in an email, is actually a play on an older word, *xixin* (洗心), or washing the heart, which alludes to a Confucian and Buddhist ideal of self-awareness. In the late 1800s, Chinese reformists such as Liang Qichao began using *xinao*—replacing the character for "heart" with "brain"—in part because they were trying to modernize Chinese philosophy. "They were eager to receive and internalize as much as they could of Western science in general, and discourse about the brain as the seat of consciousness was just one aspect of that set of imported ideas," Mitchell said.

For Liang and his circle, brainwashing wasn't some kind of mind-wiping process. "It was a sort of notion of epistemic virtue," Mitchell said, "or a personal duty to make oneself modern in order to behave properly in the modern world."

Meanwhile, scientists outside China were investigating "brainwashing" in the sense we usually think of, with experiments into mind clearing and reprogramming. Some of the earliest research into the possibility began in the 1890s, when Ivan Pavlov, the Russian physiologist who had famously conditioned dogs to drool at the sound of a bell, worked on Soviet-funded projects to investigate how trauma could change animal behavior. He found that even the most well-conditioned dogs would forget their training after intensely stressful experiences such as nearly drowning, especially when those were combined with sleep deprivation and isolation. It seemed that Pavlov had hit upon a quick way to wipe animals' memories. Scientists on both sides of the Iron Curtain subsequently wondered whether it might work on humans. And once memories were wiped, they wondered, could something else be installed their place?

During the 1949 show trial of the Hungarian anticommunist József Mindszenty, American officials worried that the Russians might have found the answer. A Catholic cardinal, Mindszenty had protested several government policies of the newly formed, Soviet-backed Hungarian People's Republic. He was arrested and tortured, and he eventually made a series of outlandish confessions at trial: that he had conspired to steal the Hungarian crown jewels, start World War III, and make himself ruler of the world. In his book *Dark Persuasion*, Joel Dimsdale, a psychiatry professor at the University of California, San Diego, argues that the US intelligence community saw these implausible claims as confirmation that the Soviets had made some kind of scientific breakthrough that allowed them to control the human mind through coercive persuasion.

Chinese reformists like Liang Qichao used the term *xinao*—a play on an older word, *xixin,* or "washing the heart"—in an attempt to bring ideas from Western science into Chinese philosophy.

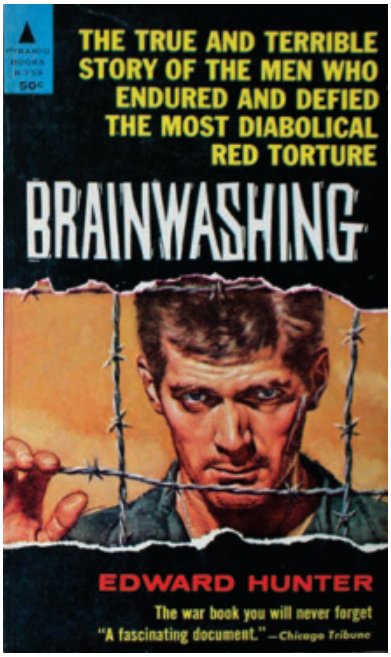
This question became more urgent when, in 1953, a handful of American POWs in China and Korea switched sides, and a Marine named Frank Schwable was quoted on Chinese radio validating the communist claim that the US was testing germ warfare in Asia. By this time, Hunter had already published a book about brainwashing in China, so the Western public quickly gravitated toward his explanation that the prisoners had been brainwashed, just like Mindszenty. People were terrified, and this was a reassuring explanation for how nice American GIs could go Red.

Over the following years, in the wake of the Korean War, "brainwashing" grew into a catchall explanation for any kind of radical or nonconformist behavior in the United States. Social scientists and politicians alike latched onto the idea. The Dutch psychologist Joost Meerloo warned that television was a brainwashing machine, for example, and the anticommunist educator J. Merrill Root claimed that high schools brainwashed kids into being weak-willed and vulnerable to communist influence. Meanwhile, popular movies like 1962's *The Manchurian Candidate*, starring Frank Sinatra, offered thrilling tales of Chinese communists whose advanced psychological techniques turned unsuspecting American POWs into assassins.

For the military and intelligence communities, mind control hovered between myth and science. Nowhere is this more obvious than in the peculiar case of an anonymously published 1955 pamphlet called *Brain-Washing: A Synthesis of the Russian Textbook on Psychopolitics*, which purported to be a translation of work by the Soviet secret-police chief Lavrentiy Beria. Full of wild claims about how the Soviets used psychology and drugs to control the masses, the pamphlet has a peculiar section devoted to the ways that Dianetics—a pseudoscience invented by the founder of Scientology, L. Ron Hubbard—could prevent brainwashing. As a result, it is widely believed that Hubbard himself wrote the pamphlet as black propaganda, or propaganda that masquerades as something produced by a foreign adversary.

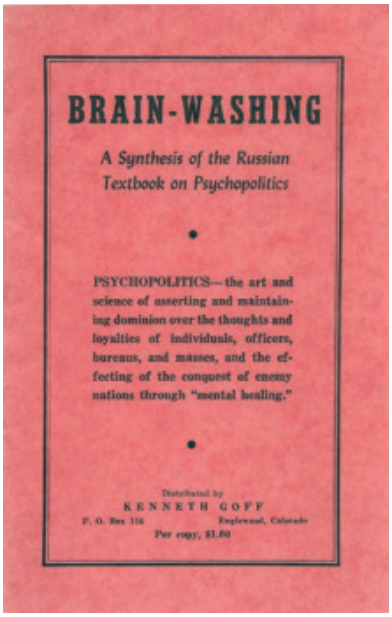
Still, US officials apparently took it seriously. David Seed, a cultural studies scholar at the University of Liverpool, plumbed the National Security Council papers at the Dwight D. Eisenhower Library, where he discovered that the NSC's Operations Coordinating Board had analyzed the pamphlet as part of an investigation into enemy capabilities. A member of the board wrote that it might be "fake" but contained so much accurate information that it was clearly written by "experts." When it came to brainwashing, government operatives made almost no distinction between black propaganda and so-called expertise.

This gobbledygook may also have struck the NSC investigator as legitimate because Hubbard borrowed lingo from the same



Right: A pamphlet published in 1955, purported to be a translation of a work by the Russian secret police, claimed that the Soviets used drugs and psychology to control the masses and that Dianetics, a pseudoscience invented by Scientology founder L. Ron Hubbard, could prevent brainwashing.

Left: Edward Hunter, who claimed to have coined the term "brainwashing," wrote a book that fueled paranoia about a "mind-control race" during the Cold War.



The 1962 film *The Manchurian Candidate*, starring Frank Sinatra, offered thrilling tales of Chinese communists whose advanced psychological techniques turned unsuspecting American POWs into assassins.

sources as many scientists of the era. Hubbard chose the name Dianetics, for instance, specifically to evoke the computer scientist Norbert Wiener's idea of cybernetics, an influential theory about information control systems that heavily informed both psychology and the burgeoning field of artificial intelligence. Cybernetics suggested that the brain functioned like a machine, with inputs and outputs, feedback and control. And if machines could be optimized, then why not brains?

An excuse for government abuse

The fantasy of brainwashing was always one of optimization. Military experts knew that adversaries could be broken with torture, but it took months and was often a violent, messy process. A fast, scientifically informed interrogation method would save time and could potentially be deployed on a mass scale. In 1953, that dream led the CIA to invest millions of dollars in MK-Ultra, a project that injected cash into university and research programs devoted to memory wiping, mind control, and "truth serum" drugs. Worried that their rivals in the Soviet Union and China were controlling people's minds to spread communism throughout the world, the intelligence community was willing to try almost anything to fight back. No operation was too weird.

One of MK-Ultra's most notorious projects was "Operation Midnight Climax" in San Francisco, where sex workers lured random American men to a safe house and dosed them with LSD while CIA agents covertly observed their behavior. At McGill University in Montreal, the CIA funded the work of the psychologist Donald Cameron, who used a combination of drugs and electroconvulsive therapy on patients with mental illness, attempting to erase and "repattern" their minds. Though many of his victims did wind up suffering from amnesia for years, Cameron never successfully injected new thoughts or memories. Marcia Holmes, a science historian who researched brainwashing for the Hidden Persuaders project at Birkbeck,

University of London, told me that the CIA used Cameron's data to develop new kinds of torture, which the US adopted as "enhanced interrogation" techniques in the wake of 9/11. "You could put a scientific spin on it and claim that's why it worked," she said. "But it always boiled down to medieval tactics that people knew from experience worked."

MK-Ultra remained secret until the mid-1970s, when the US Senate Select Committee to Study Governmental Operations with Respect to Intelligence Activities, commonly known as the Church Committee after its chair, Senator Frank Church, opened hearings into the long-running project. The shocking revelations that the CIA was drugging American citizens and paying for the torment of vulnerable Canadians changed the public's understanding of mind control. "Brainwashing" came to seem less like a legitimate threat from overseas enemies and more like a ruse or excuse for almost any kind of bad behavior. When Patty Hearst, granddaughter of the newspaper publisher William Randolph Hearst, was put on trial in 1976 for robbing a bank after being kidnapped by the Symbionese Liberation Army, an American militant organization, the judge refused to believe experts who testified that she had been tortured and brainwashed by her captors. She was convicted and spent 22 months in jail. This marked the end of the nation's infatuation with brainwashing, and experts began to debunk the idea that there was a scientific basis for mind control.

Still, the revelations about MK-Ultra led to new cultural myths. Communists were no longer the baddies—instead, people feared that the US government was trying to experiment on its citizens. Soon after the Church Committee hearings were over, the media was gripped by a crime story of epic proportions: nearly two dozen Black children had been murdered in Atlanta, and the police had no leads other than a vague idea that maybe it could be a serial killer. Wayne Williams, a Black man who was eventually convicted of two of the murders, claimed at various points that he had

Left: Believed to be a victim of communist mind control, the American POW Frank Schwable claimed on Chinese radio in 1953 that the US was testing germ warfare in Asia.

Right: After being arrested and tortured, the Catholic cardinal and anticommunist József Mindszenty made outlandish confessions at trial, like that he had conspired to steal the Hungarian crown jewels.

In publishing heiress Patty Hearst's 1976 trial for bank robbery, the judge refused to believe that she had been brainwashed as a victim of kidnapping.

PUBLIC DOMAIN (SCHWABLE); WIKIMEDIA COMMONS (MINDSZENTY); NATIONAL PORTRAIT GALLERY, SMITHSONIAN INSTITUTION, GIFT OF TIME MAGAZINE (HEARST)

been trained by the CIA. This led to popular conspiracy theories that MK-Ultra had been experimenting on Black people in Atlanta.

Colin Dickey, author of *Under the Eye of Power: How Fear of Secret Societies Shapes American Democracy*, told me these conspiracy theories became "a way of making sense of an otherwise mystifying and terrifying reality, [which is that America is] a country where Black people are so disenfranchised that their murders aren't noticed." Dickey added that this MK-Ultra conspiracy theory "gave a shape to systemic racism," placing blame for the Atlanta child murders on the US government. In the process, it also suggested that Black people had been brainwashed to kill each other.

No evidence ever surfaced that MK-Ultra was behind the children's deaths, but the idea of brainwashing continues to be a powerful metaphor for the effects of systemic racism. It haunts contemporary Black horror films like *Get Out*, where white people take over Black people's bodies through a fantastical version of hypnosis. And it provides the analytical substrate for the scathing indictment of racist marketing in the book *Brainwashed: Challenging the Myth of Black Inferiority*, by the Black advertising executive Tom Burrell. He argues that advertising has systematically pushed stereotypes of Black people as second-class citizens, instilling a "slave mindset" in Black audiences.

A social and political phenomenon

Today, even as the idea of brainwashing is often dismissed as pseudoscience, Americans are still spellbound by the idea that people we disagree with have been psychologically captured by our enemies. Right-wing pundits and politicians often attribute discussions of racism to infections by a "woke mind virus"—an idea that is a direct descendant of Cold War panics over communist brainwashing. Meanwhile, contemporary psychology researchers like UCSD's Dimsdale fear that social media is now a vector for coercive persuasion, just as Meerloo worried about television's mind-control powers in the 1950s.

Cutting-edge technology is also altering how we think about mind control. In a 2017 open letter published in *Nature*, an international group of researchers and ethicists warned that neurotechnologies like brain-computer interfaces "mean that we are on a path to a world in which it will be possible to decode people's mental processes and directly manipulate the brain mechanisms underlying their intentions, emotions and decisions." It sounds like MK-Ultra's wish list. Hoping to head off a neuro-dystopia, the group outlined several key ways that companies and universities could guard against coercive uses of this technology in the future. They suggested that we need laws to prevent companies from spying on people's private thoughts, for example, as well as regulations that bar anyone from using brain implants to change people's personalities or make them more neurotypical.

Sidney Gottlieb was an American chemist and spymaster who in the 1950s headed the Central Intelligence Agency's mind-control program known as Project MK-Ultra.

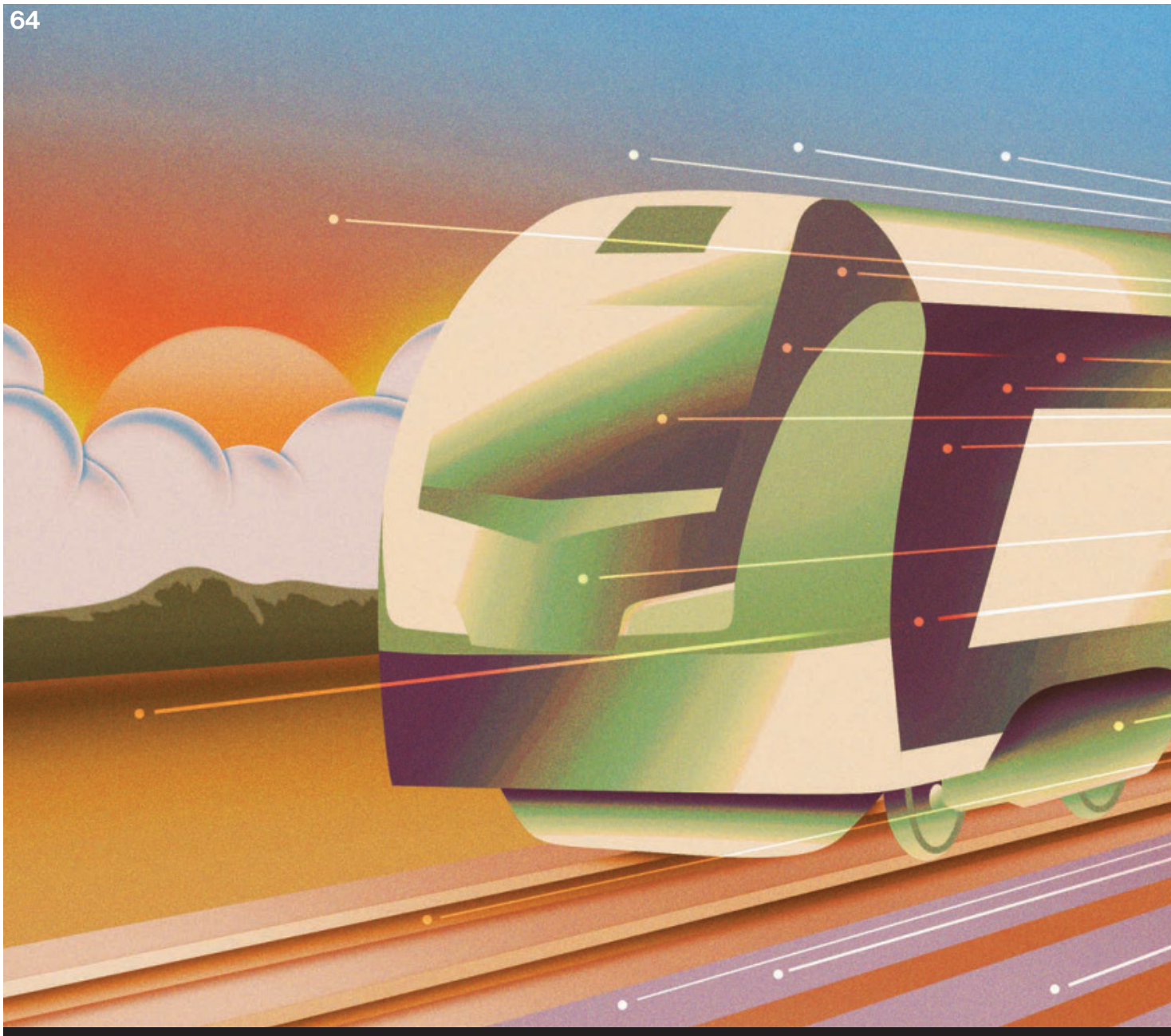
COURTESY OF THE CIA

Many neuroscientists feel that these concerns are overblown; one of them, the University of Maryland cognitive scientist R. Douglas Fields, summed up the naysayers' position with a column in *Quanta* magazine arguing that the brain is more plastic than we realize, and that neurotech mind control will never be as simple as throwing a switch. Kathleen Taylor, another neuroscientist who studies brainwashing, takes a more measured view; in her book *Brainwashing: The Science of Thought Control*, she acknowledges that neurotech and drugs could change people's thought processes but ultimately concludes that "brainwashing is above all a social and political phenomenon."

Perhaps that means the anonymous National Security Council examiner was right to call Hubbard's black propaganda the work of an "expert." If brainwashing is politics, then disinformation might be as effective (or ineffective) as a brain implant in changing someone's mind. Still, scholars have learned that political efforts at mind control do not have predictable results. Online disinformation leads to what Juliette Kayyem, a former assistant secretary of the Department of Homeland Security, identifies as stochastic terrorism, or acts of violence that cannot be predicted precisely but can be analyzed statistically. She writes that stochastic terrorism is inspired by online rhetoric that demonizes groups of people, but it's hard to know which people consuming that rhetoric will actually become terrorists, and which of them will just rage at their computer screens—the result of coercive persuasion that works on some targets and misses others.

American operatives may never have found the perfect system for brainwashing foreign adversaries or unsuspecting citizens, but the US managed to win the mind-control wars in one small way. Mitchell, the legal scholar at Hong Kong University, told me that the American definition of brainwashing, or *xinao*, is now the dominant way the word is used in modern Chinese speech. "People refer to aggressive advertising campaigns or earworm pop songs as having a *xinao* effect," he said. The Chinese government, Mitchell added, uses the term exactly the way the US military did back in the 1950s. State media, for example, "described many Hong Kong protesters in 2019 as having undergone *xinao* by the West." ■

Annalee Newitz is the author of Stories Are Weapons: Psychological Warfare and the American Mind, coming in June 2024.



The great HYDROGEN

HOW BEST TO DECARBONIZE RAIL TRANSPORTATION IS A POLITICAL QUESTION AS MUCH

Like a mirage speeding across the dusty desert outside Pueblo, Colorado, the first hydrogen-fuel-cell passenger train in the United States is getting warmed up on its test track. Made by the Swiss manufacturer Stadler and known as the FLIRT (for "Fast Light Intercity and Regional Train"), it will soon be shipped to Southern California, where it is slated to carry riders on San Bernardino County's Arrow commuter rail service before the end of the year. In the insular world of railroading, this hydrogen-powered train is a Rorschach test. To some, it represents the future of rail transportation. To others, it looks like a big, shiny distraction.

In the quest to decarbonize the transportation sector—the largest source of greenhouse-gas emissions in the United States—rubber-tired electric vehicles tend to dominate the conversation. But to reach the Biden administration's goal of net-zero emissions by 2050, other forms of transportation, including those on steel wheels, will need to find new energy sources too.

The best way to decarbonize railroads is the subject of growing debate among regulators, industry, and activists. Things are coming to a head in California, which recently enacted rules requiring all new

TRAIN DEBATE

AS A TECHNOLOGICAL ONE • By *Benjamin Schneider* • Illustration by *Aaron Lowell Denton*

passenger locomotives operating in the state to be zero-emissions by 2030 and all new freight locomotives to meet that threshold by 2035. Federal regulators could be close behind.

The debate is partly technological, revolving around whether hydrogen fuel cells, batteries, or overhead electric wires offer the best performance for different railroad situations. But it's also political: a question of the extent to which decarbonization can, or should, usher in a broader transformation of rail transportation. For decades, the government has largely deferred to the will of the big freight rail conglomerates. Decarbonization could shift that power dynamic—or further entrench it.

So far, hydrogen has been the big technological winner in California. Over the past year, the California Department of Transportation, known as Caltrans, has ordered 10 hydrogen FLIRT trains at a cost of $207 million. After the Arrow service, the next rail line to receive hydrogen trains is scheduled to be the Valley Rail service in the Central Valley. That line will connect Sacramento to California High-Speed Rail, the under-construction system that will eventually link Los Angeles and San Francisco.

In its analysis of different zero-emissions rail technologies, Caltrans found that hydrogen trains, powered by onboard fuel cells that convert hydrogen into electricity, had better range and shorter refueling times than battery-electric trains, which function much like electric cars. Hydrogen was also a cheaper power source than overhead wire (or simply "electrification," in industry parlance), which would cost an estimated $6.8 billion to install on the state's three main intercity routes. (California High-Speed Rail and its shared track on the Bay Area's Caltrain commuter service will both be powered by overhead wire, since electrification is necessary to reach speeds of over 100 miles per hour.)

Further complicating the electrification option, installing overhead wire on the rest of California's passenger network would require the consent of BNSF and Union Pacific, the two major freight rail carriers that own most of the state's tracks. The companies have long opposed the installation of wire above their tracks, which they say could interfere with double-stacked freight trains.

Electrifying all 144,000 miles of the nation's freight rail tracks would cost hundreds of billions of dollars, according to a report by the Association of American Railroads (AAR), an industry trade group, and even electrifying smaller sections of track would result in ongoing disruptions to train traffic and shift freight customers from trains to trucks, the group claims. Electrification would also require the cooperation of electric utilities, leaving railroads vulnerable to the grid connection delays that plague renewable-energy developers.

"We have long stretches of track outside of urbanized areas," says Marcin Taraszkiewicz, an engineer at the engineering and architecture firm HDR who has worked on Caltrans's hydrogen train program. Getting power to those rugged places can be a challenge, he says, especially when infrastructure must be designed to resist natural disasters like wildfires and earthquakes: "If that wire goes down, you're going to be in trouble."

The AAR thinks California's railroad emissions regulations are too much, too soon, especially given that freight rail is already three to four times more fuel efficient than trucking. Last year, the AAR sued the state over its latest railroad emissions regulations, in a case that is still pending. Though the group generally prefers hydrogen to electrification as a long-term solution, it contends that this alternative technology is not yet mature enough to meet the industry's needs.

A group called Californians for Electric Rail also views hydrogen as an immature technology. "From an environmental as well as a cost perspective, it's a really circular and indirect way of doing things," says Adriana Rizzo, the group's founder, who is an advocate for electrifying the state's regional and intercity tracks with overhead wire.

Synthesizing, transporting, and using the tiny hydrogen molecule can be very inefficient. Hydrogen trains currently require roughly three times more energy per mile than trains powered by overhead wire. And the environmental benefits of hydrogen—the ostensible purpose of this new technology—remain largely theoretical, since the vast majority of hydrogen today is produced by burning fossil fuels like methane. Natural-gas utilities have been among the hydrogen industry's biggest boosters, because they are already able to produce and transport the gas.

Opinions on the merits of hydrogen trains have been mixed. In 2022, following a pilot program, the German state of Baden-Württemberg determined that this technology would be 80% more expensive to operate over the long run than other zero-emissions alternatives.

Kyle Gradinger, assistant deputy director for rail at Caltrans, thinks there's been some "Twittersphere exaggeration" about the problems with hydrogen trains. In tests, the hydrogen-powered Stadler FLIRT is "performing as well as we expected, if not better," he says. Since they also use electric motors, hydrogen trains offer many of the same benefits as trains powered by overhead wire, Gradinger says. Both technologies will be quieter, cleaner, and faster than diesel trains.

Caltrans hopes to obtain all the hydrogen for its trains from zero-emissions sources by 2030—a goal bolstered by a draft clean-hydrogen rule issued by the Biden administration in 2023. California is one of seven "hydrogen hubs" in the US, public-private partnerships that will receive billions of dollars in subsidies from the Infrastructure Investment and Jobs Act for developing hydrogen technologies. It's too early to say whether Caltrans will be able to procure funding for its hydrogen fueling stations and supply chains through these subsidies, Gradinger says, but it's certainly a possibility. So far, California is the only US state to have purchased hydrogen trains.

Advocates like Rizzo fear, however, that all this investment in hydrogen infrastructure will get in the way of more transformative changes to passenger rail in California.

"Why are we putting millions of dollars into buying new trains and putting up all of this infrastructure and then expecting the same crappy service that we have now?" Rizzo says. "These systems could carry so many more passengers."

Rizzo's group, and allies like the Rail Passenger Association of California and Nevada, think decarbonization is an opportunity to install the type of infrastructure that supports the vast majority of fast passenger train services around the world. Though the up-front investment in overhead wire is high, electrification reduces operating costs by providing constant access to a cheap and efficient energy source. Electrification also improves acceleration so that trains can travel closer together, creating the potential for service patterns that function more like an urban metro system than a once-per-day Amtrak route.

Caltrans has a long-term plan to dramatically increase rail service and speeds, which might eventually require electrification by overhead wire, also known as a catenary system. But at least for the next couple of decades, the agency believes, hydrogen is the most feasible way to meet the state's ambitious climate goals. The money, the political will, and the stomach for a fight with the freight railroads and utility companies just aren't there yet.

"The gold standard is overhead catenary electrification, if you can do that," Gradinger says. "But we aren't going to get to a level of service on the intercity side for at least the next decade or two that would warrant investment in electrification."

Rizzo hopes that as the federal government puts more railroad emissions regulations in place, the case for electrifying rail by overhead wire will get stronger. Other countries have come to that conclusion: a 2015 policy change in India resulted in the electrification of nearly half the country's track mileage in less than a decade. The United Kingdom's Decarbonising Transport Plan states that electrification will be the "main way" to decarbonize the rail industry.

These changes are still compatible with a robust freight industry. The world's most powerful locomotives are electric, pulling ore-laden freight trains in South Africa and China. In 2002, Russia finished electrifying the 5,700-mile Trans-Siberian Railway, demonstrating that freight trains running on electric wire can travel very long distances over very harsh terrain.

Things may be starting to shift in the US as well, albeit slowly. BNSF appears to have softened its stance against electrification on a corridor it owns in Southern California, where it has agreed to allow California High-Speed Rail to construct overhead wire on its right of way. Rizzo and her group are looking to make these projects easier by sponsoring state legislation exempting overhead wire from the California Environmental Quality Act. That would prevent situations like a 2015 environmental lawsuit from the affluent Bay Area suburb of Atherton, over tree removal and visual impact, that delayed Caltrain's electrification project for nearly two years.

New innovations could blur the lines between different kinds of green rail technologies. Caltrain has ordered a battery-equipped electrified train that has the potential to charge up while traveling from San Francisco to San Jose and then run on a battery onward to Gilroy and Salinas. A similar system could someday be deployed in Southern California, where trains could charge through the Los Angeles metro area and run on batteries over more remote stretches to Santa Barbara and San Diego.

New hydrogen technologies could also prove transformative for passenger rail. The FLIRT train doing laps in the Colorado desert is version 1.0. In the future, using ammonia as a hydrogen carrier could result in much longer range for hydrogen trains, as well as more seamless refueling. "With hydrogen, there's a lot more room to grow," Taraszkiewicz says.

But in a country that has invested little in passenger rail over the past century, new technology can only do so much, Taraszkiewicz cautions. America's railroads all too often lack passing tracks, grade-separated road crossings, and modern signaling systems. The main impediment to faster, more frequent passenger service "is not the train technology," he says. "It's everything else." ■

Benjamin Schneider is a freelance writer covering housing, transportation, and urban policy.

The Shabara artisanal cobalt mine near Kolwezi, Democratic Republic of Congo.

ARLETTE BASHIZI/THE WASHINGTON POST/GETTY IMAGES

Quartz, cobalt, and the waste we leave behind

Three books reveal just how dependent we are on physical materials—and the toll their extraction takes on humans and the environment.
By Matthew Ponsford

Material World: The Six Raw Materials That Shape Modern Civilization
Ed Conway
KNOPF, 2023

Wasteland: The Secret World of Waste and the Urgent Search for a Cleaner Future
Oliver Franklin-Wallis
PROQUEST BLACK BOX B&T, 2023

Cobalt Red: How the Blood of the Congo Powers Our Lives
Siddharth Kara
ST. MARTIN'S PRESS, 2023

Some time before the first dinosaurs, two supercontinents, Laurasia and Gondwana, collided, forcing molten rock out from the depths of the Earth. As eons passed, the liquid rock cooled and geological forces carved this rocky fault line into Pico Sacro, a strange conical peak that sits like a wizard's hat near the northwestern corner of Spain.

Today, Pico Sacro is venerated as a holy site and rumored, in the local mythology, to be a portal to hell. But this magic mountain has also become valued in modern times for a very different reason: the quartz deposits that resulted from these geological processes are some of the purest on the planet. Today, it is a rich source of the silicon used to build computer chips. From this dusty ground, the mineral is plucked and transformed into an inscrutable black void of pure inorganic technology, something that an art director could have dreamed up to stand in for aliens or the mirror image of earthly nature.

Ed Conway, a columnist for the *Times* of London, catches up with this rock's "epic odyssey" in his new book, *Material World: The Six Raw Materials That Shape Modern Civilization*.

In a warehouse just a few miles from the peak, he finds a dazzling pile of fist-size quartz chunks ready to be shoveled into a smoking coal-fired furnace running at 1,800 °C, where they are enveloped in a powerful electrical field. The process is not what he expected—more *Lord of the Rings* than Bay Area startup—but he relishes every near-mystical step that follows as quartz is coaxed into liquid silicon, drawn into crystals, and shipped to the cleanest rooms in the world.

Conway's quest to understand how chips are made confronts the reality that no one person, "even those working on the supply chain itself," can really explain the entire process. Conway soon discovers that even an industrial furnace can be a scene of sorcery and wonder, partly because of the electrical current that passes through the quartz and coal. "Even after more than a hundred years of production, there are

still things people don't understand about what's happening in this reaction," he is told by Håvard Moe, an executive at the Norwegian company Elkem, one of Europe's biggest silicon producers.

Conway explains that the silicon "wafers" used to make the brains of our digital economy are up to 99.99999999% pure: "for every impure atom there are essentially 10 billion pure silicon atoms." The silicon extracted from around Pico Sacro leaves Spain already almost 99% pure. After that, it is distilled in Germany and then sent to a plant outside Portland, Oregon, where it undergoes what is perhaps its most entrancing transformation. In the Czochralski or "CZ" process, a chamber is filled with argon gas and a rod is dipped repeatedly into molten refined silicon to grow a perfect crystal. It's much like conjuring a stalactite at warp speed or "pulling candy floss onto a stick," in Conway's words. From this we get "one of the purest crystalline structures in the universe," which can begin to be shaped into chips.

Material World is one of a spate of recent books that aim to reconnect readers with the physical reality that underpins the global economy. Conway's mission is shared by *Wasteland: The Secret World of Waste and the Urgent Search for a Cleaner Future*, by Oliver Franklin-Wallis, and *Cobalt Red: How the Blood of the Congo Powers Our Lives*, by Siddharth Kara. Each one fills in dark secrets about the places, processes, and lived realities that make the economy tick.

Conway aims to disprove "perhaps the most dangerous of all the myths" that guide our lives today: "the idea that we humans are weaning ourselves off physical materials." It is easy to convince ourselves that we now live in a dematerialized "ethereal world," he says, ruled by digital startups, artificial intelligence, and financial services. Yet there is little evidence that we have decoupled our economy from its churning hunger for resources. "For every ton of fossil fuels," he writes, "we exploit six tons of other materials—mostly sand and stone, but also metals, salts, and chemicals. Even as we citizens of the ethereal world pare back our consumption of fossil fuels, we have redoubled our consumption of everything else. But, somehow, we have deluded ourselves into believing precisely the opposite."

Simply shifting to "sustainable" or "cleaner" technologies doesn't eliminate the industrial fallout from our consumption.

Conway delivers rich life stories of the resources without which our world would be unrecognizable, covering sand, salt, iron, copper, oil, and lithium. He buzzes with excitement at every stage, with a correspondent's gift for quick-fire storytelling, revealing the world's material supply chains in an avalanche of anecdote and trivia. The supply chain of silicon, he shows, is both otherworldly and incredibly fragile, encompassing massive, anonymous industrial giants as well as terrifyingly narrow bottlenecks. Nearly the entire global supply of specialized containers for the CZ dipping process, for example, is produced by two mines in the town of Spruce Pine, North Carolina. "What if something happened to those mines? What if, say, the single road that winds down from them to the rest of the world was destroyed in a landslide?" asks Conway. "Short answer: it would not be pretty. 'Here's something scary,' says one veteran of the sector. 'If you flew over the two mines in Spruce Pine with a crop duster loaded with a very particular powder, you could end the world's production of semiconductors and solar panels within six months.'" (Conway declines to print the name of the substance.)

Yet after such an impressive journey through deep time and the world economy, how long will any electronic gadget last? The useful life of our electronics and many other products is likely to be a short blip before they return to the earth. As Oliver Franklin-Wallis writes in *Wasteland,* electronic waste is one stubborn part of the 2 billion tons of solid waste we produce globally each year, with the average American discarding more than four pounds of trash each day.

Wasteland begins with a trip to Ghazipur, India, the "largest of three mega-landfills that ring Delhi." There, amid an aromatic fug of sticky-sweet vapors, Franklin-Wallis stomps through a swamp-like morass of trash, following his guide, a local waste picker named Anwar, who helps him recognize solid stepping-stones of trash so that he may safely navigate above the perilous system of subterranean rivers that rush somewhere unseen below his feet. Like the hidden icy currents that carve through glaciers, these rivers make the trash mountain prone to cleaving and crumbling, leading to around 100 deaths a year. "Over time, [Anwar] explains, you learn to read the waste the way sailors can read a river's current; he can intuit what is likely to be solid, what isn't. But collapses are unpredictable," Franklin-Wallis writes. For all its aura of decay, this is also a living landscape: there are tomato plants that grow from the refuse. Waste pickers eat the fruits off the vine.

Wasteland is best when excavating the stories buried in the dump. In 1973, academics at the University of Arizona, led by the archaeologist William Rathje, turned the study of landfills into a science, labeling themselves the "garbologists." "Trash, Rathje found, could tell you more about a neighborhood—what people eat, what

their favorite brands are—than cutting-edge consumer research, and predict the population more accurately than a census," Franklin-Wallis writes. "Unlike people," he adds, "garbage doesn't lie."

Wasteland leaves a lasting impression of the trash-worlds that we make. Most horrifying of all, the contents of landfills don't decompose the way we expect. By taking geological cores from landfills, Rathje found that even decades later, our waste remains a morbid museum: "onion parings were onion parings, carrot tops were carrot tops. Grass clippings that might have been thrown away the day before yesterday spilled from bulky black lawn and leaf bags, still tied with twisted wire."

Franklin-Wallis's histories help tell us where we as a civilization began to go wrong. In ancient Rome, waste from public latrines was washed away with wastewater from the city's fountains and bathhouses, requiring a "complex underground sewer system crowned by the Cloaca Maxima, a sewer so great that it had its own goddess, Cloacina." But by the Victorian age, the mostly circular economy of waste was coming to an end. The grim but eco-friendly job of turning human effluent into farm fertilizer (so-called "nightsoil") was made obsolete by the adoption of the home flushing toilet, which pumped effluent out into rivers, often killing them. Karl Marx identified this as the beginning of a "metabolic rift" that—later turbocharged by the development of disposable plastics—turned a sustainable cycle of waste reuse into a conveyor between city and dump.

This meditation on trash can be fascinating, but the book never quite lands on a big idea to draw its story forward. While trash piles can be places of discovery, our propensity to make waste is no revelation; it's an ever-present nightmare. Many readers will arrive in search of answers that *Wasteland* isn't offering. Its recommendations are ultimately modest: the author resolves to buy less, learns to sew, appreciates the Japanese art of *kintsugi* (mending pottery with precious metals to highlight the act of repair). A handful of other lifestyle decisions follow.

As Franklin-Wallis is quick to acknowledge, a journey through our own waste can feel hopeless and overwhelming. What we're lacking are viable ways to steer our societies from the incredibly resource-intensive paths they are on. This thought, taken up by designers and activists driving the Green New Deal, is aiming to turn our attention away from dwelling on our personal "footprint"—a murky idea that Franklin-Wallis traces to industry groups lobbying to deflect blame from themselves.

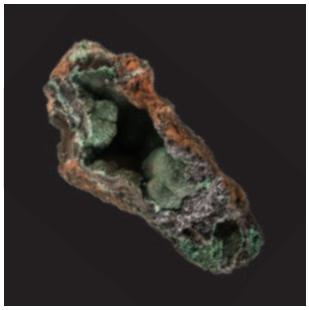
Reframing both waste and supply chains as matters that are political and international, rather than personal, could guide us away from guilt and move us toward solutions. Instead of looking at production and waste as separate problems, we can think of them as two aspects of one great challenge: How do we build homes, design transport systems, develop technology, and feed the world's billions without creating factory waste upstream or trash downstream?

Simply shifting to "sustainable" or "cleaner" technologies doesn't eliminate the industrial fallout from our consumption, as Siddharth Kara reveals in *Cobalt Red*. Cobalt is a part of just about every rechargeable device—it is used to make the positively charged end of lithium batteries, for example, and each electric vehicle requires 10 kilograms (22 pounds) of cobalt, 1,000 times the quantity in a smartphone.

Half the world's reserves of the element are found in Katanga, in the south of the Democratic Republic of Congo (DRC), which puts this resource-rich region at the center of the global energy transition. In Kara's telling, the cobalt rush is another chapter in an age-old story of exploitation. In the last two centuries, the DRC has been a center not only for the bloody trade in enslaved humans but also for the colonial extraction of rubber, copper, nickel, diamonds, palm oil, and much more. Barely a modern catastrophe has unfolded without resources stolen from this soil: copper from the DRC made the bullets for two world wars; uranium made the bombs dropped on Hiroshima and Nagasaki; vast quantities of tin, zinc, silver, and nickel fueled Western industrialization and global environmental crises. In return, the DRC's 100 million people have been left with little by way of lasting benefits. The country still languishes at the foot of the United Nations development index and now faces disproportionate impacts from climate change.

Quartz

Ghazipur's mega-landfill



Cobalt

DIDIER DESCOUENS VIA WIKIMEDIA COMMONS (QUARTZ); ALAMY (GHAZIPUR); GETTY IMAGES (COBALT)

In *Cobalt Red*, Congo's history plays out in vignettes of barbarous theft perpetrated by powerful Western-backed elites. Kara, an author and activist on modern slavery, structures the book as a journey, drawing frequent parallels to Joseph Conrad's 1899 *Heart of Darkness*, with the city of Kolwezi substituting for Kurtz's ivory-trading station, the destination in the novella. Kolwezi is the center of Katanga's cobalt trade. It is "the new heart of darkness, a tormented heir to those Congolese atrocities that came before—colonization, wars, and generations of slavery," Kara writes. The book provides a speedy summary of the nation's history starting with the colonial vampirism of the Belgian king Leopold's "Free State," described by Conrad as the "vilest scramble for loot that ever disfigured the history of human conscience." The king's private

colony forced its subjects to collect rubber under a system of quotas enforced by systematic execution and disfigurement; forced labor continued well into the 20th century in palm oil plantations that supplied the multinational Unilever company.

Kara's multiyear investigation finds the patterns of the past repeating themselves in today's green boom. "As of 2022, there is no such thing as a clean supply chain of cobalt from the Congo," he writes. "All cobalt sourced from the DRC is tainted by various degrees of abuse, including slavery, child labor, forced labor, debt bondage, human trafficking, hazardous and toxic working conditions, pathetic wages, injury and death, and incalculable environmental harm." Step by step, Kara's narrative moves from the fringes of Katanga's mining region toward Kolwezi, documenting the free flow of minerals between two parallel systems supposedly divided by a firewall: the formal industrial system, under the auspices of mining giants that are signatories to sustainability pacts and human rights conventions, and the "artisanal" one, in which miners with no formal employer toil with shovels and sieves to produce a few sacks of cobalt ore a day.

We learn of the system of *creuseurs* and *négociants*—diggers and traders—who move the ore from denuded fields into the formal supply chain, revealing that an unknown percentage of cobalt sold as ethical comes from unregulated toil. If *Material World* tells a neat story of capitalism's invisible hand, the force that whisks resources around the planet, *Cobalt Red* documents a more brutal and opaque model of extraction. In Kara's telling, the artisanal system is grueling and inefficient, involving countless middlemen between diggers and refineries who serve no purpose except to launder ore too low-grade for industrial miners and obscure its origins (while skimming off most of the earnings).

Everywhere Kara finds artisanal mining, he finds children, including girls, some with babies on backs, who huddle together to guard against the threat of sexual assault. There is no shortage of haunting stories from the frontlines. Cobalt ore binds with nickel, lead, arsenic, and uranium, and exposure to this metal mixture raises the risk of breast, kidney, and lung cancers. Lead poisoning leads to neurological damage, reduced fertility, and seizures. Everywhere he sees rashes on the skin and respiratory ailments including "hard metal lung disease," caused by chronic and potentially fatal inhalation of cobalt dust.

One woman, who works crushing 12-hour days just to fill one sack that she can trade for the equivalent of about 80 cents, tells how her husband recently died from respiratory illness, and the two times she had conceived both resulted in miscarriage. "I thank God for taking my babies," she says. "Here it is better not to be born." The book's handful of genuinely devastating moments arrive like this—from the insights of Congolese miners, who are too rarely given the chance to speak.

All of which leaves you to question Kara's strange decision to mold the narrative around the 125-year-old *Heart of Darkness*. It has been half a century since the Nigerian novelist Chinua Achebe condemned Conrad's novella as a "deplorable book" that dehumanized its subjects even as it aimed to inspire sympathy for them. Yet Kara doubles down by mirroring Conrad's storytelling device and style, from the first sentence (featuring "wild and wide-eyed" soldiers wielding weapons). When Kara describes how the "filth-caked children of the Katanga region scrounge at the earth for cobalt," who is the object of disgust: the forces of exploitation or the miners and their families, often reduced to abstract figures of suffering?

Following Conrad, *Cobalt Red* becomes, essentially, a story of morality—an "unholy tale" about the "malevolent force" of capital—and reaches a similarly moralistic conclusion: that we must all begin to treat artisanal miners "with equal humanity as any other employee." If this seems like an airy response after the hard work of detailing the intricacies of cobalt's broken supply chain, it is doubly so after Kara documents both the past waves of injustice and the moral crusades that have brought the Free State and old colonial structures to an end. Such calls for humanistic fairness toward Congo have echoed down the ages.

All three books offer to connect the reader to the feel and smell and rasping reality of a world where materials still matter.

All three books offer to connect the reader to the feel and smell and rasping reality of a world where materials still matter. But in Kara's case, such a strong focus on documenting firsthand experience edges out a deeper understanding. There is little space given to the numerous scholars from across the African continent who have made sense of how politics, commerce, and armed groups together rule the DRC's deadly mines. The Cameroonian historian Achille Mbembe has described sites like Katanga not only as places where Western-style rule of law is absent but as "death-worlds" constructed and maintained by rich actors to extract resources at low cost. More than simply making sense of the current crisis, these thinkers address the big questions that Kara asks but struggles to answer: Why do the resources and actors change but exploitation remains? How does this pattern end? ■

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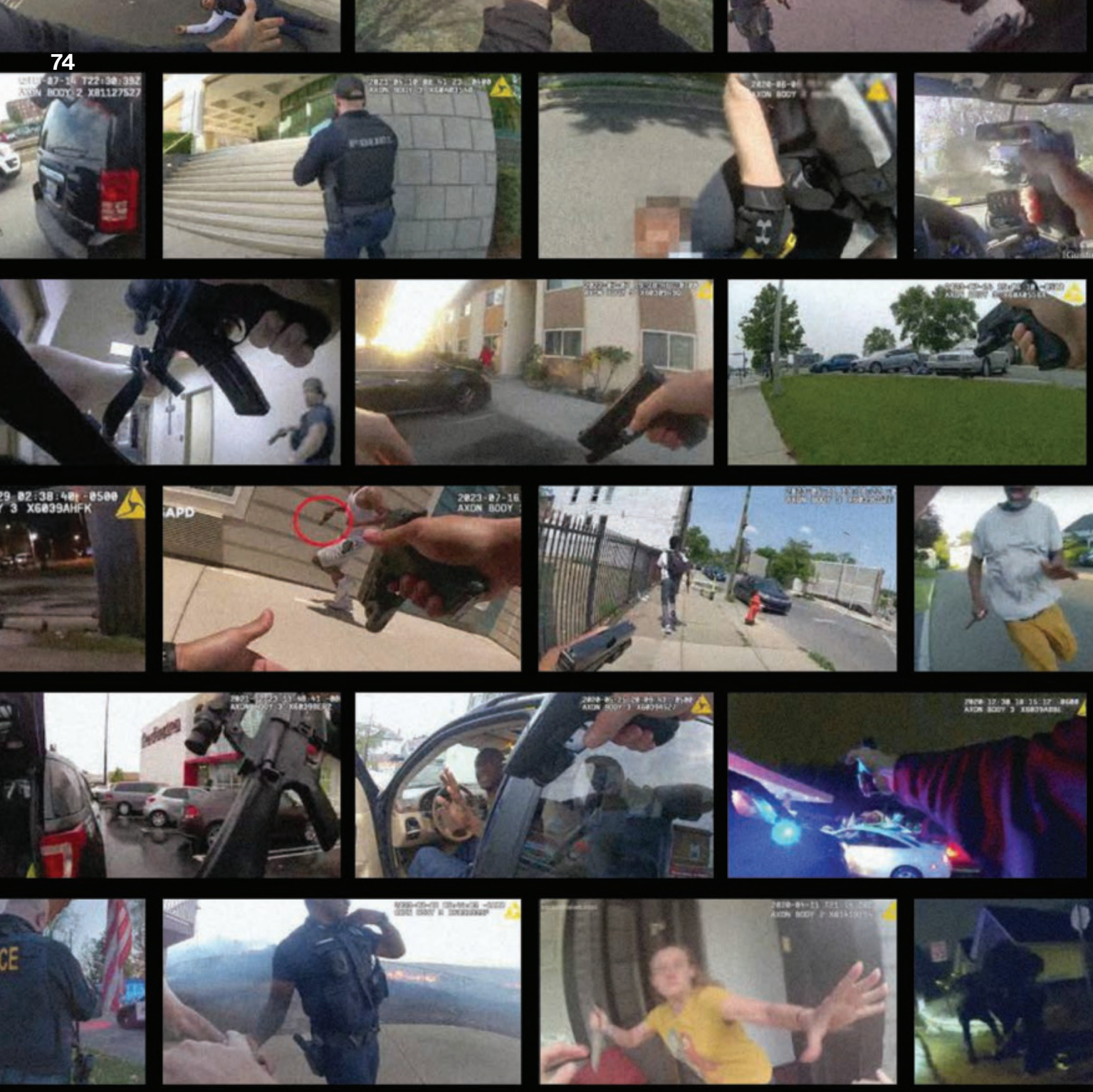
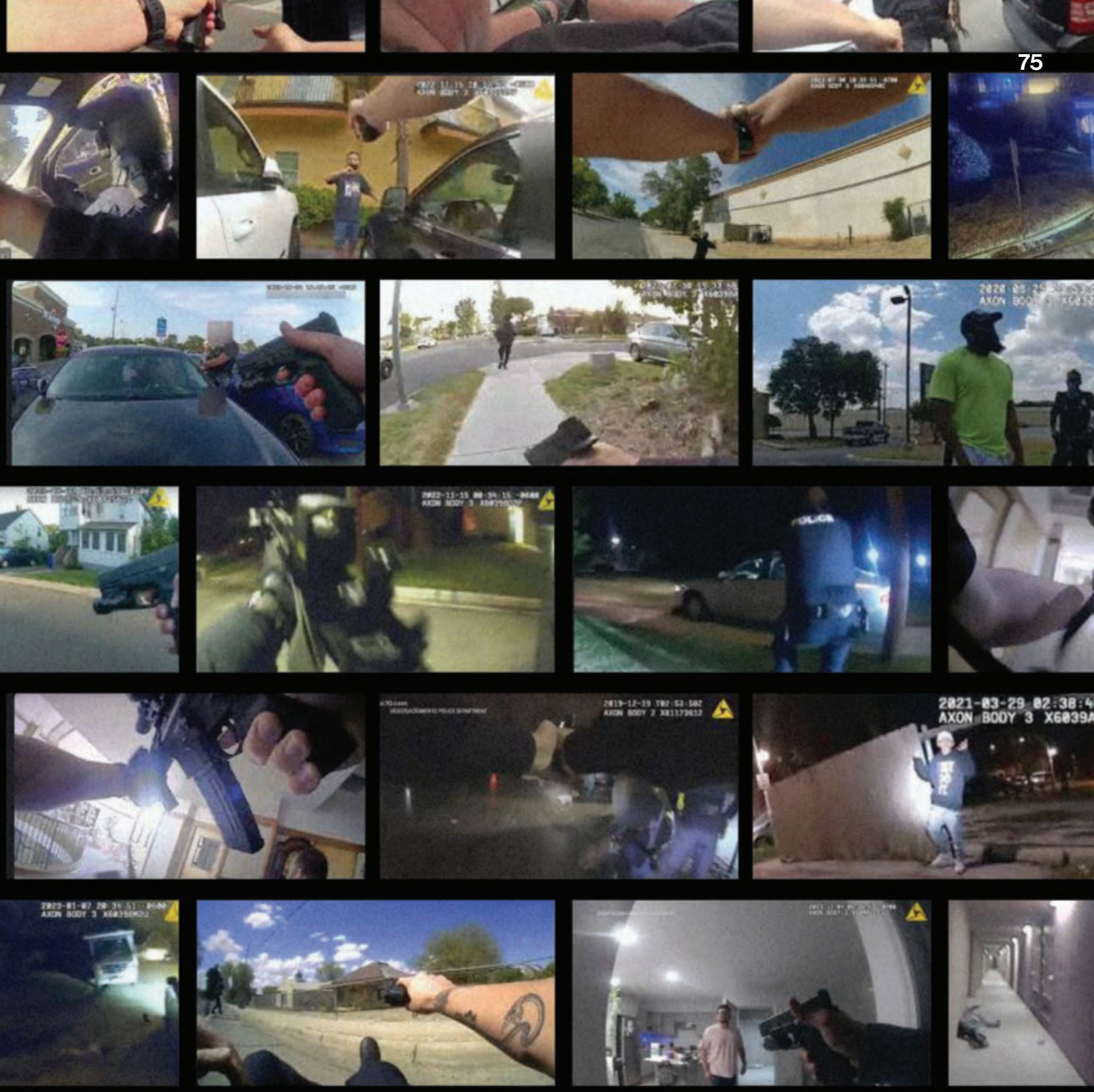


Track the police

New AI programs that analyze bodycam recordings promise more transparency. Not everybody is happy about it. By Patrick Sisson

On July 25 last year, in circuit court in Dane County, Wisconsin, a motion was filed to dismiss a criminal case as a result of what defense attorneys described as "institutional bad-faith actions" by a local police department. The evidence was unearthed, in part, because of artificial intelligence.

Attorney Jessa Nicholson Goetz had been preparing to defend her client against a sexual assault charge that arose from a 2021 Tinder date. During pretrial motions, Nicholson Goetz's co-counsel noticed discrepancies around how the lead police investigator was discussing and documenting his use of a body camera, which department policy required him to wear at all



times. Nicholson Goetz asked to review footage connected to the investigation; she said the police department delivered 40 hours of video before the trial began.

This kind of data dump is commonplace, typically right before the start of a trial. Manually reviewing body camera footage isn't always a useful source of insight into a case; more often, especially for defense attorneys without resources, it's a nightmare. Actually watching the tapes is very time consuming, and paying to have them transcribed can add tens of thousands of dollars to tight budgets.

But this time, Nicholson Goetz and her team were using JusticeText, an AI-powered evidence management program that two former University of Chicago computer science students named Devshi Mehrotra and Leslie Jones-Dove developed when they were outraged at the police killing of Laquan McDonald in their city in 2014. JusticeText analyzes the audio from bodycam footage, transcribes it, and marks it up in minutes, not hours. Released in 2021, it now aids private criminal attorneys as well as public defenders in states such as Texas, Massachusetts, and Kentucky.

Although it did not reveal anything that would have directly proved her client's innocence, JusticeText did bring to light possible evidence of police malfeasance—specifically, destruction of "apparently and potentially exculpatory evidence," according to the motion.

Bodycams have generated millions of hours of video footage, most of which goes unwatched.

After going through just a few JusticeText analyses of videos, Nicholson Goetz froze when she read the following transcribed directions the investigator gave to the alleged victim, who was a prosecution witness: "Okay, I'm trying to speak vaguely here. Um. Just because, you know, I don't want this on record." The witness would later ask the investigator whether they were speaking in confidence, and he responded that he wasn't going to put their conversation into police reports. In light of this exchange and what Nicholson Goetz describes in the motion as the department's alleged propensity to "mishandle, destroy, intentionally omit, recklessly fail to preserve evidence," including camera footage from the night in question that could have had exculpatory value, she filed the motion to dismiss. The judge would eventually dismiss the case, noting in a decision on March 8 that "[the defendant's] defense has suffered irreparable prejudice due to [the investigator's] actions."

"Without JusticeText, the trial would have started, instead of being delayed and dismissed," Nicholson Goetz says. "This has changed the way that I do my discovery, because now I'm really very curious as to what's out there."

No one is entirely sure what *is* out there. When police departments began buying and deploying bodycams in earnest in the wake of the police killing of Michael Brown in Ferguson, Missouri, in 2014, activists hoped it would bring about real change. The cameras were originally hailed as "supervisory force multipliers," says Seth Stoughton, a law professor at the University of South Carolina who studies the technology.

Years later, despite what's become a multibillion-dollar market for these devices, the tech is far from a panacea.

Part of the problem is scale: bodycams have generated millions of hours of video footage, most of which goes unwatched. Police departments also systematically delay releasing footage, and they often refuse to discipline officers who fail to wear the cameras properly. And when they do finally provide video to the public, it's often selectively edited, lacking context and failing to tell the complete story. A recent *New York Times* analysis concluded that bodycams "may do more to serve police interests than those of the public they are sworn to protect."

A handful of AI startups see this problem as an opportunity to create what are essentially bodycam-to-text programs for different players in the legal system, mining this footage for misdeeds. That could help improve professionalism within the police. But like the bodycams themselves, the technology still faces procedural, legal, and cultural barriers to success.

In essence, bodycam analysis programs work in three steps. First, a speech recognition algorithm turns the audio into draft text; after recordings get broken up into phonemes, the smallest unit of sound, a probability analysis determines how these building blocks come together in words and sentences. Then a machine-learning algorithm and natural-language-processing programs, trained on vast collections of text and previous conversations, clean up the rough copy and remove errors. Finally, the system checks that finished copy for specific keywords and patterns, which are flagged and analyzed.

The true test of the technology will be whether it can accurately scan and scour hours and hours of unwatched video. But a more important question is whether it can meet a bigger challenge: moving the process and culture of policing toward accountability.

JusticeText is tackling these issues at the court level. During its development, cofounder Mehrotra and her colleagues surveyed public defenders and found that roughly 80% of their cases involved data of some sort. Most defenders, serving dozens of defendants simultaneously, couldn't ingest this type of evidence, understand it, and present it in court, putting them at a disadvantage. To help address the problem, JusticeText spent time building tools to set up timelines for attorneys and making sure the system was able to read files from different vendors and police departments.

Mehrotra says she's hearing from attorneys who have gotten high-level felony cases dismissed outright after using the program to analyze bodycam recordings. Before, she says, they didn't have time to pull clips from these files. Now they're walking into court with highlight reels.

Other firms working on similar technology think its best use is in helping the police more effectively police themselves. Polis Solutions is developing an AI tool to analyze not only audio but also facial expressions caught by these cameras. Another company, Truleo, offers tailored video-to-text transcription services for police departments. Cofounder Anthony Tassone envisions flagging incidents that need review, bringing attention to positive policing, and sharing video clips for training; he hopes to create a "TikTok for cops." His sales pitch has connected with law enforcement. Currently, 28 departments use the service, including New York City's. The NYPD signed up for a Truleo trial last October; 1,000 of the force's roughly 36,000 officers are set to be tracked and trained with the system.

A tech-savvy stock trader who has been building natural-language-processing models for decades, Tassone has long been dedicated to police foundations and causes, donating to fundraisers and serving on the board of the FBI National Academy. The police chiefs he met while fundraising had common complaints: a shortage of supervisors, challenges with new recruits who didn't meet current performance standards, and the difficulty of rewarding good policing. Tassone saw AI as a way to help address these challenges. Turn the tech loose on the audio of bodycam footage, he thought, and you could create transcripts that supervisors could use to track, study, and improve officers' interactions with members of the public.

"Everyone's perception was that bodycam footage was a liability," Tassone says. "They [police department higher-ups] didn't want to view it unless there's a horrific use-of-force or civilian complaint. I just thought that was dumb. This is like game-time footage of all your athletes."

Tassone claims that Truleo, which hit the market in 2021, can identify events like an officer frisking someone or reading Miranda rights to a suspect, and calculate a professionalism score. The software doesn't eliminate human review, he says; it augments it. Police chiefs or supervisors set up lists of keywords or events, get emails and notifications when the system detects these triggers, and then review the footage. Truleo's tech is installed on department servers, so the data remains sequestered.

In the company's own studies, Tassone claims, officers monitored by Truleo always score better than the control group; a study of one client, the police department in Alameda, California, found a 36% reduction in uses of force. No third-party analyses of Truleo have yet been completed; researchers at the nonprofit RTI are currently studying its analysis of bodycam footage from Georgia state parole and probation officers, but results aren't expected anytime soon. Secure Justice, a nonprofit based in Oakland, California, that focuses on police tech and abuses of power, briefly considered pushing a bill to mandate the use of Truleo across the state, but executive director Brian Hofer says the group hadn't "done sufficient due diligence at this stage to be comfortable making an aggressive move like that" and may revisit the idea in 2025.

Still, Hofer suspects the technology does work. In fact, that very efficacy may be one reason it hasn't been universally welcomed: drama has erupted within two police departments that used and then dropped Truleo. In Vallejo, California, officers and police union officials objected to the introduction of the technology, with its potential to reveal unsavory behavior, and blamed it for inaccuracies and labor violations. The controversy helped accelerate the departure of the department's reformist chief, Shawny Williams, last July. In Seattle, where the police department also canceled its contract with Truleo amid union objections, an officer was caught on bodycam footage last fall mocking a woman's death; Truleo had flagged the incident.

Police officers aren't the only ones with reasons to question this technology, though. The growing use of bodycam-to-text programs, along with increased use of cameras and drones, further normalizes surveillance by law enforcement, adding more everyday interactions to a searchable, indexable database. Jennifer Lee, former manager of the technology and liberty project at the ACLU of Washington, said in a statement that "the potential to use AI technology for purposes other than accountability raises significant questions that must be addressed."

"It just opens up law enforcement's frame of surveillance in a way that we haven't really previously had to deal with so much but increasingly have to deal with constantly," says Beryl Lipton, an investigative researcher at the Electronic Frontier Foundation, a nonprofit digital rights group. The recording, transcription, and cataloguing of what someone says on the street in public during interactions with police raises a red flag, she says. She also points to concerns about bias and inaccuracy in the technology

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itself that arose when phone calls from prisoners were recorded, analyzed, and later made searchable via AI.

It's difficult to fully address such concerns because, as with many AI systems, the exact way these bodycam-to-text systems work remains opaque, and it's all the more so when outsiders can't know what terms police departments are searching for. Besides, the significance of their findings depends on context, says Rob Voigt, a Northwestern University researcher and linguistics expert, who coauthored a 2017 paper that used bodycam footage to measure racial disparities in police attitudes toward minorities.

"Can you make a computational model that can identify what's a threat or not? That's really complicated," he says.

Police departments have little incentive to ask pointed questions about racial bias, Voigt says, and those questions are central to reforming the policing model. The promise of these bodycam-to-text programs won't be fully met if key terms, phrases, and interactions aren't commonly tagged and analyzed. And even if they are, trusting law enforcement to do the right thing with whatever data a system like Truleo or Polis produces might be misguided.

Even Truleo's Tassone can't answer the "Who's watching the watchmen?" question in a wholly satisfying way.

Tassone claims that Truleo has identified otherwise unrecorded use-of-force incidents or police pursuits, but he declines to provide examples. When pressed about whether those incidents get reported to the public, he said, "We have no idea what happens downstream from our technology. That's on the department to follow up with that. Our mission is to give them the tools to find these things."

Tools are no good unless they're used, of course, and the ability to analyze police performance isn't helpful if bodycam recordings don't exist in the first place. Cops can simply turn off the camera or "forget" to turn it on, in which case there is simply nothing to examine. And since Truleo sequesters each department's data, there's no opportunity to do any meta-analysis of police performance, which academics say would provide a gold mine of data. Advocates for police reform also can't, say, file a public records request and use the tool to comb archival footage for the past actions of certain cops, or find patterns of misbehavior; no third party is using it to watch how cops are behaving. EFF's Lipton says if the technology works as advertised, and its makers really want to improve public trust, it seems like "a waste of money and a missed opportunity" not to make it available to the public.

Finally, law enforcement will likely continue to push back against the release of bodycam recordings, and slow-walk and delay the release of any questionable footage.

"We need to worry about applying technological solutions to sociological problems," says the University of South Carolina's Stoughton. "Nothing about Truleo will fundamentally change the culture of a police department, or alter a public commitment to accountability that doesn't have behind-the-doors follow-through."

Truleo's track record when it comes to changing the culture of law enforcement is decidedly mixed so far. The police force in Castle Shannon, Pennsylvania, has used the system for roughly two years with generally positive results. Chief of police Ken Truver, a self-described evangelist for law enforcement tech, says that even with just 14 officers in his department, actually watching and utilizing hours of bodycam footage becomes overwhelming. He's constantly thinking about what he's missing, since even mandated spot checks involve only about 1% of what's stored. Truleo helps him efficiently review behavior; every day at 6 p.m. he gets an email with incidents to flag and check. He claims he hasn't found any untoward behavior.

"Police are generally cynical of technology," he says. "The first thing they're gonna say is, 'How could I possibly get in trouble with this technology?' The purpose of the technology is not to find an officer doing something wrong. Matter of fact, the opposite is true. I want to find my officers doing something right."

But the rank-and-file officers in Vallejo, California, argued that the technology did the reverse. Their frustration with the system was one factor that led to the departure of the chief responsible for setting up Truleo. Michael Nichelini, president of the Vallejo Police Officers' Association, feels the technology was meant for discipline. He's not against transparency, he says, but he's sick of efforts to change the department's culture. He's frustrated with poor pay and understaffing, and he objects to what he sees as efforts to fix those issues with software instead of addressing them with better leadership and compensation. In the Seattle case, too, a police union president accused department leaders of using the tech to "spy" on officers.

Tassone, who was raised in a police and military family on Chicago's South Side, dismisses the privacy complaints from cops.

"Nothing they say on camera is considered private. That's all public records," he says. "All my work on Wall Street for 20 years, all my emails, had identical employee quality assurance monitoring in place. The idea that police wouldn't have it when they have guns and badges, ability to take people's rights—nobody's going to support that."

Truleo takes issues of privacy for police and civilians very seriously; video is never analyzed, and personally identifiable information is automatically scrubbed. "We need to be super sensitive and super delicate around how the technology is deployed to maximize civilian privacy," Tassone says.

He believes these kinds of safeguards make the proposition simply irresistible: better transparency for a low monthly fee. He expects that local and state lawmakers will mandate the use of Truleo or other bodycam-to-text software.

"This is going to be the future of policing," he says. "It'll be the law within five years." ■

Patrick Sisson, a Chicago expat living in Los Angeles, covers technology and urbanism.

No more users

By Taylor Majewski

IF ARTIFICIAL INTELLIGENCE IS NOW A THOUGHT PARTNER, WHAT ARE WE?

Illustration by Tom Humberstone

Every Friday, Instagram chief Adam Mosseri speaks to the people. He has made a habit of hosting weekly "ask me anything" sessions on Instagram, in which followers send him questions about the app, its parent company Meta, and his own (extremely public-facing) job. When I started watching these AMA videos years ago, I liked them. He answered technical questions like "Why can't we put links in posts?" and "My explore page is wack, how to fix?" with genuine enthusiasm. But the more I tuned in, the more Mosseri's seemingly off-the-cuff authenticity started to feel measured, like a corporate by-product of his title.

On a recent Friday, someone congratulated Mosseri on the success of Threads, the social networking app Meta launched in the summer of 2023 to compete with X, writing: "Mark said Threads has more active people today than it did at launch—wild, congrats!" Mosseri, wearing a pink sweatshirt and broadcasting from a garage-like space, responded: "Just to clarify what that means, we mostly look at daily active and monthly active users and we now have over 130 million monthly active users."

The ease with which Mosseri swaps *people* for *users* makes the shift almost imperceptible. Almost. (Mosseri did not respond to a request for comment.)

People have been called "users" for a long time; it's a practical shorthand enforced by executives, founders, operators, engineers, and investors ad infinitum. Often, it *is* the right word to describe people who *use* software: a user is more than just a customer or a consumer. Sometimes a user isn't even a person; corporate bots are known to run accounts on Instagram and other social media platforms, for example. But "users" is also unspecific enough to refer to just about everyone. It can accommodate almost any big idea or long-term vision. We use—and are used by—computers and platforms and companies. Though "user" seems to describe a relationship that is deeply transactional, many of the technological relationships in which a person would be considered a user are actually quite personal. That being the case, is "user" still relevant?

"People were kind of like machines"

The original use of "user" can be traced back to the mainframe computer days of the 1950s. Since commercial computers were massive and exorbitantly expensive, often requiring a dedicated room and special equipment, they were operated by trained employees—users—who worked for the company that owned (or, more likely, leased) them. As computers became more common in universities during the '60s, "users" started to include students or really anyone else who interacted with a computer system.

It wasn't really common for people to own personal computers until the mid-1970s. But when they did, the term "computer owner" never really took off. Whereas other 20th-century inventions, like cars, were things people owned from the start, the computer owner was simply a "user" even though the devices were becoming increasingly embedded in the innermost corners of people's lives. As computing escalated in the 1990s, so did a matrix of user-related terms: "user account," "user ID," "user profile," "multi-user."

Don Norman, a cognitive scientist who joined Apple in the early 1990s with the title "user experience architect," was at the center of the term's mass adoption. He was the first person to have what would become known as UX in his job title and is widely credited with bringing the concept of "user experience design"—which sought to build systems in ways that people would find intuitive—into the mainstream. Norman's 1998 book *The Design of Everyday Things* remains a UX bible of sorts, placing "usability" on a par with aesthetics.

Norman, now 88, explained to me that the term "user" proliferated in part because early computer technologists mistakenly assumed that people were kind of like machines. "The user was simply another component," he said. "We didn't think of them as a person—we thought of [them] as part of a system." So early user experience design didn't seek to make human-computer interactions "user friendly," per se. The objective was to encourage people to complete tasks quickly and efficiently. People and their computers were just two parts of the larger systems being built by tech companies, which operated by their own rules and in pursuit of their own agendas.

Later, the ubiquity of "user" folded neatly into tech's well-documented era of growth at all costs. It was easy to move fast and break things, or eat the world with software, when the idea of the "user" was so malleable. "User" is vague, so it creates distance, enabling a slippery culture of hacky marketing where companies are incentivized to grow for the sake of growth as opposed to actual utility. "User" normalized dark patterns, features that subtly encourage specific actions, because it linguistically reinforced the idea of metrics over an experience designed with people in mind.

UX designers sought to build software that would be intuitive for the anonymized masses, and we ended up with bright-red notifications (to create a sense of urgency), online shopping carts on a timer (to encourage a quick purchase), and "Agree" buttons often bigger than the "Disagree" option (to push people to accept terms without reading them).

A user is also, of course, someone who struggles with addiction. To be an addict is—at least partly—to live in a state of powerlessness. Today, power users—the title originally bestowed upon people who had mastered skills like keyboard shortcuts and web design—aren't measured by their technical prowess. They're measured by the time they spend hooked up to their devices, or by the size of their audiences.

Defaulting to "people"

"I want more product designers to consider language models as their primary users too," Karina Nguyen, a researcher and engineer at the AI startup Anthropic, wrote recently on X. "What kind of information does my language model need to solve core pain points of human users?"

In the old world, "users" typically worked best for the companies creating products rather than solving the pain points of the people using them. More users equaled more value. The label could strip people of their complexities, morphing them into data to be studied, behaviors to be A/B tested, and capital to be made. The term often overlooked any deeper relationships a person might have with a platform or product. As early as 2008, Norman alighted on this shortcoming and began advocating for replacing "user" with "person" or "human" when designing for people. (The subsequent years have seen an explosion of bots, which has made the issue that much more complicated.) "Psychologists depersonalize the people they study by calling them 'subjects.' We depersonalize the people we study by calling them 'users.' Both terms are derogatory," he wrote then. "If we are designing for people, why not call them that?"

In 2011, Janet Murray, a professor at Georgia Tech and an early digital media theorist, argued against the term "user" as

too narrow and functional. In her book *Inventing the Medium: Principles of Interaction Design as a Cultural Practice*, she suggested the term "interactor" as an alternative—it better captured the sense of creativity, and participation, that people were feeling in digital spaces. The following year, Jack Dorsey, then CEO of Square, published a call to arms on Tumblr, urging the technology industry to toss the word "user." Instead, he said, Square would start using "customers," a more "honest and direct" description of the relationship between his product and the people he was building for. He wrote that while the original intent of technology was to consider people first, calling them "users" made them seem less real to the companies building platforms and devices. Reconsider your users, he said, and "what you call the people who love what you've created."

Recently, I met with a founder who cringed when his colleague used the word "humans" instead of "users." He wasn't sure why.

Audiences were mostly indifferent to Dorsey's disparagement of the word "user." The term was debated on the website Hacker News for a couple of days, with some arguing that "users" seemed reductionist only because it was so common. Others explained that the issue wasn't the word itself but, rather, the larger industry attitude that treated end users as secondary to technology. Obviously, Dorsey's post didn't spur many people to stop using "user."

Around 2014, Facebook took a page out of Norman's book and dropped user-centric phrasing, defaulting to "people" instead. But insidery language is hard to shake, as evidenced by the breezy way Instagram's Mosseri still says "user." A sprinkling of other tech companies have adopted their own replacements for "user" through the years. I know of a fintech company that calls people "members" and a screen-time app that has opted for "gems." Recently, I met with a founder who cringed when his colleague used the word "humans" instead of "users." He wasn't sure why. I'd guess it's because "humans" feels like an overcorrection.

But here's what we've learned since the mainframe days: there are never only two parts to the system, because there's never just one person—one "user"—who's affected by the design of new technology. Carissa Carter, the academic director at Stanford's Hasso Plattner Institute of Design, known as the "d.school," likens this framework to the experience of ordering an Uber. "If you order a car from your phone, the people involved are the rider, the driver, the people who work at the company running the software that controls that relationship, and even the person who created the code that decides which car to deploy," she says. "Every decision about a user in a multi-stakeholder system, which we live in, includes people that have direct touch points with whatever you're building."

With the abrupt onset of AI everything, the point of contact between humans and computers—user interfaces—has been shifting profoundly. Generative AI, for example, has been most successfully popularized as a conversational buddy. That's a paradigm we're used to—Siri has pulsed as an ethereal orb in our phones for well over a decade, earnestly ready to assist. But Siri, and other incumbent voice assistants, stopped there. A grander sense of partnership is in the air now. What were once called AI bots have been assigned lofty titles like "copilot" and "assistant" and "collaborator" to convey a sense of partnership instead of a sense of automation. Large language models have been quick to ditch words like "bot" altogether.

Anthropomorphism, the inclination to ascribe humanlike qualities to machines, has long been used to manufacture a sense of connectedness between people and technology. We—people—remained users. But if AI is now a thought partner, then *what are we?*

Well, at least for now, we're not likely to get rid of "user." But we could intentionally default to more precise terms, like "patients" in health care or "students" in educational tech or "readers" when we're building new media companies. That would help us understand these relationships more accurately. In gaming, for instance, users are typically called "players," a word that acknowledges their participation and even pleasure in their relationships with the technology. On an airplane, customers are often called "passengers" or "travelers," evoking a spirit of hospitality as they're barreled through the skies. If companies are more specific about the people—and, now, AI—they're building for rather than casually abstracting everything into the idea of "users," perhaps our relationship with this technology will feel less manufactured, and it will be easier to accept that we're inevitably going to exist in tandem.

Throughout my phone call with Don Norman, I tripped over my words a lot. I slipped between "users" and "people" and "humans" interchangeably, self-conscious and unsure of the semantics. Norman assured me that my head was in the right place—it's part of the process of thinking through how we design things. "We change the world, and the world comes back and changes us," he said. "So we better be careful how we change the world." ■

Taylor Majewski is a writer and editor based in San Francisco. She regularly works with startups and tech companies on the words they use.

Hydrobiologist Jari Ilmonen and his team set out across Lake Saimaa in Finland, where they are building artificial snowbanks for endangered Saimaa ringed seals.

A shelter in the snow

In Finland, snow dens protect seal pups from a harsh climate. But building them now requires human assistance.

By Matthew Ponsford

Just before 10 a.m., hydrobiologist Jari Ilmonen and his team of six step out across a flat, half-mile-wide disk of snow and ice. For half the year this vast clearing is open water, the tip of one arm of the labyrinthine Lake Saimaa, Finland's biggest lake, which reaches almost to Russia's western border. As each snow boot lands, there's a burst of static, like the spine-tingling scrape of a freezer drawer closing. "It's a poor amount of snow," complains Ilmonen, who sees less than half the 20 centimeters (eight inches) he'd hope for in mid-January.

To reach their destination, one of the roughly 14,000 islands that poke out from the lake's frozen surface, the team must walk for almost an hour in temperatures of −17 °C (1.4 °F). Ilmonen pays close attention to the snow underfoot because today it will be the material from which they construct lifesaving shelters for the Saimaa ringed seal, one of the world's most endangered seals.

One key question brings volunteers out in these icy conditions: How will an animal that's born inside a grotto of snow survive on a warming planet? For millennia, during Saimaa's blistering winters, wind drove snow into meters-high snowbanks along the lake's shoreline, offering prime real estate from which these seals carved cave-like dens to shelter from the elements and raise newborns. But in recent decades, these snowdrifts have failed to form in sufficient numbers, as climate change has brought warming temperatures and rain in place of snow.

For the last 11 years, humans have stepped in to construct what nature can no longer reliably provide. Human-made snowdrifts, built using handheld snowplows to mimic the actions of strong winds, are the latest in a raft of measures that have brought Saimaa's seals back from the brink of extinction, following curbs on hunting and industrial pollution, and seasonal bans

To date, three-quarters of the nearly 2,000 snowdrifts made by volunteers like these around Lake Saimaa have been used by seals, and in recent mild winters, they have housed 90% of seal pups.

Saimaa's ringed seals are among the world's most endangered seals.

Volunteers pile up and compact layers of snow to build a meter-high snowbank.

For the last 11 years, humans have stepped in to construct what nature can no longer reliably provide.

on fishing with gill nets. Now the seal population is rebounding, from lows of 100 or so in the 1980s to about 400 today. Some 320 pups—half of all Saimaa ringed seals born since 2014—took their first breath inside these shelters.

This year, Ilmonen and his colleagues at Finland's parks and wildlife agency have been watching since winter began for signs of trouble ahead. By December, an ice sheet typically covers the lake, and seals will use sharp claws on their front flippers to make a hole in the ice from the water below before carving out their den inside the snow piled above. A lack of snow or ice could spell the death of all the year's pups.

As ice and snow arrive, the teams spring into action, joined by groups run by the charity World Wildlife Fund in southern parts of Lake Saimaa. All of today's volunteers—including a nurse and yoga instructor—are constructing seal habitats for the first time. Their destinations are plotted on a map kept secret under Finnish law to protect these rare creatures. The first site is in a sheltered cove shadowed by rocks and trees on the north side of a small island, where the snowdrifts they make will be protected from melting through spring. On arrival, Ilmonen hammers a heavy metal spike called a *tuura* through the ice and uses a measuring stick to check that there is close to a meter of space for the seals to swim below.

Today, the levels are right, and he marks out an area for the snowdrift. Construction begins by driving loose snow into a bank about eight meters (26 feet) long and three meters wide. As snow piles up, Ilmonen stomps it down to form compact layers until it reaches a height of about a meter. If all goes to plan, fresh snowfall will add a further layer of cover.

Over the last decade, the locations, designs, and construction methods for anthropogenic snowdrifts have been

SHUTTERSTOCK (SEAL)

In warmer winters, when the lake does not freeze over, floating nesting structures are used to allow seals to shelter safely.

developed by scientists from the University of Eastern Finland and the Finnish parks agency. Each year data is gathered by a seal census (some years with the help of camera traps that record seals' preferences and the performance of their shelters), and the process is tweaked the following year. The first shelters were smaller, with loosely piled snow, explains ecologist Miina Auttila, who invented the artificial snowdrift for her PhD thesis in 2010, but "after the first winter, the drifts we had piled up had melted surprisingly quickly and the roofs of the lairs collapsed." Pups left exposed can freeze or be eaten by foxes, wolves, lynx, or wolverines.

Stanislav Roudavski, founder of Deep Design Lab at the University of Melbourne, says this type of rigorous data gathering and iterative design is one way we can begin to treat other species as collaborators and "co-design" with them.

Environmental scientists and designers are envisioning more ways to support wild organisms through what's sometimes called "interspecies" or "more-than-human" design, such as by producing artificial reefs or wildlife bridges. The shelters are one of many solutions meant to respond to specific populations' conservation needs. Other examples include the grisly vulture restaurants in Nepal—enclosures where the scavenging birds are fed cattle carcasses free from the poisons that have decimated populations—and 3D-printed nesting boxes that Deep Design Lab has built for rare owls.

Whether this year's snowdrifts have been used will not be known until spring, after the seals have departed and left visible holes where dens have been, along with white fluff from newborns. To date, three-quarters of the nearly 2,000 snowdrifts made by humans around Lake Saimaa have been used by seals, and in recent mild winters, those dens have housed 90% of seal pups.

Since 2016, Auttila and researchers from the University of Eastern Finland have searched for a solution that will last through the years ahead, when climate models predict that Saimaa will no longer be covered by ice and snow each year. This year, 33 reusable floating artificial nest structures were deployed around Saimaa, using plastic tubes as floats and organic siding made of peat or willow, to provide the first artificial habitats for large, free-ranging wild mammals.

Wildlife cameras revealed five pups born in earlier prototypes of these shelters, which have meanwhile repelled foxes, raccoon dogs, and lynx. Yet seals still prefer snow if they can find it. The project aims to next produce a seal-safe shelter that is easy to transport by snowmobile. Most crucially, Auttila adds, "seals have to accept it." ■

Matthew Ponsford is a freelance reporter based in London.

RIIKKA ALAKOSKI

Taking inspiration from Daedalus

For centuries, people have imagined using technology to overcome physical limits. By Bill Gourgey

Today's climate-change kraken may have been unleashed by human activity—which has discharged greenhouse-gas emissions into Earth's atmosphere for centuries—but reversing course and taming nature's growing fury seems beyond human means, a quest only mythical heroes could fulfill. Yet the dream of human-powered flight—of rising over the Mediterranean fueled merely by the strength of mortal limbs—was also the stuff of myths for thousands of years. Until 1988.

That year, in October, *MIT Technology Review* published the aeronautical engineer John Langford's account of his mission to retrace the legendary flight of Daedalus, described in an ancient Greek myth recorded by the Roman poet Ovid in *Metamorphoses*. Imprisoned on the island of Crete with his son Icarus, Daedalus, a skilled inventor, crafts wings of feathers and wax to escape. In his exuberance, Icarus defies Daedalus's warning not to fly too close to the sun. His wings melt and he plummets to his death. With heavy heart, Daedalus completes the flight, landing in Sicily.

"Daedalus became a quest to build a perfect airplane," says Langford, reflecting on his project team's mission. By some measures, they succeeded. Their plane, Daedalus 88, still holds the record for absolute distance (71.5 miles, or 115 kilometers) and duration (nearly four hours) of a human-powered flight.

Of course, Langford's team modified some of the mythical parameters. The aircraft replaced feathers and wax with carbon-fiber wings, and the pilot, the Greek cyclist Kanellos Kanellopoulos, didn't flap his way into history—he pedaled. Plus, the 500-mile journey to Sicily seemed beyond mortal capacity, so Langford and his team set their sights on Santorini.

The problem with the Daedalus project, and human-powered aircraft of any kind, is the grueling effort to remain aloft, the risk of crashing, and the expense—none of which was lost on Langford. "In itself, our Daedalus project could never answer the question 'So what?'" he admits.

At the time, unseen clouds of human-generated chlorofluorocarbons, gathering in Earth's stratosphere for half a century, had blasted a seasonal hole in the protective ozone layer over Antarctica, signifying a disaster unfolding across Earth's atmosphere. As the global community rallied, the "So what?" he was looking for emerged.

To Langford, an entrepreneur whose twin passions are climate research and sustainable aeronautics, the perfect plane is an unmanned aerial vehicle able to ply the stratosphere, collect climate data such as ozone readings, and harness the sun for its energy needs. Aurora Flight Sciences, his first company, unveiled such a plane, Odysseus, in 2018. His latest company, Electra, wants to decarbonize all aviation.

That a human-powered plane able to fly mere meters above the sea for a handful of hours managed to inspire solar-powered robotic planes that continuously comb Earth's stratosphere could make sense only in the context of our climate challenges. Such novel aircraft symbolize the ability of human beings to achieve mythic feats when joined in a common quest, however daunting. ■

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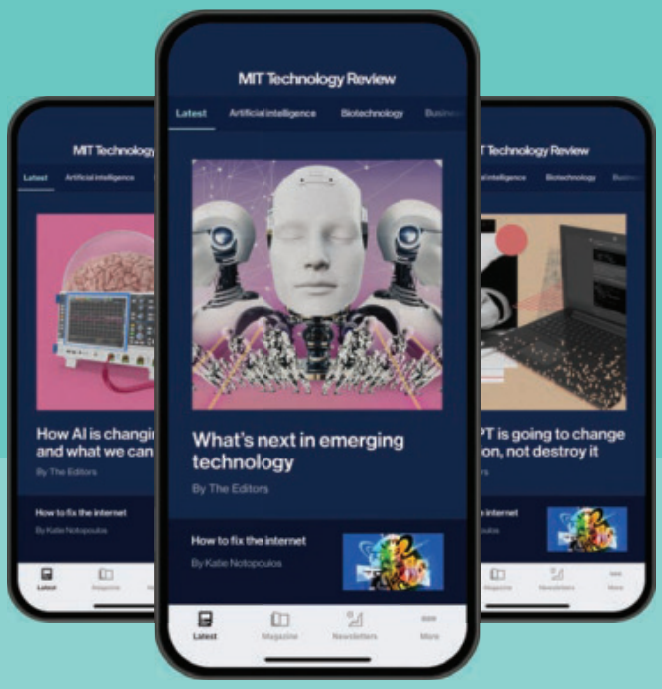

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