MIT Technology Review

The Innovation Issue

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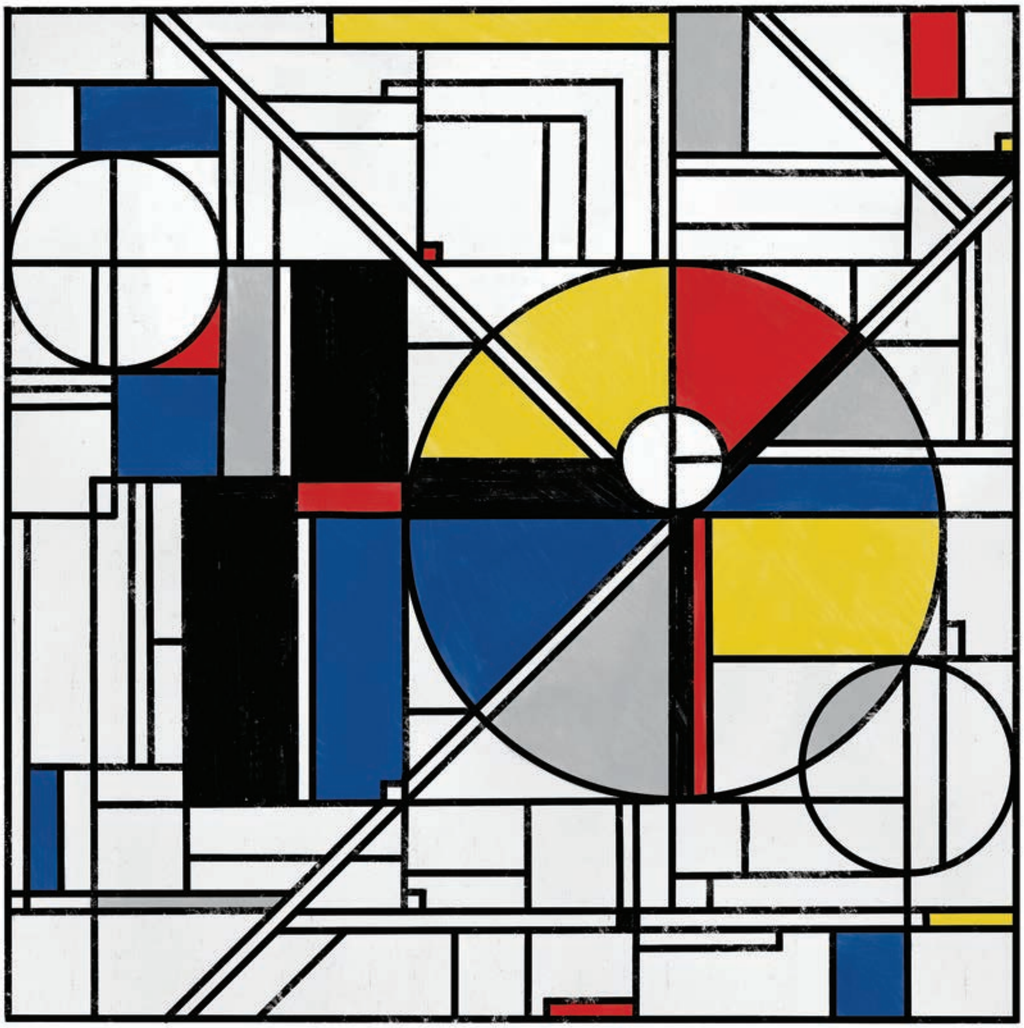
JAMES WEBB SPACE TELESCOPE

CRISPR FOR HIGH CHOLESTEROL

AI THAT MAKES IMAGES

ORGANS ON DEMAND

ABORTION PILLS VIA TELEMEDICINE



BREAKTHROUGH TECHNOLOGIES

A CHIP DESIGN THAT CHANGES EVERYTHING

ANCIENT DNA ANALYSIS

BATTERY RECYCLING

THE INEVITABLE EV

MASS-MARKET MILITARY DRONES

MIT Technology Review Insights

The Green Future Index 2nd edition

The Green Future Index 2022 is the second edition of the comparative ranking of 76 nations and territories on their ability to develop a sustainable, low-carbon future. It measures the degree to which economies are pivoting toward clean energy, industry, agriculture, and society through investment in renewables, innovation, and green policy.

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

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

KEY

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

- ↑ Countries that have gone up in the ranking since last year
- ↔ Countries that have retained the same ranking as last year
- ↓ Countries that have gone down in the ranking since last year

Overall top 10

Rank 2022		Rank 2021	Territory	Score
1	↔	1	**Iceland**	6.9
2	↔	2	**Denmark**	6.6
3	↑	10	**Netherlands**	6.4
4	↑	17	**United Kingdom**	6.3
5	↓	3	**Norway**	6.2
6	↔	6	**Finland**	6.2
7	↓	4	**France**	6.1
8	↑	11	**Germany**	6.1
9	↑	12	**Sweden**	6.1
10	↑	31	**South Korea**	6.0

- Nearly 36% of UK's power came from clean sources in the third quarter of 2021, with the aim of reaching 100% by 2035.
- In January 2022, Finland took on €217 million in pre-financing, which will partially go to efforts to decarbonize the energy sector.
- South Korea and Japan have seen significant rises in their innovation scores, thanks to their world-beating green IP contributions.

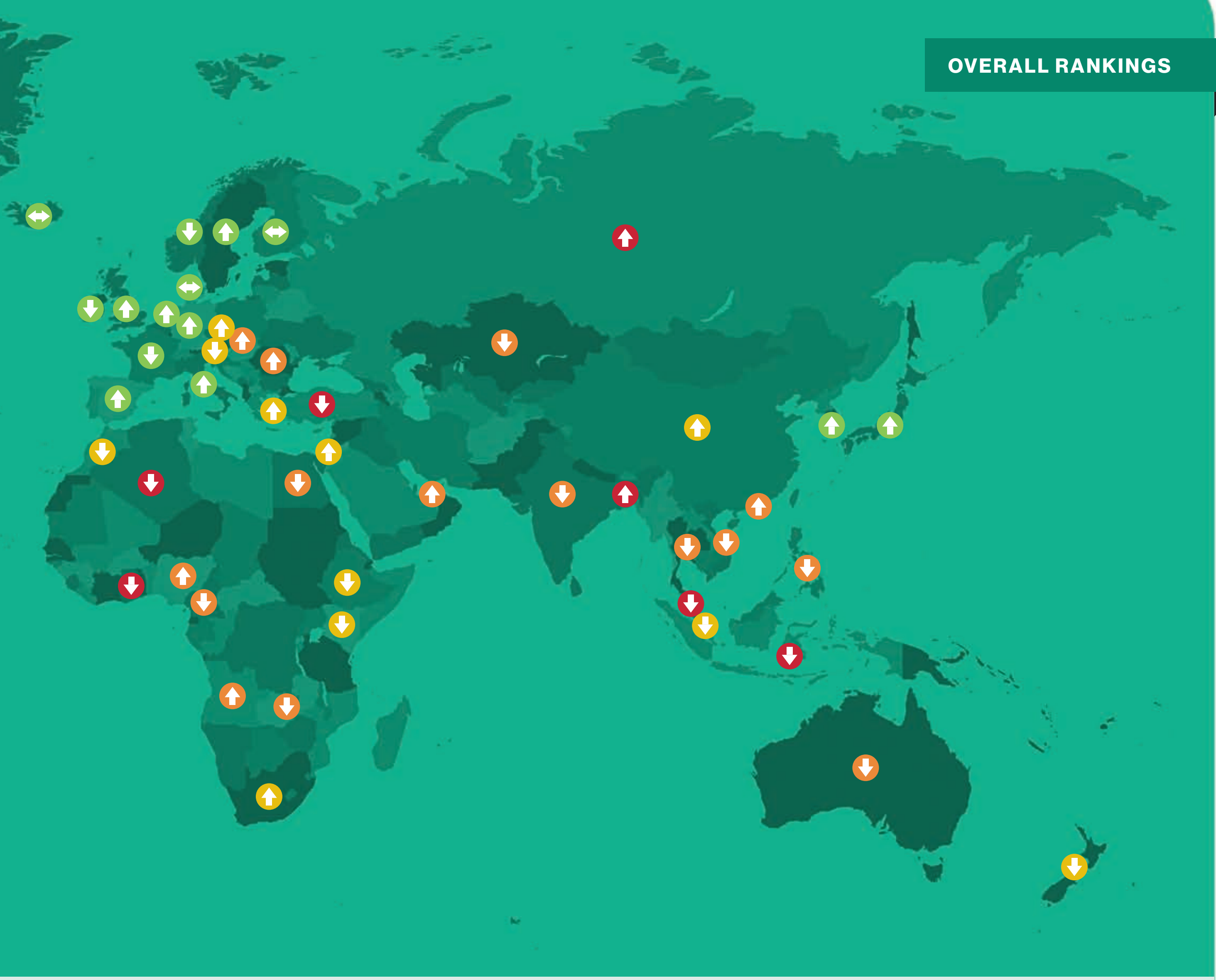
Experience the interactive index, view the data, and download the full report at: technologyreview.com/gfi

The Green Future Index 2nd edition was produced in association with

Gold partner Morgan Stanley

Silver partners citrix IRIS CERAMICA GROUP

OVERALL RANKINGS



Green society top 10

Rank 2022		Rank 2021	Territory	Score
1	↑	3	**South Korea**	7.0
2	↓	1	**Singapore**	6.8
3	↓	2	**Ireland**	6.8
4	↑	8	**Germany**	6.5
5	↑	7	**United States**	6.5
6	↑	17	**Iceland**	6.4
7	↓	4	**Taiwan**	6.4
8	↓	5	**Philippines**	6.3
9	↓	6	**Czech Republic**	6.3
10	↑	13	**Canada**	6.2

- This pillar ranks each country on how well it is pivoting toward clean energy, industry, agriculture, and society.
- Leaders in the green society pillar are over-represented by nations that have incorporated strong civil planning and societal development goals into policy, regulation, and public infrastructure spending.
- Singapore and South Korea are the world's best-ranked recycling economies.

Interested in partnering with us? Contact: insights@technologyreview.com

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

The constant is change

For the past 22 years, we've been publishing an annual list of the 10 biggest breakthrough technologies. In 2018, we defined a breakthrough as "a technology, or perhaps even a collection of technologies, that will have a profound effect on our lives." That's pretty broad! But it gets at the heart of what we try to identify: transformative, world-changing technologies.

I love digging through our back catalogue and perusing the lists from previous years because you can see that change happening. The lists are fascinating snapshots of the evolution of big tech breakthroughs. They document the progress we have made in many of the core areas at the intersection of science and engineering—energy, AI, biotech, quantum computing, and climate tech, to name a few.

But they are also snapshots of the times we live in. Last year I wrote that I would be pleased if we did not need to include anything covid-19-related on this year's list. In the previous two years mRNA vaccines, digital contact tracing, covid treatments, and variant tracking had made the list—all grim reminders of the severity of the pandemic. But it was precisely this progression of technologies that helped us, finally, begin to beat covid-19 back to the point where we can live with some sense of normalcy again.

While we don't have a covid-related technology on the list this year, there are other reminders of the monumental challenges we face. There is the ongoing war in Ukraine. Abortion access has been limited in many states and banned in several others. We continue to face headwinds as we try to make progress against climate change.

Some of the items on the list—such as the widening availability of military drones—aren't exactly good news. One of the more interesting discussions we had putting this year's list together was about whether or not we should include technologies that are designed, literally, to kill people. But ultimately, inclusion is not an endorsement as much as it is a statement about the potential impact of a technology.

There are also real reasons for optimism related to other things we see happening. We're making progress in helping humans live longer, healthier lives with tools such as CRISPR and the potential to produce organs on demand. We're also getting better at recycling batteries and making EVs truly practical alternatives to gas-powered cars.

Finally, some of my favorite things on the list this year are the ones that just inspire a sense of awe and wonder at the scope of human achievement. The James Webb Space Telescope, for example, was a no-brainer to include. So was image-generating AI—which in the coming years will have implications for all sorts of applications beyond just creating art. And while the ability to analyze ancient DNA has the potential to unlock many new scientific discoveries, it's also just pretty cool. Neanderthal DNA!

I hope you enjoy this issue. And in the coming weeks, we will have even more for you to check out at technologyreview.com—including a poll where you can vote on what you think the 11th breakthrough technology should be.

One last note: If you enjoy our coverage and think others may too, please consider giving a gift subscription. You can do so at technologyreview.com/join.

Thank you for reading,

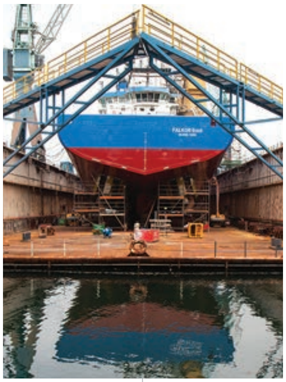
Mat

Mat Honan is editor in chief of MIT Technology Review

ROBYN KESSLER


"THE
FASTEST,
SMARTEST,
SAFEST,
PASSAGE
TO
THE
CLOUD."

"We believe it's going to work and that it's going to change everything." –p.32



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The Innovation Issue

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Cover illustration by Matthijs Herzberg

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The Download

AI brings the internet to submerged Roman ruins

The underwater network is making it easier to monitor archaeological sites.

By Manuela Callari

Over 2,000 years ago, Baiae was the most magnificent resort town on the Italian peninsula. Wealthy statesmen including Mark Antony, Cicero, and Caesar were drawn to its natural springs, building luxurious villas with heated spas and mosaic-tiled thermal pools. But over the centuries, volcanic activity submerged this playground for the Roman nobility—leaving half of it beneath the Mediterranean.

Today, Baiae is one of the world's few underwater archaeological parks, and its 435 acres are open to visitors wanting to explore the remains of the ancient Roman city. A protected marine area, the site needs to be monitored for damage caused by divers and environmental factors. However, explains Barbara Davidde, Italy's national superintendent for underwater cultural heritage, "communication underwater is challenging."

Cabled systems are the most reliable, but they are difficult to maintain and cover a limited operational area. And wireless internet doesn't work well in water, because of the way water interacts with electromagnetic waves. Scientists have tried optic and acoustic waves, but light and sound aren't efficient forms of wireless underwater communication—water temperature, salinity, waves, and noise can alter signals as they travel between devices.

So Davidde teamed up with a group of engineers led by Chiara Petrioli, a professor at Sapienza University and director of Sapienza's spinoff WSense, a startup specializing in underwater monitoring and communication systems. Petrioli's team has developed a network of acoustic modems and underwater wireless sensors capable of gathering environmental data and transmitting it to land in real time. "We can now monitor the site remotely and at any time," says Davidde.

Aided by algorithms, divers explore the underwater ruins at Baiae in Naples, Italy.

COURTESY OF BARBARA DAVIDDE

Their system relies on AI algorithms to constantly change the network protocol. As the sea conditions change, the algorithms modify the information path from one node to the other, allowing the signal to travel up to two kilometers. The system can send data between transmitters one kilometer apart at a kilobit per second and reaches tens of megabits per second over shorter distances, explains Petrioli. This bandwidth is enough to transmit environmental data collected by sensors anchored to the seafloor, such as images and information on water quality, pressure, and temperature; metal, chemical, and biological elements; and noise, currents, waves, and tides.

At Baiae, underwater internet allows remote, continuous monitoring of environmental conditions such as pH and carbon dioxide levels, which can influence the growth of microorganisms that could disfigure the artifacts. In addition, it allows divers to communicate with one another and with colleagues above the surface, who can also use the technology to locate them with a high degree of accuracy.

Davidde anticipates that the network will be available to tourists visiting the archaeological site in the coming months. As they swim over the ruins, visitors will use waterproof smart tablets to communicate—and to view 3D reconstructions of the ruins via augmented reality.

"Underwater internet has made monitoring of the archaeological site simpler and more efficient," says Davidde. "At the same time, we can offer the public a new, interactive way to explore the underwater park of Baiae."

Even at low bandwidth, this underwater wireless communication technology is extremely useful, particularly for dynamic systems, such as divers in motion during a site exploration.

Systems like these are now used at several archaeological sites in Italy and have many other applications, including studying the effects of climate change on marine environments and monitoring underwater volcanoes. Italy's National Agency for New Technologies, Energy, and Sustainable Economic Development uses WSense networks to study how algae, aquatic invertebrate animals, and corals adapt to climate change in the bay of Santa Teresa, for example. WSense systems have also spread outside Italy; in Norway, for instance, they are used to monitor water quality and fish health in salmon farms.

"It's nothing like what a cabled system can do," Petrioli says, "but the flexibility of a cable-free network is extremely valuable." ■

Microcars for mobility

A small vehicle designed for people with disabilities is taking off in the Netherlands.

By Niamh Ní Hoireabhaird

The Netherlands is known internationally for its bicycle culture. Now it's also home to another, more broadly accessible form of transportation: the Canta.

For people with disabilities in the country, the compact four-wheeled, two-seat vehicle has become the primary form of micromobility—a term encompassing a range of small, lightweight vehicles typically operating at around 15 miles per hour. The Canta looks a bit like a little Fiat or Mini and has all the main features of a car: engine, drivetrain, roof, windows, and doors. But it is an especially compact one: it is a microcar that measures just over three feet wide, making it narrow enough to be driven in the country's wider bike lanes while also being able to accommodate wheelchairs and other mobility aids.

Designed specifically for people with disabilities, the Canta was created in 1995 by a small Dutch vehicle manufacturer

This is what diversity sounds like

A participatory project explores the linguistic landscape of the US.

By Whitney Bauck

What do the people of the United States sound like? Census language data would give you one kind of answer. But numbers don't capture all the factors in play—assimilation, the past and present of language, whose voices are prioritized. It's this gap that multidisciplinary artist Ekene Ijeoma and his group Poetic Justice at the MIT Media Lab are exploring in the ongoing participatory project "A Counting."

"We were thinking about what it means to count and be counted, and how the Census has historically undercounted and underrepresented marginalized communities," says Ijeoma. "And we were thinking what a poetic response would be."

Presented online and in person at spaces like Houston's Contemporary Arts Museum and the Museum of the City of New called Waaijenberg Mobility. It operates at speeds typically below 45 kilometers (27.9 miles) per hour and is not allowed on major motorways.

"We started manufacturing the Canta because there was a demand," says Frank Vermin, owner of Waaijenberg Mobility. Many of their customers, he explains, were unable to obtain a driver's license owing to their disability. Canta may look like a car. But it is classified as a mobility device, which means people can "get mobility from door to door" without needing a license.

The various Canta models are customizable, allowing the vehicle to meet the mobility needs of a broad range of riders, including wheelchair users. The Canta 2 Inrijwagen, for example, has no seats and lowers down to allow a wheelchair to roll in through a door at the back. Different types of controls for gas or brakes can be installed to suit the driver. The Canta is not the only microcar that can be seen driving around the Netherlands, but it is only the only one with these accessibility adaptations and advantages.

The cars range in price from around €15,500 for the Canta Comfort to more than €23,000 for the Canta 2 Inrijwagen.

Older models of the Canta were gas-powered, but the latest model is electric, in line with municipal efforts. Amsterdam, for example, aims to be an emissions-free city by 2025. Micromobility can and must play a big role.

The Canta was created for, but is not exclusive to, disabled drivers.

"When we look at non-cars, a vast space of opportunity for mobility solutions becomes possible," says Horace Dediu, an expert on the future of micromobility. "This means not just more efficient and less demanding alternatives for short trips, but also vehicles for those who are too young, too old, or disabled."

Dediu notes that "8 billion people need mobility. Only 1 billion currently can drive." Everyone, he says, "will be served by micromobility." ■

York, the artwork features audio recordings of 100 individuals counting from 1 to 100 in a variety of languages, accompanied by a transcription in white lettering on a black screen. Localized versions reflect the linguistic landscapes of New York City, St. Louis, Houston, Omaha, and Ogden, Utah, as well as the US overall. A sign language version is also in the works.

Most of the voices are those of people who called in to record themselves. The Poetic Justice team then built an algorithm that "selects and weights languages that are the least recorded so that you hear them more frequently," says Ijeoma. The video changes over time as new recordings are added.

"A Counting" is the latest in a string of artworks that leverage Ijeoma's background in information technology to translate cold data into something laden with feeling. "I want to create a contemporary portrait. What better way to do it [than] with contemporary tools and techniques—those of data analysis and data visualization—not in a way that's literal, but poetic?" he says.

The first word in "A Counting" is always spoken in an indigenous language from the area being represented. For the New York City edition, this meant using the voice of someone no longer living: when Ijeoma and his team reached out to the Lenape, Manhattan's original inhabitants, they were sent a recording featuring Nora Thompson Dean, a.k.a. Weènchipahkihëlèxkwe, one of the last fluent speakers of the southern Unami dialect of Lenape, who died in 1984. The recording, provided by the Lenape Center, expands the project beyond a mere "living portrait" of this land's current population, inviting viewers and listeners to wrestle with how this nation came to be and whose voices have been buried along the way.

Ultimately, Ijeoma says, the project "is really a speculation on what it would sound like if this were a truly united society."

To participate in "A Counting," call 844-959-3197, or for the sign language version, visit the website a-counting.us/sign to record yourself. ■

NIAMH NÍ HOIREABHAIRD

The newest crop found on the farm: solar panels

A little shade could be a helpful thing for some crops.

By Matt Whittaker

On a recent cool, sunny morning, Meg Caley could be found at Jack's Solar Garden showing visitors a bed of kale plants. As executive director of Sprout City Farms, Caley has more than a decade of experience farming in unlikely urban spaces in the Denver area. Today, about an hour north of the city, she works alongside researchers on an experimental agricultural method called agrivoltaics.

Agrivoltaics is pretty low-tech. Instead of being placed 18 to 36 inches off the ground, as in traditional solar farms, the solar panels are raised significantly higher to accommodate grazing animals and to allow more sunlight to reach plants growing beneath them.

The approach could be a boon for both energy generation and crop production. Less direct sunlight helps keep plants cooler during the day, allowing them to retain more moisture and thus require less watering. Having plants underneath the solar panels also reduces the amount of heat reflected by the ground, which keeps the panels cooler and makes them more efficient. Farm workers tending the crops also benefit from cooler temperatures, as do grazing animals.

Wide-scale adoption of the practice could help reduce carbon dioxide emissions in the United States by 330,000 tons a year and add more than 100,000 rural jobs without affecting crop yield very much. A 2019 study in the journal Scientific Reports predicted that the world's energy needs could be met by solar panels if less than 1% of cropland were converted to agrivoltaic systems.

Combining agriculture and energy generation has multiple benefits, says Joshua Pearce, a solar energy expert at Western

Agrivoltaics can help reduce heat stress in dairy cows.

JOE DELNERO/NREL

Wide-scale adoption of agrivoltaics could help reduce carbon dioxide emissions in the United States by 330,000 tons a year.

University in London, Ontario. "The solar energy and the increased land-use efficiency is worth money, and thus increases revenue for a given acre for the farmer," he says. "The local community also benefits from protecting access to fresh food and renewable energy."

But researchers are still sorting out the best ways to implement agrivoltaic systems. One variable is height: at Jack's Solar Garden, for example, scientists are experimenting with panels raised either six feet or eight feet from the ground. There is also the question of which types of plants respond best to the additional shade from solar panels.

Until these questions are resolved, agrivoltaics will remain an experiment. "Farmers aren't known to be risk takers," says Allison Jackson, education director of the Colorado Agrivoltaic Learning Center, which conducts tours at Jack's Solar Garden.

It's also expensive. While agrivoltaics could save farmers money on irrigation and electricity, or provide an extra source of cash if they sell electricity to the grid, installing solar panels is a significant upfront cost.

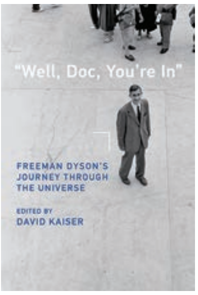
Despite the challenges, agrivoltaics projects are being installed around the world. According to the Fraunhofer Institute for Solar Energy Systems ISE, electricity production capacity from agrivoltaics projects grew from about five megawatts in 2012 to more than 14 gigawatts last year, amid the rise of national funding programs in Japan, China, Korea, France, and the United States.

"More research is needed for dual-use solar practices to scale," says Peter Perrault, head of circular economy at the renewable energy developer Enel North America. "But we already know the fundamentals are viable." ■

Farmer Brittany Staie harvests produce.

WERNER SLOCUM/NREL

Book reviews



"Well, Doc, You're In": Freeman Dyson's Journey through the Universe

Edited by David Kaiser
MIT Press, 2022

When Freeman Dyson died in 2020 at the age of 96, he left behind a vast body of work, in areas as wide-ranging as modern physics, nuclear reactor design, and the energy infrastructure of alien civilizations. Here, diverse writers—including family members—explore his path and interests, providing glimpses into a life guided by indefatigable curiosity.

Apocalypse Ready, The Manual of Manuals: A Century of Panic Prevention

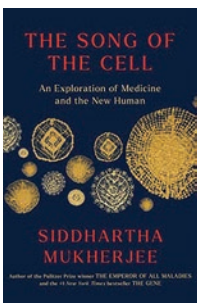
By Taras Young
Thames & Hudson, 2022

First rule of surviving catastrophe? "Don't die of ignorance." Drawn from 100 years of survival advice, this guidebook to the end times offers strategies old and new (plus fantastic visuals) for avoiding disasters that run the gamut from alien invasion to nuclear attack.

Extinct: A Compendium of Obsolete Objects

Edited by Barbara Penner, Adrian Forty, Olivia Horsfall Turner, and Miranda Critchley
Reaktion Books, 2021

An innovation that seemed life changing in one era might seem ridiculous or useless—or even deadly—in another. This illustrated cavalcade of inventions highlights the rise (and fall) of such things as the Concorde, arsenic wallpaper, pneumatic tubes, and flying cars.



The Song of the Cell: An Exploration of Medicine and the New Human

By Siddhartha Mukherjee
Simon & Schuster, 2022

A better understanding of the cell holds immense power for medicine, argues Mukherjee. He shows how all manner of maladies—from Alzheimer's to covid to arthritis—have been reconceived as resulting from abnormal cells or cell systems, thus transforming the way scientists thought about treating them. ■

A new platform for ocean exploration

By Ashley Balzer

COURTESY OF SCHMIDT OCEAN INSTITUTE

Humans rely on the ocean for food, pharmaceuticals, and even global climate regulation. Yet mysteries remain hidden beneath its surface. Researchers hope the Schmidt Ocean Institute's new vessel *Falkor (too)* will help reveal some of them.

Originally used for offshore industry, the 100-meter-long ship has been refitted over the last year and a half with state-of-the-art science gear. Available to scientists for free, it hosts eight laboratories, two moon pools (openings in the hull that allow for easier and safer access to the water), and two systems to handle remotely operated vehicles (ROVs). Few research ships have so much space for science.

Each ROV dive will be livestreamed, so anyone on the internet can catch new glimpses of things like cold-water coral reefs or hydrothermal vents alongside the scientists.

The ship will be able to venture out for months at a time and slice through ice up to half a foot thick, allowing scientists to reach regions that were previously inaccessible with the vessel's predecessor, *Falkor*. Some of its first expeditions will explore the Mid-Atlantic Ridge, where new ocean floor is being made. Researchers will test new tech to map the seafloor in this region with extreme precision—down to two centimeters in resolution. ■

Why Meta's latest large language model survived only three days online

Galactica was supposed to help scientists. Instead, it mindlessly spat out biased and incorrect nonsense.

By Will Douglas Heaven

In November, Meta unveiled a new large language model called Galactica, designed to assist scientists. But instead of landing with the big bang Meta hoped for, Galactica died with a whimper after three days of intense criticism. The company took down the public demo that it had encouraged everyone to try out.

Meta's misstep—and its hubris—show once again that Big Tech has a blind spot about the severe limitations of large language models. There is a large body of research that highlights the flaws of this technology, including its tendencies to reproduce prejudice and assert falsehoods as facts. However, Meta and other companies working on large language models, including Google, have continually failed to take it seriously.

Galactica is a large language model for science, trained on 48 million examples of scientific articles, websites, textbooks, lecture notes, and encyclopedias. Meta promoted its model as a shortcut for researchers and students. In the company's words, Galactica "can summarize academic papers, solve math problems, generate wiki articles, write scientific code, annotate molecules and proteins, and more."

But the shiny veneer wore through fast. Like all language models, Galactica is a mindless bot that cannot tell fact from fiction. Within hours, scientists were sharing its biased and incorrect results on social media. In response to a request to comment, Meta just pointed MIT Technology Review to a tweet it had posted announcing that the demo was being pulled.

A fundamental problem with Galactica is that it is not able to distinguish truth from falsehood, a basic requirement for a language model designed to generate scientific text. People found that it made up fake papers (sometimes attributing them to real authors), and generated wiki articles about the history of bears in space as readily as ones about protein complexes and the speed of light. It's easy to spot fiction when it involves space bears, but harder with a subject users may not know much about.

Many scientists pushed back hard. Michael Black, director at the Max Planck Institute for Intelligent Systems in Germany, who works on deep learning, tweeted: "In all cases, it was wrong or biased but sounded right and authoritative. I think it's dangerous."

The Meta team behind Galactica argues that language models are better than search engines. "We believe this will be the next interface for how humans access scientific knowledge," the researchers write.

This is because language models can "potentially store, combine, and reason about" information. But that "potentially" is crucial. It's a coded admission that language models cannot yet do all these things. And they may never be able to.

"Language models are not really knowledgeable beyond their ability to capture patterns of strings of words and spit them out in a probabilistic manner," says Chirag Shah at the University of Washington, who studies search technologies. "It gives a false sense of intelligence."

And it wasn't just the fault of Meta's marketing team. Yann LeCun, a Turing Award winner and Meta's chief scientist, defended Galactica to the end. On the day the model was released, LeCun tweeted: "Type a text and Galactica will generate a paper with relevant references, formulas, and everything."

Three days later, he tweeted: "Galactica demo is offline for now. It's no longer possible to have some fun by casually misusing it. Happy?" *To read the full story, visit www.technologyreview.com.* ■

STEPHANIE ARNETT; SOURCES: GETTY, ENVATO, NASA

Inside the billion-dollar meeting for the mega-rich who want to live forever

Hope, hype, and self-experimentation collided at an exclusive conference for ultra-rich investors who want to extend their lives past 100. I went along for the ride.

By Jessica Hamzelou

It's still dark when I arrive at the Grand Bellevue hotel at 7 a.m., and it's tipping with rain. I've braved the elements to make it to an early "longevity workout." It's the first event scheduled at an aging conference in Gstaad, an upmarket, picture-postcard Alpine town popular with celebrities.

The hotel where the conference takes place is ridiculously posh. The walk from reception to the gym takes me past a makeup and hairdressing area and a large children's playroom complete with giant teddy bear and ball pit. It is nothing like the science conference venues I usually visit. The location is stunning. The food is exquisite. The champagne comes with a backstory. But then, this isn't a typical science conference.

The Longevity Investors Conference brings academic scientists and biotech companies together with deep-pocketed investors. There were 150 people at this meeting, and its organizers told me that 120 of them were investors with millions or even billions of dollars at their disposal—and at least a million dollars ready to pump into a longevity project. Plenty of would-be attendees were denied a $4,500 ticket because they didn't meet this criterion, an event co-organizer tells me.

It was also a hotbed of hype and self-experimentation. At a "rejuvenation dinner" later that day, I see a group of men huddled over what looks like a napkin. One of them has cut his hand and is squeezing out drops of blood. He's probably doing some kind of test to estimate his biological age, says Martin Borch Jensen, chief science officer at Gordian Biotechnology, who is sitting beside me. Barely anyone else bats an eyelid.

I'd never before seen a scientist work up a sweat during a longevity workout before a presentation, nor conference attendees dropping to do pushups in between sessions. Much less bleeding into a napkin at dinner. Many attendees were taking bags of pills on a daily basis—all in the hope of extending their years of good health. As the hotel's co-owner put it at the start of the conference: "Here's to drinking wine well into our hundreds!"

Over the course of the two-day meeting, these researchers, entrepreneurs, and investors would make the case for longevity science and anti-aging strategies. There are plenty of promising approaches.

Scientists have found ways to reliably extend the life spans of yeast, worms, and even mice. A drug called rapamycin, originally used to suppress the immune systems of people undergoing organ transplants, can extend the life spans of lab mice by around 25%, for example. A treatment that clears out aged, worn-out cells has the same effect. Even injecting old mice with the blood of human teenagers seems to rejuvenate them. These approaches don't just delay death in the rodents. They prolong good health and help the animals stave off diseases associated with old age.

Yet it can be difficult to make heads or tails of claims that similar approaches might help humans, partly because we don't have a good way to tell if a treatment really has slowed or reversed aging in a person. To test the same treatments in human beings, we'd need to run clinical trials for decades, which would be very difficult and extremely expensive.

So the hunt is on for chemical clues in the blood or cells that might reveal how quickly a person is aging. Quite a few "aging clocks," which purport to give a person's biological rather than chronological age, have been developed. But none are reliable enough to test anti-aging drugs—yet.

As I leave to head back to my own slightly less posh hotel, I'm handed a gift bag. It's loaded up with anti-aging supplements, a box with a note saying it contains an AI longevity assistant, and even a regenerative toothpaste. At first glance, I have absolutely no idea if any of them are based on solid science. They might be nothing more than placebos.

Of all the supplements, drugs, and various treatments being promoted here, the workout is the one that's most likely to work, judging from the evidence we have so far.

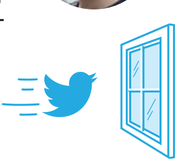
Ultimately, of all the supplements, drugs, and various treatments being promoted here, the workout is the one that's most likely to work, judging from the evidence we have so far. Workouts designed to strengthen our muscles seem to be particularly beneficial for keeping us healthy, especially in later life. They can even help keep our brains young.

It is undoubtedly an exciting time for longevity science and medicine. I hope I live long enough to see some positive results.

Portions of this story originally appeared online and in MIT Technology Review's weekly email health and biotech newsletter, The Checkup. Subscribe at techreview.com/checkup. ■

Greater Than/ Less Than/ Equal To

A highly (un)scientific definitive ranking of the biggest events in tech you maybe need to know about.





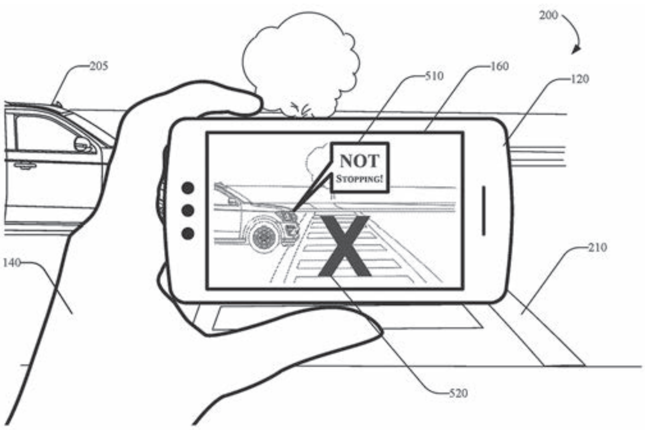




DART crashing into an asteroid	<	Taylor Swift fans crashing into **Ticketmaster**
Jeff Bezos giving all his money to charity	>	**Sam Bankman-Fried** giving all his customers' money to Sam Bankman-Fried
The sudden collapse of **FTX**	<	The slow-motion collapse of **Twitter**
Twitter's new "official" badge	<	On the internet **nobody knows you're a dog**
Steve Jobs's $200,000 Birkenstocks	>	**Meta's** fake legs scandal
BeReal retakes	>	**TikTok** retail
Corn Kid TikTok	>	A **Negroni** . . . Sbagliato . . . With Prosecco memes
170,000 attendees converging on Las Vegas for **CES**	=	The worst **flu season** in more than a decade

Patent: Please don't hit me

In July 2022, Ford filed US Patent 11396271 for an app that would allow cars operating in self-driving mode to communicate with pedestrians (whom the patent refers to as "vulnerable road users") via their phones. The app is meant to alert people when autonomous vehicles won't stop for them—essentially putting the onus on pedestrians to not get hit. ■



IMAGES COURTESY: NASA/JOHNS HOPKINS APL/STEVE GRIBBEN (ASTEROID); GETTY IMAGES (CASH, BOX, DOG, TIKTOK RETAIL, NEGRONI, CES, FLU); COINTELEGRAPH/WIKIMEDIA (BANKMAN-FRIED); JULIEN'S AUCTIONS (BIRKENSTOCKS); META (AVATAR). ILLUSTRATIONS BY SHAWN HAZEN. PATENT: INVENTED BY HELEN ELIZABETH KOUROUS-HARRIGAN.

Chasing bugs on the blockchain

In the crypto ecosystem, programming errors can mean $100 million lost in the blink of an eye. Ronghui Gu is trying to help.

By Clive Thompson
Portrait by Matchull Summers

In the spring of 2022, before some of the most volatile events to hit the crypto world last year, an NFT artist named Micah Johnson set out to hold a new auction of his drawings. Johnson is well known in crypto circles for images featuring his character Aku, a young Black boy who dreams of being an astronaut. Collectors lined up for the new release. On the day of the auction, they spent $34 million on the NFTs.

Then tragedy (or, depending on your point of view, comedy) struck. The "smart contract" code that Johnson's software team wrote to run the crypto auction contained a critical bug. All $34 million worth of Johnson's sales was locked on the Ethereum blockchain. Johnson couldn't withdraw the funds; nor could he refund money to people who'd bid on an NFT but lost their auction. The virtual money was frozen, untouchable—"locked on chain," as they say.

Johnson might wish he'd hired Ronghui Gu.

Gu is the cofounder of CertiK, the largest smart-contract auditor in the fizzy and unpredictable world of cryptocurrencies and Web3. An affable and talkative computer science professor at Columbia University, Gu leads a team of more than 250 that pores over crypto code to try to make sure it isn't filled with bugs.

CertiK's work won't prevent you from losing your money when a cryptocurrency collapses. Nor will it stop a crypto exchange from using your funds inappropriately. But it could help prevent an overlooked software issue from doing irreparable damage. The company's clients include some of crypto's biggest players, like the Bored Ape Yacht Club and the Ronin Network, which runs a blockchain used in games. Clients sometimes come to Gu after they've lost hundreds of millions—hoping he can make sure it doesn't happen again.

"This is a real wild world," Gu says with a laugh.

Crypto code is much more unforgiving than traditional software. Silicon Valley engineers generally try to make their programs as bug-free as possible before they ship, but if a problem or bug is later found, the code can be updated.

That's not possible with many crypto projects. They run using smart contracts—computer code that governs the transactions. (Say you want to pay an artist 1 ETH for an NFT; a smart contract can be coded to automatically send you the NFT token once the money arrives in the artist's wallet.) The thing is, once smart-contract code is live on a blockchain, you can't update it. If you discover a bug, it's too late: the whole point of blockchains is that you can't alter stuff that's been written to them. Worse, code that's hosted on a blockchain is publicly visible—so black-hat hackers can study it at their leisure and look for mistakes to exploit.

The sheer number of hacks is dizzying, and they are wildly lucrative. Early last year, the Wormhole network had more than $320 million worth of crypto stolen. Then the Ronin Network lost upwards of $600 million in crypto.

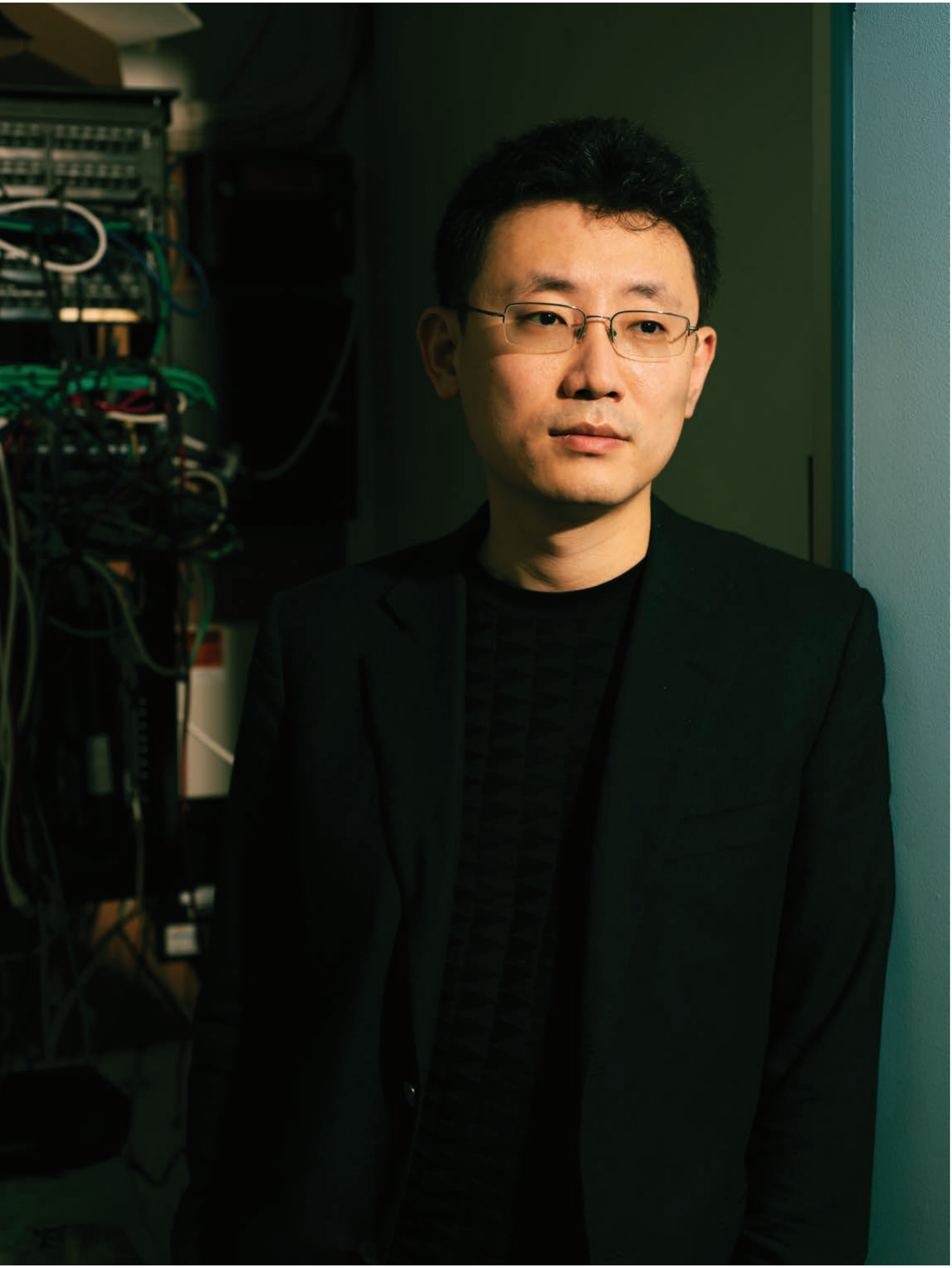
"The most expensive hack in history," Gu says, shaking his head in near disbelief. "They say Web3 is eating the world—but hackers are eating Web3."

A bustling field of auditors has emerged in recent years, and Gu's CertiK is the biggest: the company, which has been valued at $2 billion, figures it has done an estimated 70% of all smart-contract audits. It also runs a system that monitors smart contracts to detect in real time if any are being hacked.

Not bad for someone who stumbled into the field sideways. Gu didn't start off in crypto; he did his PhD in provable and verifiable software, exploring ways to write code that behaves in a mathematically predictable fashion. But this subject turned out to be highly applicable to the unforgiving world of smart contracts; he cofounded CertiK with his PhD supervisor in 2018. Gu now straddles the worlds of academia and crypto. He still teaches Columbia courses on compilers and the formal verification of system software, and manages several grad students (one of whom is researching compilers for quantum computing)—while also jetting around to Davos and Morgan Stanley events, clad in his habitual black shirt and black jacket as he attempts to convince crypto and financial bigwigs to take blockchain hacks seriously.

Crypto famously runs in boom-bust cycles; the collapse of the FTX exchange in November was just a recent blow. Gu, however, believes he'll have work to do for years to come. Mainstream firms like banks and, he says, "a major search engine" are beginning to launch their own blockchain products and hiring CertiK to help keep their ships tight. If established businesses start pushing more code onto blockchains, it'll attract ever more hackers, including nation-state actors. "The threats we have been facing," he says, "are more and more tough." ■

Clive Thompson is a science and technology journalist based in New York City.



Hot spots of scarcity

Extreme heat will kill more people as the world warms. Poorer countries will bear the brunt of that burden.

By Hana Kiros / Map by Arthur Mount

Extreme heat kills. Your body works nonstop to keep its core temperature around 98 °F, but searing heat can push it beyond its ability to self-regulate. Your cardiovascular system works furiously to cool your body by redirecting blood flow, making heart attacks and strokes much more likely. And intense sweating can dehydrate organs so much they begin to fail.

Deaths from heatstroke will only grow as temperatures climb because of climate change. But the danger is not the same for everyone: poorer countries will suffer a far greater share of temperature-related deaths, even though richer countries are responsible for 90% of carbon emissions.

Late last year, leaders at COP27 agreed to establish a fund, which richer countries will bankroll, to compensate poorer countries for damages caused by climate change.

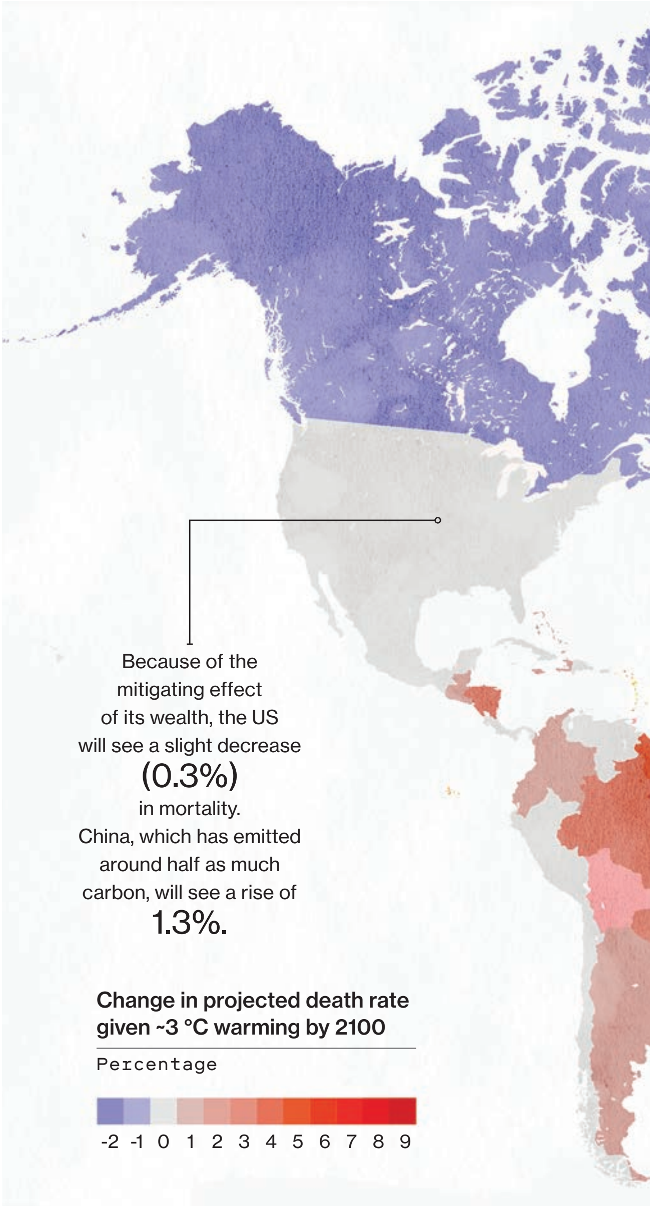
This map shows one aspect of that burden—how many more people heat will kill. The data here builds on work done in 2021 by R. Daniel Bressler, a sustainable-development researcher at Columbia University, and his colleagues. The researchers started with data from the United Nations that projects countries' crude death rates—the total number of deaths divided by the population—for the next 80 years. Those estimates don't consider how mortality could be affected by climate change. Bressler and his colleagues updated the figures, taking increased temperatures into account.

The team considered deaths caused directly by heat exposure—not by droughts, hurricanes, and disease, which are all fueled by rising temperatures. This map shows the group's projections for a "realistically bad" scenario, as Bressler puts it, where there's been some progress to curb greenhouse-gas emissions but global temperatures still rise around 3 °C by 2100.

Crucially, they found that the death rate depends not only on where a country is with respect to the equator but also on its wealth. When it feels as hot as 125 °F, turning on the AC or avoiding strenuous activity can be lifesaving. "If you're in a richer place, perhaps you could take a day off if it's a really deadly hot day," Bressler says. "If you're in a poor place, you might not have that ability."

Take Greece and Jamaica. The World Bank projects that the two countries will face similar hot weather in 2100. Without taking income into account, both are predicted to have the same increase in mortality—1.6%. But factoring in income cuts Greece's increase in death rate to just 0.09%, while Jamaica's will be 0.9%.

As the century marches on, heat-related deaths will only exacerbate poverty's already profound impact on mortality. A 30-year gulf already exists between the highest national life expectancy (about 85 in Japan) and the lowest (54 in the Central African Republic, where over 70% of the population lives below the international poverty line). ■

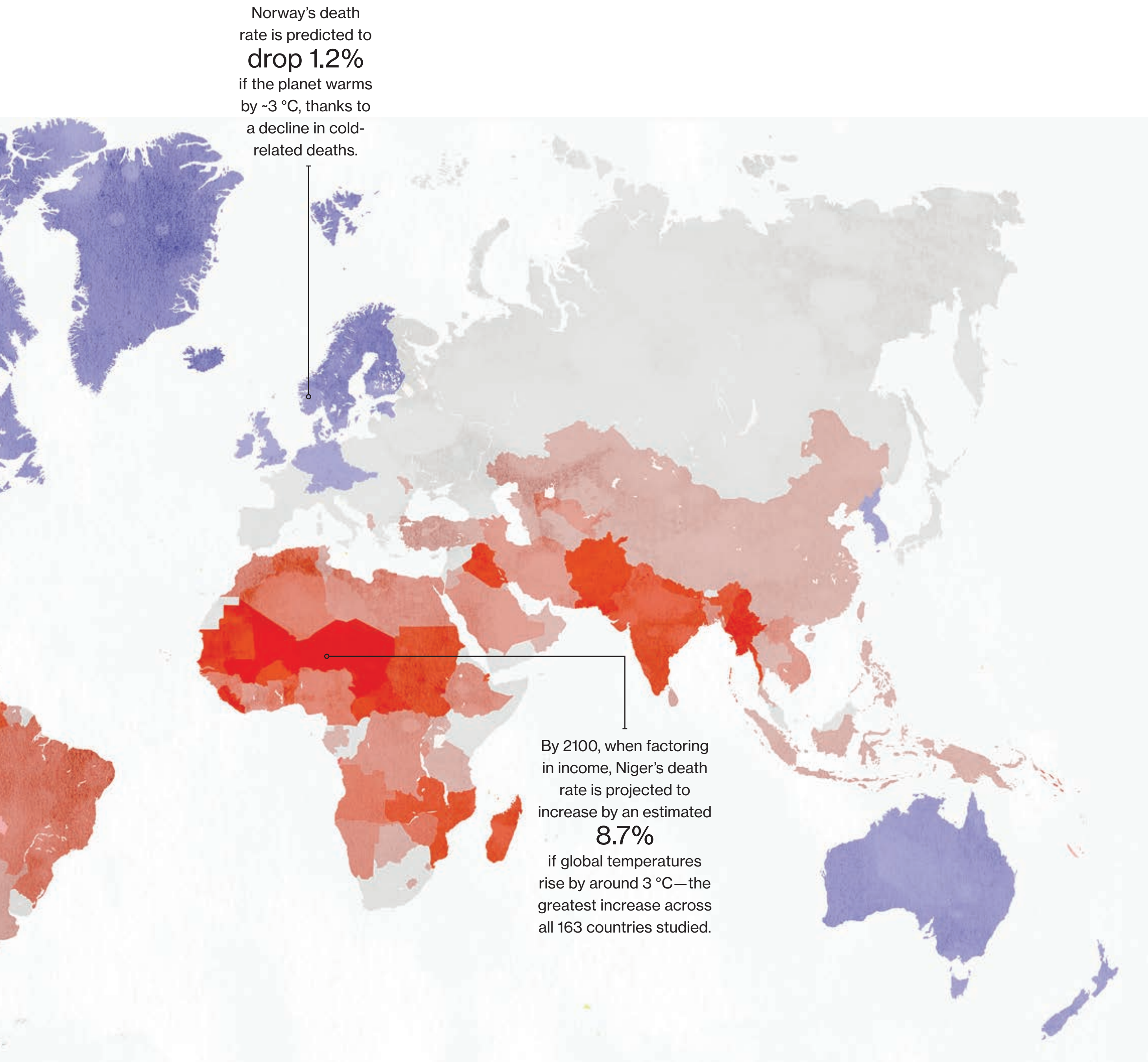


A world of difference

The 10 countries that will see the greatest death rate increase are all lower-income countries in Africa, Asia, or the Middle East.

Each of the hardest-hit countries produces less than 1% of the world's carbon emissions.

Colder, wealthier countries will fare better. Some will see a decrease in mortality, in part because there will be fewer cold-weather-related deaths.



Countries with greatest INCREASE in projected deaths by 2100

Rank	Country	Change (%)	Deaths per year by 2100
1	Niger	8.7	92,710
2	Mali	6.6	54,820
3	Chad	6.0	45,130
4	Pakistan	5.4	280,870
5	Iraq	5.3	53,010

Countries with greatest DECREASE in projected deaths by 2100

Rank	Country	Change (%)	Deaths per year by 2100
1	Norway	-1.2	-970
2	Finland	-1.2	-750
3	Iceland	-1.2	-50
4	Sweden	-1.0	-1,390
5	Canada	-1.0	-5,670

SOURCE: BRESSLER, R. DANIEL, ET AL. "ESTIMATES OF COUNTRY LEVEL TEMPERATURE-RELATED MORTALITY DAMAGE FUNCTIONS." SCIENTIFIC REPORTS; UNITED NATIONS WORLD POPULATION PROSPECTS 2022

10 Breakthrough Technologies 23

James Webb Space Telescope

CRISPR for high cholesterol

AI that makes images

Organs on demand

Abortion pills via telemedicine

A chip design that changes everything

Ancient DNA analysis

Battery recycling

The inevitable EV

Mass-market military drones

A marvel of precision engineering, JWST could revolutionize our view of the early universe.

James Webb Space Telescope

Launched in December 2021 after decades of work, NASA's $10 billion James Webb Space Telescope—a collaboration between the US, Europe, and Canada—is the largest telescope ever sent to space and some 100 times more powerful than its predecessor, the Hubble Space Telescope. It is also specifically designed to detect infrared radiation, allowing it to cut through dust and look far back in time to a period when the universe's first stars and galaxies formed.

WHO
NASA, European Space Agency, Canadian Space Agency, Space Telescope Science Institute

WHEN
Now

JWST is tailor-made for this kind of astronomical time travel. Its main mirror is 21 feet across, three times the diameter of Hubble's, giving it far greater resolving power. It carries a sunshield as big as a tennis court to protect its mirror and instruments from the heat and light of the sun. To help it get to space, engineers designed JWST's mirror and sunshield to fold up so they would fit inside a rocket fairing, unfolding after launch as the telescope made its journey to its final orbit 1.5 million kilometers from Earth.

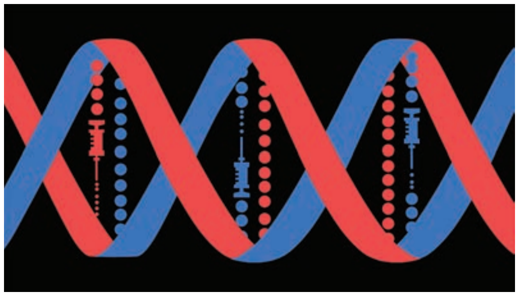
Astronomers hope that with JWST, they will be able to piece together how the universe's first galaxies came to be following the Big Bang. But that is not JWST's only goal. The telescope is being used across the breadth of astronomy. It could provide unprecedented insight into planets in other solar systems, allowing us to work out what their atmospheres are made of. It will witness the birth of new worlds, take magnificent images of nebulae, probe the structure of galaxies, and much, much more.

New discoveries rain down almost every day and will do so for the lifetime of the telescope, estimated at more than 20 years. —JONATHAN O'CALLAGHAN

SPACE TELESCOPE SCIENCE INSTITUTE OFFICE OF PUBLIC OUTREACH

CRISPR for high cholesterol

New forms of the gene-editing tool could enable treatments for common conditions.



WHO
Verve Therapeutics, Beam Therapeutics, Prime Medicine, Broad Institute

WHEN
10 to 15 years

Last year, a New Zealand woman became the first to receive a gene-editing treatment to permanently lower her cholesterol. The woman had heart disease, along with an inherited risk for high cholesterol. But scientists behind the experimental treatment think it could help pretty much anyone.

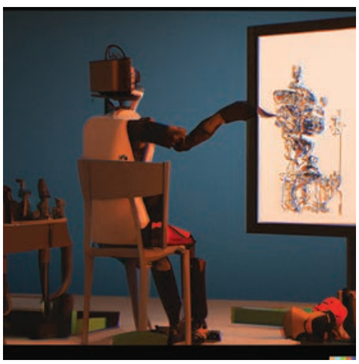
The trial is a potential turning point for CRISPR, the editing tool they used. Since the technology was first programmed to edit genomes about a decade ago, we've seen CRISPR move from scientific labs to clinics. But the first experimental treatments have focused on rare genetic disorders. A high-cholesterol treatment has wider potential.

The cholesterol-lowering treatment, developed by Verve Therapeutics, relies on a form of gene editing called base editing, or "CRISPR 2.0." It's a more targeted approach—instead of simply making cuts to shut off specific genes, scientists can now swap a single DNA base for another. In theory, this should be safer because you're less likely to cut an important gene by mistake, and you can avoid potential errors that may occur when DNA repairs itself after being cut.

An even newer form of CRISPR could take things further still. Prime editing—or "CRISPR 3.0"—allows scientists to insert chunks of DNA into a genome. If it works in people, it could let scientists replace disease-causing genes.

Together, these newer forms of CRISPR could broaden the scope of gene editing to take on many conditions—not all of them genetic. Someday, people may have the option to add genes thought to protect against high blood pressure, or certain diseases, to their genetic code.

All CRISPR treatments are experimental at this point, and we don't know if they're safe. Some argue we should focus on treating those with severe diseases in the meantime. But if these new forms of CRISPR do work, they could help many others. —JESSICA HAMZELOU



AI that makes images

AI models that generate stunning imagery from simple phrases are evolving into powerful creative and commercial tools.

WHO
OpenAI, Stability AI, Midjourney, Google

WHEN
Now

OpenAI introduced a world of weird and wonderful mash-ups when its text-to-image model DALL-E was released in 2021. Type in a short description of pretty much anything, and the program spat out a picture of what you asked for in seconds. DALL-E 2, unveiled in April 2022, was a massive leap forward. Google also launched its own image-making AI, called Imagen.

Yet the biggest game-changer was Stable Diffusion, an open-source text-to-image model released for free by UK-based startup Stability AI in August. Not only could Stable Diffusion produce some of the most stunning images yet, but it was designed to run on a (good) home computer.

By making text-to-image models accessible to all, Stability AI poured fuel on what was already an inferno of creativity and innovation. Millions of people have created tens of millions of images in just a few months. But there are problems, too. Artists are caught in the middle of one of the biggest upheavals in a decade. And, just like language models, text-to-image generators can amplify the biased and toxic associations buried in training data scraped from the internet.

The tech is now being built into commercial software, such as Photoshop. Visual-effects artists and video-game studios are exploring how it can fast-track development pipelines. And text-to-image technology has already advanced to text-to-video. The AI-generated video clips demoed by Google, Meta, and others in the last few months are only seconds long, but that will change. One day movies could be made just by feeding a script into a computer.

Nothing else in AI grabbed people's attention more last year—for the best and worst reasons. Now we wait to see what lasting impact these tools will have on creative industries—and the entire field of AI.

—WILL DOUGLAS HEAVEN

AMRITA MARINO; ERIK CARTER (AI)

Organs on demand

Engineered organs could put an end to transplant waiting lists.

For two months last year, a 57-year-old man named David Bennett lived with a pig heart beating inside his chest. Surgeons at the University of Maryland had put it there to see: Could a gene-edited pig's heart keep a person alive?

Far more people need an organ transplant to live than can get one. There are around 130,000 organ transplants each year around the world, but many more people die waiting for an organ or because they never even made it onto a transplant waiting list.

WHO
eGenesis, Makana Therapeutics, United Therapeutics

WHEN
10 to 15 years

Animal organs are one potential solution. But it's not easy to overcome the human body's natural revolt against them. For example, sugars on the surface of pig tissue can send our immune system into attack mode. Drugs can help mute the response, but it's not enough. So biotech companies have used gene editing to modify pigs, removing those sugar molecules and adding other genes to make the pigs seem more human-like.

By editing the DNA of pigs in this way, several biotech companies have now created animals whose organs are more compatible with human bodies. Though Bennett died, and a virus was found in the transplanted organ, his doctors claim the pig heart he received never developed classic signs of organ rejection. Now they're planning studies with more patients.

In the future, organ engineering might not involve animals at all. Researchers are in the early stages of exploring how to engineer complex tissue from the ground up. Some are 3D-printing scaffolds in the shape of lungs. Others are cultivating blob-like "organoids" from stem cells to imitate specific organs. In the long term, researchers hope to grow custom organs in factories.

Whether they're grown in animals or built inside manufacturing plants, an unlimited supply of organs could make transplantation more common, and give far more people access to replacement parts. —ANTONIO REGALADO

Abortion pills via telemedicine

Medication abortion has become increasingly common, but the US Supreme Court's decision to overturn *Roe v. Wade* brought a new sense of urgency.

WHO
Choix, Hey Jane, Aid Access, Just the Pill, Abortion on Demand, Planned Parenthood, Plan C

WHEN
Now

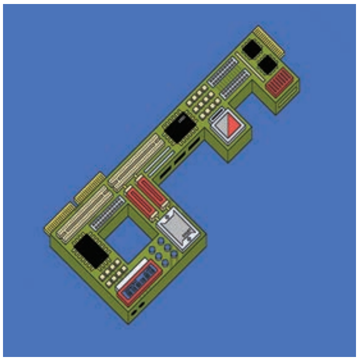
Access to abortion care has narrowed dramatically in the US. But there's been one big shift in the other direction: the ability to access care without leaving home. In 2021, during the pandemic, the US Food and Drug Administration temporarily allowed health-care providers to mail patients two pills—mifepristone and misoprostol—that, when taken together, can induce an abortion. Years before, the FDA had found the pills to be safe and effective at ending a pregnancy in the first trimester, and by 2020 they accounted for more than half of all abortions in the US. Then, at the end of 2021, the FDA made its decision permanent.

Six months later, the US Supreme Court ruled that abortion is not a constitutional right. As state "trigger laws" prohibiting abortion took effect, interest in and demand for abortion pills surged. Nonprofits like Aid Access and startups like Choix, Just the Pill, and Hey Jane were ready to help. Though the process varies by service, eligible patients generally sign up with a photo ID and then consult with a medical provider via video call, text, or app. The provider prescribes the pills, which the service ships to the patient.

Access to medication abortion is not a solved problem. Aid Access, with headquarters in Europe, is unique in that it will ship pills to any US state. But most startups offering abortion pills by mail follow state laws, which means people living in the 13 states that ban abortion, or in the additional seven states that require a doctor to prescribe the medications in person, must travel across state lines or set up an alternative mailing address to use these services.

Still, the organizations helping people obtain abortion pills remotely have brought care to many at a critical time. Their foresight and tireless efforts meant these solutions were ready when people needed them. —REBECCA ACKERMANN

JOE CARROTTA FOR NYU LANGONE HEALTH; AMRITA MARINO (PILLS)



A chip design that changes everything

Computer chip designs are expensive and hard to license. That's all about to change thanks to the popular open standard known as RISC-V.

WHO
RISC-V International, Intel, SiFive, SemiFive, China RISC-V Industry Alliance

WHEN
Now

Ever wonder how your smartphone connects to your Bluetooth speaker, given they were made by different companies? Well, Bluetooth is an open standard, meaning its design specifications, such as the required frequency and its data encoding protocols, are publicly available. Software and hardware based on open standards—Ethernet, Wi-Fi, PDF—have become household names.

Now an open standard known as RISC-V (pronounced "risk five") could change how companies create computer chips.

Chip companies such as Intel and Arm have long kept their blueprints proprietary. Customers would buy off-the-shelf chips, which may have had capabilities irrelevant to their product, or pay more for a custom design. Since RISC-V is an open standard, anyone can use it to design a chip, free of charge.

RISC-V specifies design norms for a computer chip's instruction set. The instruction set describes the basic operations that a chip can do to change the values its transistors represent—for example, how to add two numbers. RISC-V's simplest design has just 47 instructions. But RISC-V also offers other design norms for companies seeking chips with more complex capabilities.

About 3,100 members worldwide, including companies and academic institutions, are now collaborating via the nonprofit RISC-V International to establish and develop these norms. In February 2022, Intel announced a $1 billion fund that will, in part, support companies building RISC-V chips.

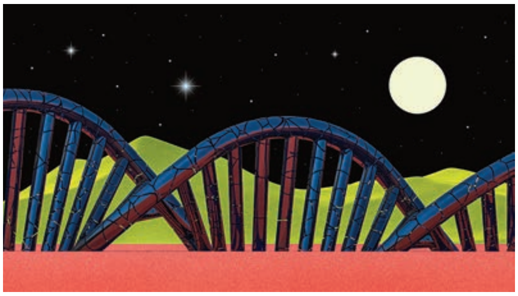
RISC-V chips have already begun to pop up in earbuds, hard drives, and AI processors, with 10 billion cores already shipped. Companies are also working on RISC-V designs for data centers and spacecraft. In a few years, RISC-V proponents predict, the chips will be everywhere. — SOPHIA CHEN

Ancient DNA analysis

New methods that make damaged DNA legible to commercial sequencers have produced stunning revelations about the deep past.

WHO
Max Planck Institute for Evolutionary Anthropology, David Reich Lab at Harvard

WHEN
Now



Scientists have long sought better tools to study teeth and bones from ancient humans. In the past, they've had to scour many ancient remains to find a sample preserved well enough to analyze.

Now cheaper techniques and new methods that make damaged DNA legible to commercial sequencers are powering a boom in ancient DNA analysis.

Today, scientists can even analyze microscopic traces of DNA found in dirt Neanderthals urinated in—no teeth or bones required. In November, the field now known as paleogenetics took center stage when Svante Pääbo, a geneticist at the Max Planck Institute for Evolutionary Anthropology, won a Nobel Prize for his foundational work.

Ancient DNA analysis has led to the discovery of two extinct species of human—*Homo luzonensis* and Denisovans—and taught us that modern humans carry a substantial amount of Denisovan and Neanderthal DNA. And the number of ancient human individuals for whom we now have whole-genome data has jumped drastically, from just five in 2010 to 5,550 in 2020.

By indicating that India's population came from a mix of ancestors, these techniques have undermined the caste system. DNA from a 2,500-year-old battlefield in Sicily has revealed that ancient Greek armies were more diverse than historians depicted.

Old samples can unravel modern health mysteries, too. Last year scientists identified a single mutation that made people 40% likelier to survive the Black Death—and it's also a risk factor for autoimmune issues like Crohn's disease.

Differences in how cultures believe human remains should be treated will keep creating ethical and logistical questions for scholars seeking to work with ancient DNA. But its revelations are already rewriting history. —HANA KIROS

NICK LITTLE; DAVID ALABO (DNA)

REDWOOD MATERIALS

New ways to recover the crucial metals in batteries could make electric vehicles more affordable.

Battery recycling

High-value metals recovered from old laptops, corroded power drills, and electric vehicles could power tomorrow's cars, thanks to recycling advances that make it possible to turn old batteries into new ones.

Demand for lithium-ion batteries is skyrocketing as electric vehicles become more common. Greater use of electric vehicles is good news for the climate. But supplies of the metals needed to build battery cells are already stretched thin, and demand for lithium could increase 20 times by 2050.

WHO
CATL, Umicore, Redwood Materials, Li-Cycle, Cirba

WHEN
Now

Recycling may help. Older methods of processing spent batteries struggled to reliably recover enough of these individual metals to make recycling economical. But new approaches have swiftly changed that, enabling recyclers to more effectively dissolve the metals and separate them from battery waste.

Recycling facilities can now recover nearly all of the cobalt and nickel and over 80% of the lithium from used batteries and manufacturing scrap left over from battery production—and recyclers plan to resell those metals for a price nearly competitive with that of mined materials. Aluminum, copper, and graphite are often recovered as well.

China leads the world in battery recycling today, dominated by subsidiaries of major battery companies like CATL. The EU recently proposed extensive recycling regulations with mandates for battery manufacturers. And companies in North America, like Redwood Materials and Li-Cycle, are quickly scaling operations, funded by billions of dollars in public and private investment.

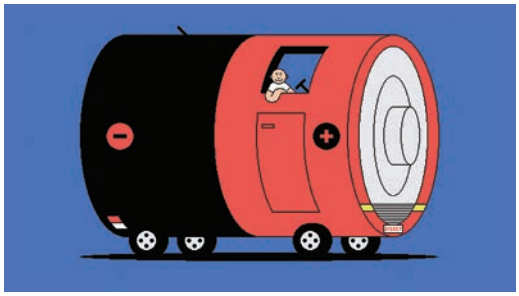
Battery demand is expected to grow exponentially for decades. Recycling alone won't be enough to satisfy it. And these new recycling processes aren't perfect. But battery recycling factories will create a supply of materials the world needs to meet its climate goals. —CASEY CROWNHART

The inevitable EV

Electric vehicles have been available for decades. Now they've finally become mainstream.

WHO
BYD, Hyundai, Tesla, Volkswagen

WHEN
Now



Electric vehicles are transforming the auto industry.

While sales have slowly ticked up for years, they're now soaring. The emissions-free cars and trucks will likely account for 13% of all new auto sales globally in 2022, up from 4% just two years earlier, according to the International Energy Agency. They're on track to make up about 30% of those sales by the end of this decade.

A mix of forces has propelled the vehicles from a niche choice to a mainstream option.

Governments have enacted policies compelling automakers to retool and incentivizing consumers to make the switch. Notably, California and New York will require all new cars, trucks, and SUVs to be zero-emissions by 2035, and the EU had nearly finalized a similar rule at press time.

Auto companies, in turn, are setting up supply chains, building manufacturing capacity, and releasing more models with better performance, across price points and product types.

The Hongguang Mini, a tiny car that starts a little below $5,000, has become the best-selling electric vehicle in the world, reinforcing China's dominance as the largest manufacturer of EVs.

A growing line-up of two- and three-wheelers from Hero Electric, Ather, and other companies helped EV sales triple in India over the last year (though the total number is still only around 430,000). And models ranging in size and price from the Chevy Bolt to the Ford F-150 Lightning are bringing more Americans into the electric fold.

There are still big challenges ahead. Most of the vehicles must become cheaper. Charging options need to be more convenient. Clean electricity generation will have to increase dramatically to accommodate the surge in vehicle charging. And it will be a massive undertaking to make enough batteries. But it's now clear that the heyday of the gas-guzzler is dimming.

—JAMES TEMPLE

Mass-market military drones

Turkish-made aircraft like the TB2 have drastically expanded the role of drones in warfare.

WHO
Baykar Technologies, Shahed Aviation Industries

WHEN
Now

For decades, high-end precision-strike American aircraft, such as the Predator and Reaper, dominated drone warfare. The war in Ukraine, however, has been defined by low-budget models made in China, Iran, or Turkey. Their widespread use has changed how drone combat is waged and who can wage it.

Some of these new drones are off-the-shelf quadcopters, like those from DJI, used for both reconnaissance and close-range attacks. Others, such as the $30,000 Iranian-made exploding Shahed drones, which Russia has used to attack civilians in Kiev, are capable of longer-range missions. But the most notable is the $5 million Bayraktar TB2, made by Turkey's Baykar corporation.

The TB2 is a collection of good-enough parts put together in a slow-flying body. It travels at speeds up to 138 miles per hour and has a communication range of around 186 miles. Baykar says it can stay aloft for 27 hours. But when combined with cameras that can share video with ground stations, the TB2 becomes a powerful tool for both targeting the laser-guided bombs carried on its wings and helping direct artillery barrages from the ground.

Most important is simply its availability. US-made drones like the Reaper are more capable but costlier and subject to stiff export controls. The TB2 is there for any country that wants it.

Turkey's military used the drones against Kurds in 2016. Since then, they've been used in Libya, Syria, and Ethiopia, and by Azerbaijan during its war against Armenia. Ukraine bought six in 2019 for military operations in the Donbas, but the drones caught the world's attention in early 2022, when they helped thwart Russian invaders.

The tactical advantages are clear. What's also sadly clear is that these weapons will take an increasingly horrible toll on civilian populations around the world.

—KELSEY D. ATHERTON

NICK LITTLE; DAVID ALABO (DRONES)

By:
Antonio Regalado

Illustrations:
Michael Byers

A factory of unlimited organs

MARTINE ROTHBLATT SEES A DAY WHEN TRANSPLANTABLE ORGANS AND 3D-PRINTED ONES WILL BE READILY AVAILABLE, SAVING COUNTLESS LIVES—INCLUDING HER DAUGHTER'S.

I met the entrepreneur Martine Rothblatt for the first time at a meeting at West Point in 2015 that was dedicated to exploring how technology might expand the supply of organs for transplant. At any given time, the US transplant waiting list is about 100,000 people long. Even with a record 41,356 transplants last year in the US, 6,897 people died while waiting. Many thousands more never made the list at all.

Rothblatt arrived at West Point by helicopter, powering down over the Hudson River. It was an arrival suitable for a president, but it also brought to mind the delivery of an organ packed in dry ice, arriving somewhere just in time to save a person's life. I later learned that Rothblatt, an avid pilot with a flying exploit registered by Guinness World Records, had been at the controls herself.

Rothblatt's dramatic personal story was already well known. She had been a successful satellite entrepreneur, but after her daughter Jenesis was diagnosed with a fatal lung disease, she had started a biotechnology company, United Therapeutics. Drugs like the one that United developed are now keeping many patients like Jenesis alive. But she might eventually need a lung transplant. Rothblatt therefore had set out to solve that problem too, using technology to create what she calls an "unlimited supply of transplantable organs."

The entrepreneur explained her plans with the help of an architect's rendering of an organ farm set on a lush green lawn, its tube-like sections connected whimsically in a snowflake pattern. Solar panels dotted the roofs, and there were landing pads for electric drones. The structure would house a herd of a thousand genetically modified pigs, living in strict germ-free conditions. There would be a surgical theater and veterinarians to put the pigs to sleep before cutting out their hearts, kidneys, and lungs. These lifesaving organs—designed to be compatible with human bodies—would be

loaded into electric copters and whisked to transplant centers.

Back then, Rothblatt's vision seemed not only impossible but "phantasmagoric," as she has called it. But in the last year it has come several steps closer to reality. In September 2021, a surgeon in New York connected a kidney from a genetically engineered pig developed by Rothblatt's company to a brain-dead person—an experiment to see whether the kidney survived. It did. Since then, US doctors have attempted another six pig-to-human transplants.

The most dramatic of these, and the only one in a living person, was a 2022 case in Maryland, where a 57-year-old man with heart failure lived two months with a pig heart supplied by Rothblatt's company. The surgeon, Bartley Griffith, said it was "quite amazing" to be able to converse with a man with a pig's heart beating in his chest. The patient eventually died, but the experiment nonetheless demonstrated the first life-sustaining pig-to-human organ transplant. According to United, formal trials of pig organs could get underway in 2024.

At the center of all this is Rothblatt, a lawyer with a PhD in medical ethics whom New York magazine dubbed the "Trans-Everything CEO." That isn't only because she changed her gender from male to female in midlife, as she writes in her book *From Transgender to Transhuman*. She's also a prolific philosopher on the ethics of the future who has advocated civil rights for computer programs, compared the traditional division of the sexes to racial apartheid, and founded a transhumanist religion, Terasem, which holds that "death is optional and God is technological." She is a frank proponent of human immortality, whether it's achieved by creating software versions of living people or, perhaps, by replacing their organs as they age.

Since the pig organ transplants garnered front-page headlines, Rothblatt has been on a tour of medical meetings, taking the podium to describe the work. But she has rebuffed calls from journalists, including me. The reason: "I promised myself no more interviews until I accomplished something I felt worthy of one," she wrote in an email. She included a list of the further successes she is aiming for. These include keeping a pig heart beating for three months in a patient, saving a person's life with a pig kidney, or keeping any animal alive with a 3D-printed lung, another technology United is developing.

The next big step for pig organs will be an organized clinical trial to prove they save lives consistently. United and two competitors, eGenesis and Makana Therapeutics, which have their own pigs, are all in consultation with the US Food and Drug Administration about how to conduct such a trial. Kidney transplants are likely to be first.

Before the larger human trials can begin, companies and doctors say, the FDA is asking them to perform one more series of experiments on monkeys. The agency is looking for "consistent" survival of animals for six months or more, and it is requiring that the pigs be raised in special germ-free facilities. "If you don't have those two things, it's going to be a hard stop," says Joseph Tector, a surgeon at the University of Miami and the founder of Makana.

Which company or hospital will start a trial first isn't clear. Tector says the atmosphere of competition is kept in check by the risk of missteps. Just two or three failed transplants could doom a program. "Do we want to do the first trial? Sure we do. But it's really, really, important that we don't treat this like a race," he says. "It's not the America's Cup."

Maybe not, but leading transplant centers are jockeying to be part of the trials and help make history. "It's 'Who will be the astronauts?'" says Robert Montgomery, the New York University surgeon who carried out the first transplant of a pig kidney. "We believe it's going to work and that it's going to change everything."

And that's not because pig organs will replace human-to-human transplants. Those work so well—kidney transplants succeed 98% of the time and often last 10 or 20 years—that pig organs almost certainly won't be as good. The difference is that if "unlimited organs" really become available,

PETER HAPAK/TRUNK ARCHIVE; BELOW: JACQUELYN MARTIN/AP

ABOVE

Lawyer and entrepreneur Martine Rothblatt in a 2014 photo.

OPPOSITE

Rothblatt started a biotechnology company, United Therapeutics, after learning that her daughter Jenesis (pictured in background) suffered from a deadly lung disease.

> “Many people are not on the list because of the scarcity of organs. Only the most ideal patients get listed.”

it’s going to vastly increase the number of people who might be eligible, uncorking needs currently masked by strict transplant rules and procedures.

“Many people are not on the list because of the scarcity of organs. Only the most ideal patients get listed—the ones who have the highest likelihood of doing well,” says Montgomery. “There is a selection procedure that goes on. We don’t really talk about it, but if there were unlimited organs, you could replace dialysis, replace heart assist devices, even replace medicines that don’t work that well. I think there are a million people with heart failure, and how many get a transplant? Only 3,500.”

A sick child

Before becoming a biotech entrepreneur, Rothblatt had started a satellite company; she’d been early to see that with a powerful enough satellite in stationary orbit over the Earth, receivers could shrink to the size of a playing card, an idea that became SiriusXM Radio. But her plans took a turn in the early 1990s, when her young daughter was diagnosed with pulmonary arterial hypertension. That’s a rare disease in which the pressure in the artery between the lungs and the heart is too high. It is fatal within a few years.

“We had a problem: I was going to die,” Jenesis—who now works for United in a project leader role—recalled during a 2017 speech.

Rothblatt and her wife were shocked when doctors said there wasn’t a cure. Rothblatt has compared her feelings then to seeing black or rolling on the floor in helpless pain. But instead of giving up, she began attacking the problem. She would duck out of the ICU where her daughter was and visit the hospital library, reading everything she could about the disease, she has recalled.

Eventually she read about a drug that could lower arterial pressure but had been mothballed by the drug giant Glaxo. She badgered the company until they sold it to her for $25,000 and a promise of a 10% royalty, she recalls. According to Rothblatt, she received in return one bag


HUMAN ORGAN FOR TRANSPORT
KIDNEY
LUNGS
HUMAN ORGAN FOR TRANSPORT
- HEART -
HUMAN ORGAN FOR TRANSPORT
- HEART -

of the chemical, a patent, and declarations that the drug would never work.

The drug, treprostinil sodium, did work; it was approved in 2002. You might expect that with just a few thousand patients affected by the disease, it would never make money. Once the drug was available, though, patients started to live, not die, and they needed to keep taking it. A family of related drugs now generates $1.5 billion in sales each year for United.

Rothblatt understood early on that the drugs were only a life-extending bridge to a lung transplant.

Though these drugs work well to ease symptoms, patients may eventually need new lungs. Rothblatt understood early on that the drugs were only a life-extending bridge to a lung transplant. Yet there aren't nearly enough human lungs to help everyone. And that was the real problem.

The most obvious place to get a lot of organs was from animals, but at the time "xenotransplantation"—moving organs between species—didn't seem to have good prospects. Tests showed that organs from pigs would be viciously destroyed by the human immune system; this "hyper-acute" rejection takes just minutes or hours. In the US, some scientists called for a moratorium in the face of public panic over whether a pig virus could jump to humans and cause a pandemic.

In 2011 United Therapeutics paid $7.6 million to purchase Revivicor, a struggling biotech company that, under its earlier name PPL Therapeutics, had funded the Scottish scientist Ian Wilmut's cloning of Dolly the sheep in 1996. Using cloning techniques, Revivicor had already produced pigs lacking one sugar molecule, alpha-gal, whose presence everywhere on pig organs was known to cause organ rejection within minutes. Now Rothblatt convened experts to prioritize a further eight to 12 genes for modification and undertake "a moonshot to edit additional genes until we have an animal that could provide us with tolerable organs." She gave herself 10 years to do it, keeping in mind that time was running out for patients like Jenesis.

Getting into humans

By last year, United had settled on a list of 10 gene modifications. Three of these were "knockouts," pig genes removed from the genome to eliminate molecules that alarm the human immune system. Another six were added human genes, which would give the organ a kind of stealth coating—helping to cover over differences between the pig and human immune systems that had developed since apes like us and pigs diverged from a common ancestor, 80 to 100 million years ago. A final touch: disabling a receptor that senses growth hormone. Pigs are bigger than we are; this change would keep the organ from growing too large.

Organs with these modifications, especially when combined with new types of immune suppression drugs, have been proving successful in monkeys. "I think the genetic modifications they have made to these organs have been incredible. I will tell you that we have primates going for a year with a [pig] kidney with good function," says Leonardo Riella, director of kidney transplantation at Massachusetts General Hospital, in Boston.

By 2021, some transplant surgeons were ready to try the organs in humans—and so was Rothblatt. The obstacle was that before green-lighting a formal trial in humans, the FDA, in a meeting that fall, had asked for one further set of monkey experiments that would have all the planned procedures, drugs, and tests locked in and standardized. The FDA also wanted to see consistent evidence that the organs survive for a long time in monkeys—half a year or more, people briefed by the agency say.

Each experiment cost $750,000, according to Griffith, a transplant surgeon at the University of Maryland, and some doctors felt the monkeys could no longer tell them much more. "We left that meeting [thinking], 'Does that mean we are sentenced for the next two years to keep doing what we were doing?'" Griffith remembers. What they really needed to see was how the organs fared in a human being—a question more monkeys wouldn't answer. "We knew we hadn't learned enough," he says.

Montgomery, the NYU surgeon, recalls an hours-long conversation with Rothblatt after which United agreed he could try a kidney in a brain-dead person being kept alive on a ventilator. Because the individual was dead, no FDA approval would be needed. "The thing about a xenograft is that it's far more complex than a drug. And that has been its Achilles' heel. That is why it has remained in animal models," he says. "So this was an attempt to do an intermediary step to get it into the target species." That surgery occurred in September 2021, and the organ was attached to the subject for only 54 hours.

In Maryland, Griffith, a heart surgeon, conceived a different strategy. He asked the FDA to approve a "compassionate use" study—essentially a Hail Mary attempt to save one life. To his surprise, the agency agreed, and in early 2022 he transplanted a pig heart into the chest of David Bennett Sr., a man with advanced heart failure who wasn't eligible for a human heart transplant. According to Rothblatt, Bennett was interviewed by four psychologists before undergoing surgery.

To observers like Arthur Caplan, a bioethicist at New York University, the use of one-off transplants to gain information raises an ethical question. "So are you thinking, 'This guy is a goner—maybe we can learn something'? But the guy is thinking, 'Maybe I can survive and get a bridge to a human heart,'" says Caplan. "I think there is a little bit of a back-door experiment being carried out."

Bennett survived two months before his new heart gave out, making him the first person in the world to get a lifesaving transplant from a genetically engineered pig. To Rothblatt, it meant success—even on autopsy, there were no evident signs the organ had been rejected, exactly the result she had been working toward. "There is no way to know if we could have made a better heart in the allotted time … [but] this 10-gene heart seemed to work very well," she told an audience of doctors last April. In Griffith's view, the organ performed like a "rock star."

But in the end Bennett died. And in Rothblatt's lectures, she has elided a serious misstep, one that some doctors suspect is what actually killed the patient. When Bennett was still alive in the hospital, researchers monitoring his blood discovered that the transplanted heart was infected with a pig virus. The germ, called cytomegalovirus, is well known to cause transplants to fail. The Maryland team could have further hurt Bennett's chances as they battled the infection, changing his drugs and giving him plasma.

Without the virus, would the heart have gone on beating? The closest Rothblatt has come to acknowledging the problem in public was telling a legal committee of the National Academy of Sciences that she didn't put the blame on the pig heart. "If I were to put it in layman's terms, I would say the heart did not fail the patient," she said.

The bigger problem with the infection, and with Rothblatt's failure to own the error, is that United's pigs were supposed to be tested and free of germs. United's silence is unnerving, because if this virus could slip through, it's possible other, more harmful germs could as well. Rothblatt did not answer our questions about the virus.

Printing lungs

United says that it is now building a new, germ-proof pig facility, which will be ready in 2023 and support a clinical trial starting the following year. It's not the

ABOVE

A genetically modified pig heart is prepared for transplantation at New York University in July 2022.

JOE CARROTTA FOR NYU LANGONE HEALTH

fantastical commercial pig factory shown in Rothblatt's architectural rendering, but it is a stepping-stone toward it. Eventually, Rothblatt believes, a single facility could supply organs for the whole country, delivering them via all-electric air ambulances. Over the summer, she claims, an aeronautics company she invested in, Beta Technologies, flew a vertical-lift electric plane from North Carolina to Arkansas, more than 1,000 nautical miles.

Ironically, pigs may never be a source of the lungs that Rothblatt's daughter may need. That is because lungs are delicate and more susceptible to immune attack. By 2018, the results were becoming clear. Each time the company added a new gene edit to the pigs, hearts and kidneys transplanted into monkeys would last an extra few weeks or months. But the lungs weren't improving. Time and again, after being transplanted into monkeys, the pig lungs would last two weeks and then suddenly fail.

"I actually believe there is no part of the body that cannot be 3D-printed."

To create lungs, Rothblatt is betting on a different approach, establishing an "organ manufacturing" company that is trying to make lungs with 3D printers. That effort is now operating out of a former textile mill in Manchester, New Hampshire, where researchers print detailed models of lungs from biopolymers. The eventual idea is to seed these structures with human cells, including (in one version of the technology) cells grown from the tissue of specific patients. These would be perfect matches, without the risk of immune rejection.

This past spring, Rothblatt unveiled a set of printed "lungs" that she called "the most complex 3D-printed object of any sort, anywhere, ever." According to United, the spongy structure, about the size of a football, includes 4,000 kilometers of capillary channels, detailed spaces mimicking lung sacs, and a total of 44 trillion "voxels," or individual printed locations. The printing was performed with a method called digital light processing, which works by aiming a projector into a vat of polymer that solidifies wherever the light beams touch. It takes a while—three weeks—to print a structure this detailed, but the method permits the creation any shape, some no larger than a single cell. Rothblatt compared the precision of the printing process to driving across the US and never deviating more than the width of a human hair from the center line.

"I actually believe there is no part of the body that cannot be 3D-printed ... including colons and brain tissue," Rothblatt said while presenting the printed lung scaffolds in June at a meeting in California.

Some scientists say bioprinting remains a research project and question whether the lifeless polymers, no matter how detailed, should be compared to a real organ. "It's a long way to go from that to a lung," says Jennifer Lewis, who works with bioprinting at Harvard University. "I don't want to rain on the parade, and there has been significant investment, so some smart minds see something there. But from my perspective, that has been pretty hyped. Again, it's a scaffold. It's a beautiful shape, but it's not a lung." Lewis and other researchers question how feasible it will be to breathe real life into the printed structures. Sticking human cells into a scaffold is no guarantee they will organize into working tissue with the complex functions of a lung.

Rothblatt is aware of the doubters and knows how difficult the technology is. She knows that other people think it won't ever work. That isn't stopping her. Instead, she sees it as her next chance to solve problems other people can't. During an address to surgeons this year, Rothblatt rattled off the list of challenges ahead—including growing the trillions of cells that will be needed. "What I do know is that doing so does not violate any laws of physics," she said, predicting that the first manufactured lungs would be placed in a person's chest cavity this decade.

She closed her talk with a scene from *2001: A Space Odyssey*, the one where an ape-man hurls a bone upward and it takes flight as a space station circling the Earth. Except Rothblatt substituted a photograph of herself piloting the zero-carbon electric plane she believes will someday deliver unlimited organs around the country. ■

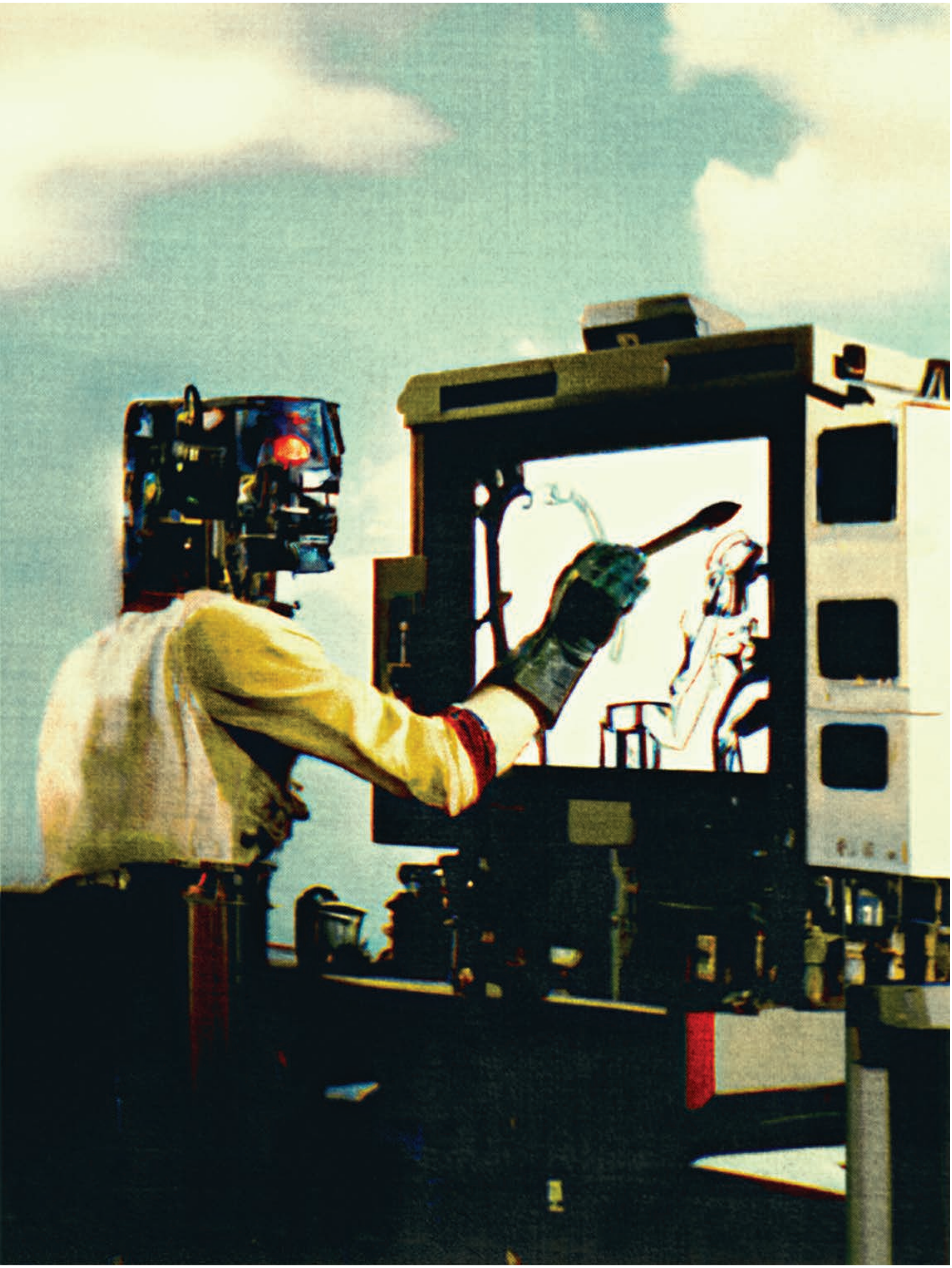
Antonio Regalado is MIT Technology Review's senior editor for biomedicine.

THE YEAR CREATIVITY exploded

THE GENERATIVE REVOLUTION IS HERE—
AND NOTHING WILL EVER BE THE SAME.

BY WILL DOUGLAS HEAVEN
ARTWORK BY ERIK CARTER

Turn the pages to learn how digital artist Erik Carter used the text-to-image AI tool DALL-E 2 to create these unsettling images



It was clear that OpenAI was on to something. In late 2021, a small team of researchers was playing around with an idea at the company's San Francisco office. They'd built a new version of OpenAI's text-to-image model, DALL-E, an AI that converts short written descriptions into pictures: a fox painted by Van Gogh, perhaps, or a corgi made of pizza. Now they just had to figure out what to do with it.

"Almost always, we build something and then we all have to use it for a while," Sam Altman, OpenAI's cofounder and CEO, tells MIT Technology Review. "We try to figure out what it's going to be, what it's going to be used for."

Not this time. As they tinkered with the model, everyone involved realized this was something special. "It was very clear that this was it—this was the product," says Altman. "There was no debate. We never even had a meeting about it."

But nobody—not Altman, not the DALL-E team—could have predicted just how big a splash this product was going to make. "This is the first AI technology that has caught fire with regular people," says Altman.

DALL-E 2 dropped in April 2022. In May, Google announced (but did not release) two text-to-image models of its own, Imagen and Parti. Then came Midjourney, a text-to-image model made for artists. And August brought Stable Diffusion, an open-source model that the UK-based startup Stability AI has released to the public for free.

The doors were off their hinges. OpenAI signed up a million users in just 2.5 months. More than a million people started using Stable Diffusion via its paid-for service Dream Studio in less than half that time; many more used Stable Diffusion through third-party apps or installed the free version on their own computers. (Emad Mostaque, Stability AI's founder, says he's aiming for a billion users.)

And then in October we had Round Two: a spate of text-to-*video* models from Google, Meta, and others. Instead of just generating still images, these can create short video clips, animations, and 3D pictures.

The pace of development has been breathtaking. In just a few months, the technology has inspired hundreds of newspaper headlines and magazine covers, filled social media with memes, kicked a hype machine into overdrive—and set off an intense backlash.

"The shock and awe of this technology is amazing—and it's fun, it's what new technology should be," says Mike Cook, an AI researcher at King's College London who studies computational creativity. "But it's moved so fast that your initial impressions are being updated before you even get used to the idea. I think we're going to spend a while digesting it as a society."

Artists are caught in the middle of one of the biggest upheavals in a generation. Some will lose work; some will find new opportunities. A few are headed to the courts to fight legal battles over what they view as the misappropriation of images to train models that could replace them.

Creators were caught off guard, says Don Allen Stevenson III, a digital artist based in California who has worked at visual-effects studios such as DreamWorks. "For technically trained folks like myself, it's very scary. You're like, 'Oh my god—that's my whole job,'" he says. "I went into an existential crisis for the first month of using DALL-E."

But while some are still reeling from the shock, many—including Stevenson—are finding ways to work with these tools and anticipate what comes next.

The exciting truth is, we don't really know. For while creative industries—from entertainment media to fashion, architecture, marketing, and more—will feel the impact first, this tech will give creative superpowers to everybody. In the longer term, it could be used to generate designs for almost anything, from new types of drugs to clothes and buildings. The generative revolution has begun.

A magical revolution

For Chad Nelson, a digital creator who has worked on video games and TV shows, text-to-image models are a once-in-a-lifetime breakthrough. "This tech takes you from that lightbulb in your head to a first sketch in seconds," he says. "The speed at which you can create and explore is revolutionary—beyond anything I've experienced in 30 years."

Within weeks of their debut, people were using these tools to prototype and brainstorm everything from magazine illustrations and marketing layouts to video-game environments and movie concepts. People generated fan art, even whole comic books, and shared them online in the thousands. Altman even used DALL-E to generate designs for sneakers that someone then made for him after he tweeted the image.

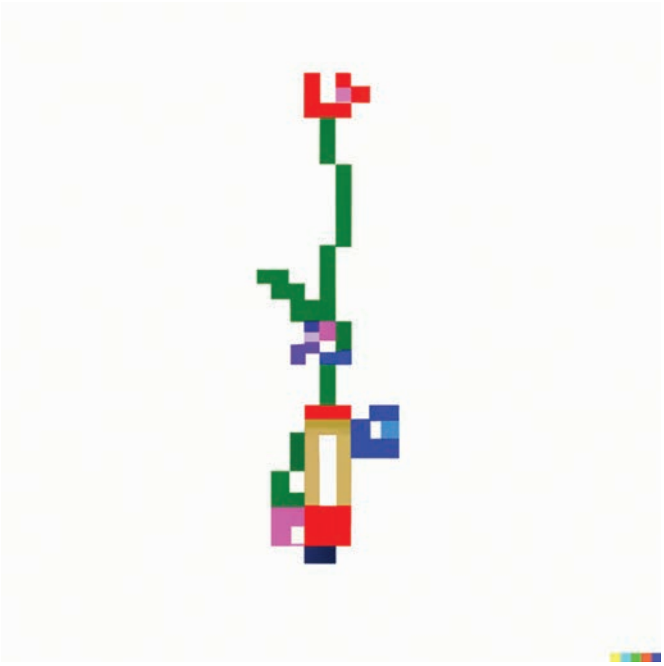
Amy Smith, a computer scientist at Queen Mary University of London and a tattoo artist, has been using DALL-E to design tattoos. "You can sit down with the client and generate designs together," she says. "We're in a revolution of media generation."

Paul Trillo, a digital and video artist based in California, thinks the technology will make it easier

The prompt I used in DALL-E 2 for the main piece (p. 41) was "an artist making art with an AI art tool in *Alien* (1979)." After landing on an image I was happy with, I went in and made adjustments to clean up any AI artifacts and make it look more "real." I'm a big fan of sci-fi from that era. The image at right is based on a variation of that same prompt.

and faster to brainstorm ideas for visual effects. “People are saying this is the death of effects artists, or the death of fashion designers,” he says. “I don’t think it’s the death of anything. I think it means we don’t have to work nights and weekends.”

Stock image companies are taking different positions. Getty has banned AI-generated images. Shutterstock has signed a deal with OpenAI to embed DALL-E in its website and says it will start a fund to reimburse artists whose work has been used to train the models.



Stevenson says he has tried out DALL-E at every step of the process that an animation studio uses to produce a film, including designing characters and environments. With DALL-E, he was able to do the work of multiple departments in a few minutes. “It’s uplifting for all the folks who’ve never been able to create because it was too expensive or too technical,” he says. “But it’s terrifying if you’re not open to change.”

Nelson thinks there’s still more to come. Eventually, he sees this technology being embraced not only by media giants but also by architecture and design firms. It’s not ready yet, though, he says.

“Right now it’s like you have a little magic box, a little wizard,” he says. That’s great if you just want to keep generating images, but not if you need a creative partner. “If I want it to create stories and build worlds, it needs far more awareness of what I’m creating,” he says.

That’s the problem: these models still have no idea what they’re doing.

Inside the black box

To see why, let’s look at how these programs work. From the outside, the software is a black box. You type in a short description—a prompt—and then wait a few seconds. What you get back is a handful of images that fit that prompt (more or less). You may have to tweak your text to coax the model to produce something closer to what you had in mind, or to hone a serendipitous result. This has become known as prompt engineering.

Prompts for the most detailed, stylized images can run to several hundred words, and wrangling the right words has become a valuable skill. Online marketplaces have sprung up where prompts known to produce desirable results are bought and sold.

Prompts can contain phrases that instruct the model to go for a particular style: “trending on ArtStation” tells the AI to mimic the (typically very detailed) style of images popular on ArtStation, a website where thousands of artists showcase their work; “Unreal engine” invokes the familiar graphic style of certain video games; and so on. Users can even enter the names of specific artists and have the

AI produce pastiches of their work, which has made some artists very unhappy.

Under the hood, text-to-image models have two key components: one neural network trained to pair an image with text that describes that image, and another trained to generate images from scratch. The basic idea is to get the second neural network to generate an image that the first neural network accepts as a match for the prompt.

The big breakthrough behind the new models is in the way images get generated. The first version of DALL-E used an extension of the technology behind OpenAI's language model GPT-3, producing images by predicting the next pixel in an image as if they were words in a sentence. This worked, but not well. "It was not a magical experience," says Altman. "It's amazing that it worked at all."

Instead, DALL-E 2 uses something called a diffusion model. Diffusion models are neural networks trained to clean images up by removing pixelated noise that the training process adds. The process involves taking images and changing a few pixels in them at a time, over many steps, until the original images are erased and you're left with nothing but random pixels. "If you do this a thousand times, eventually the image looks like you have plucked the antenna cable from your TV set—it's just snow," says Björn Ommer, who works on generative AI at the University of Munich in Germany and who helped build the diffusion model that now powers Stable Diffusion.

The neural network is then trained to reverse that process and predict what the less pixelated version of a given image would look like. The upshot is that if you give a diffusion model a mess of pixels, it will try to generate something a little cleaner. Plug the cleaned-up image back in, and the model will produce something cleaner still. Do this enough times and the model can take you all the way from TV snow to a high-resolution picture.

The trick with text-to-image models is that this process is guided by the language model that's trying to match a prompt to the images the diffusion model is producing. This pushes the diffusion model toward images that the language model considers a good match.

But the models aren't pulling the links between text and images out of thin air. Most text-to-image models today are trained on a large data set called LAION, which contains billions of pairings of text and images scraped from the internet. This means that the images you get from a text-to-image model are a distillation of the world as it's represented online, distorted by prejudice (and pornography).

One last thing: there's a small but crucial difference between the two most popular models, DALL-E 2 and Stable Diffusion. DALL-E 2's diffusion model works on full-size images. Stable Diffusion, on the other hand, uses a technique called latent diffusion, invented by Ommer and his colleagues. It works on compressed versions of images encoded within the neural network in what's known as a latent space, where only the essential features of an image are retained.

This means Stable Diffusion requires less computing muscle to work. Unlike DALL-E 2, which runs on OpenAI's powerful servers, Stable Diffusion can run on (good) personal computers. Much of the explosion of creativity and the rapid development of new apps is due to the fact that Stable Diffusion is both open source—programmers are free to change it, build on it, and make money from it—and lightweight enough for people to run at home.

Redefining creativity

For some, these models are a step toward artificial general intelligence, or AGI—an over-hyped buzzword referring to a future AI that has general-purpose or even human-like abilities. OpenAI has been explicit about its goal of achieving AGI. For that reason, Altman doesn't care that DALL-E 2 now competes with a raft of similar tools, some of them free. "We're here to make AGI, not image generators," he says. "It will fit into a broader product road map. It's one smallish element of what an AGI will do."

That's optimistic, to say the least—many experts believe that today's AI will never reach that level. In terms of basic intelligence, text-to-image models are no smarter than the language-generating AIs that underpin them. Tools like GPT-3 and Google's PaLM regurgitate patterns of text ingested from the many billions of documents they are trained on. Similarly, DALL-E and Stable Diffusion reproduce associations between text and images found across billions of examples online.

The results are dazzling, but poke too hard and the illusion shatters. These models make basic howlers—responding to "salmon in a river" with a picture of chopped-up fillets floating downstream, or to "a bat flying over a baseball stadium" with a picture of both a flying mammal and a wooden stick. That's because they are built on top of a technology that is nowhere close to understanding the world as humans (or even most animals) do.

Even so, it may be just a matter of time before these models learn better tricks. "People say it's not very good at this thing now, and of course it isn't," says Cook. "But a hundred million dollars later, it could well be."

I tried to metaphorically represent AI with the prompt "the Big Bang" and ended up with these abstract bubble-like forms (left, bottom). It wasn't exactly what I wanted, so I then went more literal with "explosion in outer space 1980s photograph" (left, top), which seemed too aggressive. I also tried growing some digital plants by putting in "plant 8-bit pixel art."

That's certainly OpenAI's approach.

"We already know how to make it 10 times better," says Altman. "We know there are logical reasoning tasks that it messes up. We're going to go down a list of things, and we'll put out a new version that fixes all of the current problems."

If claims about intelligence and understanding are overblown, what about creativity? Among humans, we say that artists, mathematicians, entrepreneurs, kindergarten kids, and their teachers are all exemplars of creativity. But getting at what these people have in common is hard.

For some, it's the results that matter most. Others argue that the way things are made—and whether there is intent in that process—is paramount.

Still, many fall back on a definition given by Margaret Boden, an influential AI researcher and philosopher at the University of Sussex, UK, who boils the concept down to three key criteria: to be creative, an idea or an artifact needs to be new, surprising, and valuable.

Beyond that, it's often a case of knowing it when you see it. Researchers in the field known as computational creativity describe their work as using computers to produce results that would be considered creative if produced by humans alone.

Smith is therefore happy to call this new breed of generative models creative, despite their stupidity. "It is very clear that there is innovation in these images that is not controlled by any human input," she says. "The translation from text to image is often surprising and beautiful."

Maria Teresa Llano, who studies computational creativity at Monash University in Melbourne, Australia, agrees that text-to-image models are stretching previous definitions. But Llano does not think they are creative. When you use these programs a lot, the results can start to become repetitive, she says. This means they fall short of some or all of Boden's requirements. And that could be a fundamental limitation of the technology. By design, a text-to-image model churns out new images in the likeness of billions of images that already exist. Perhaps machine learning will only ever produce images that imitate what it's been exposed to in the past.

That may not matter for computer graphics. Adobe is already building text-to-image generation into Photoshop; Blender, Photoshop's open-source cousin, has a Stable Diffusion plug-in. And OpenAI is collaborating with Microsoft on a text-to-image widget for Office.

It is in this kind of interaction, in future versions of these familiar tools, that the real impact may be felt: from machines that don't replace human creativity but enhance it. "The creativity we see today comes from the use of the systems, rather than from the systems themselves," says Llano—from the back-and-forth, call-and-response required to produce the result you want.

This view is echoed by other researchers in computational creativity. It's not just about what these machines do; it's how they do it. Turning them into true creative partners means pushing them to be more autonomous, giving them creative responsibility, getting them to curate as well as create.

Aspects of that will come soon. Someone has already written a program called CLIP Interrogator that analyzes an image and comes up with a prompt to generate more images like it. Others are using machine learning to augment simple prompts with phrases designed to give the image extra quality and fidelity—effectively automating prompt engineering, a task that has only existed for a handful of months.

Meanwhile, as the flood of images continues, we're laying down other foundations too. "The internet is now forever contaminated with images made by AI," says Cook. "The images that we made in 2022 will be a part of any model that is made from now on."

We will have to wait to see exactly what lasting impact these tools will have on creative industries, and on the entire field of AI. Generative AI has become one more tool for expression. Altman says he now uses generated images in personal messages the way he used to use emoji. "Some of my friends don't even bother to generate the image—they type the prompt," he says.

But text-to-image models may be just the start. Generative AI could eventually be used to produce designs for everything from new buildings to new drugs—think text-to-*X*.

"People are going to realize that technique or craft is no longer the barrier—it's now just their ability to imagine," says Nelson.

Computers are already used in several industries to generate vast numbers of possible designs that are then sifted for ones that might work. Text-to-*X* models would allow a human designer to fine-tune that generative process from the start, using words to guide computers through an infinite number of options toward results that are not just possible but desirable.

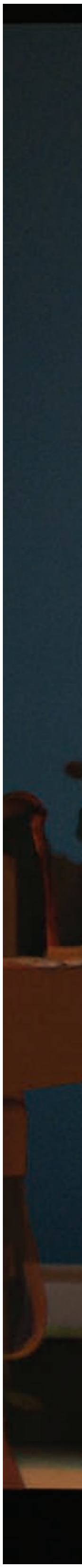
Computers can conjure spaces filled with infinite possibility. Text-to-*X* will let us explore those spaces using words.

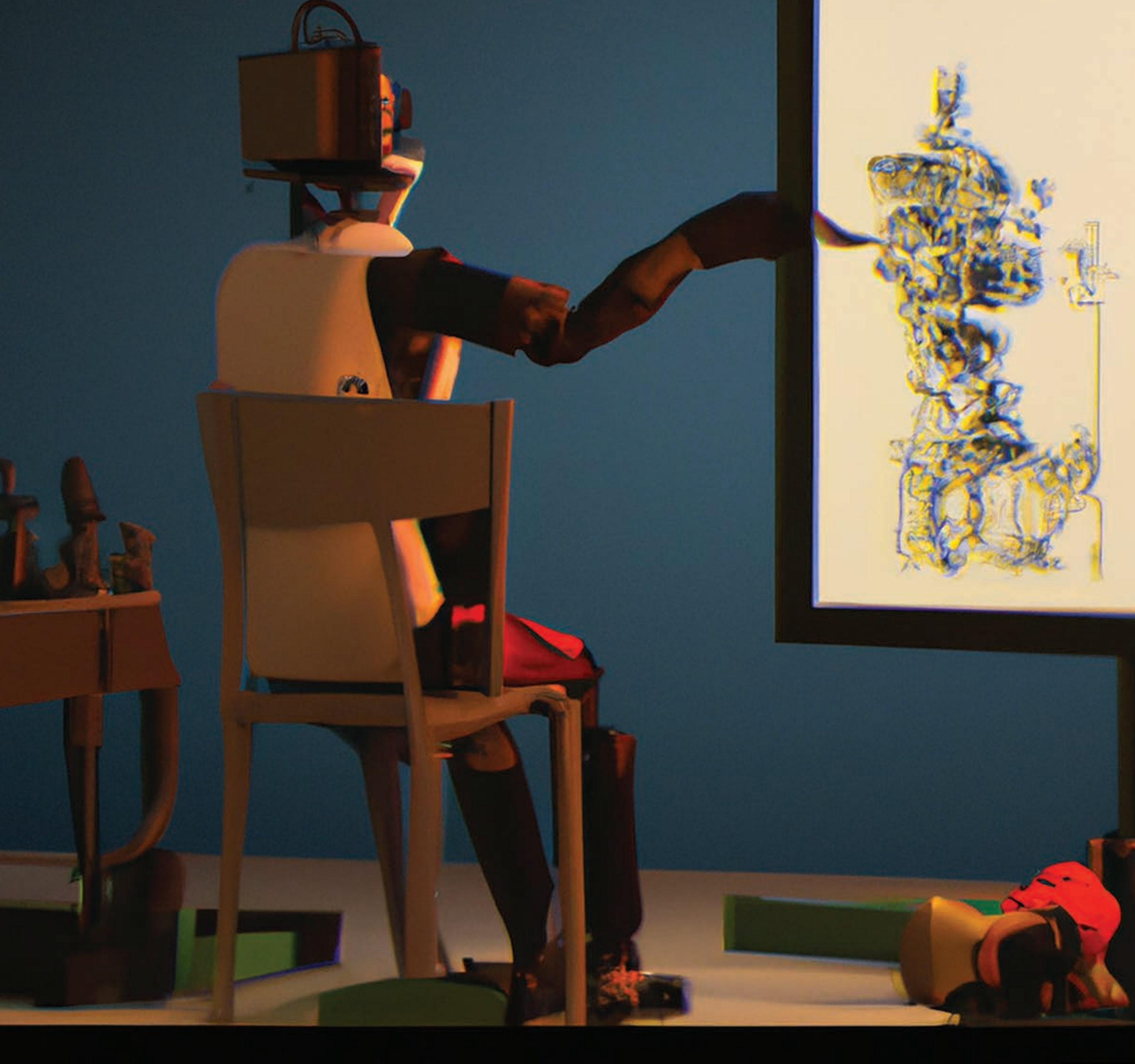
"I think that's the legacy," says Altman. "Images, video, audio—eventually, everything will be generated. I think it is just going to seep everywhere." ■

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

AI art generators never work exactly how you want them to. They often produce hideous results that can resemble distorted stock art, at best. In my experience, the only way to really make the work look good is to add a descriptor at the end with a style that looks aesthetically pleasing.

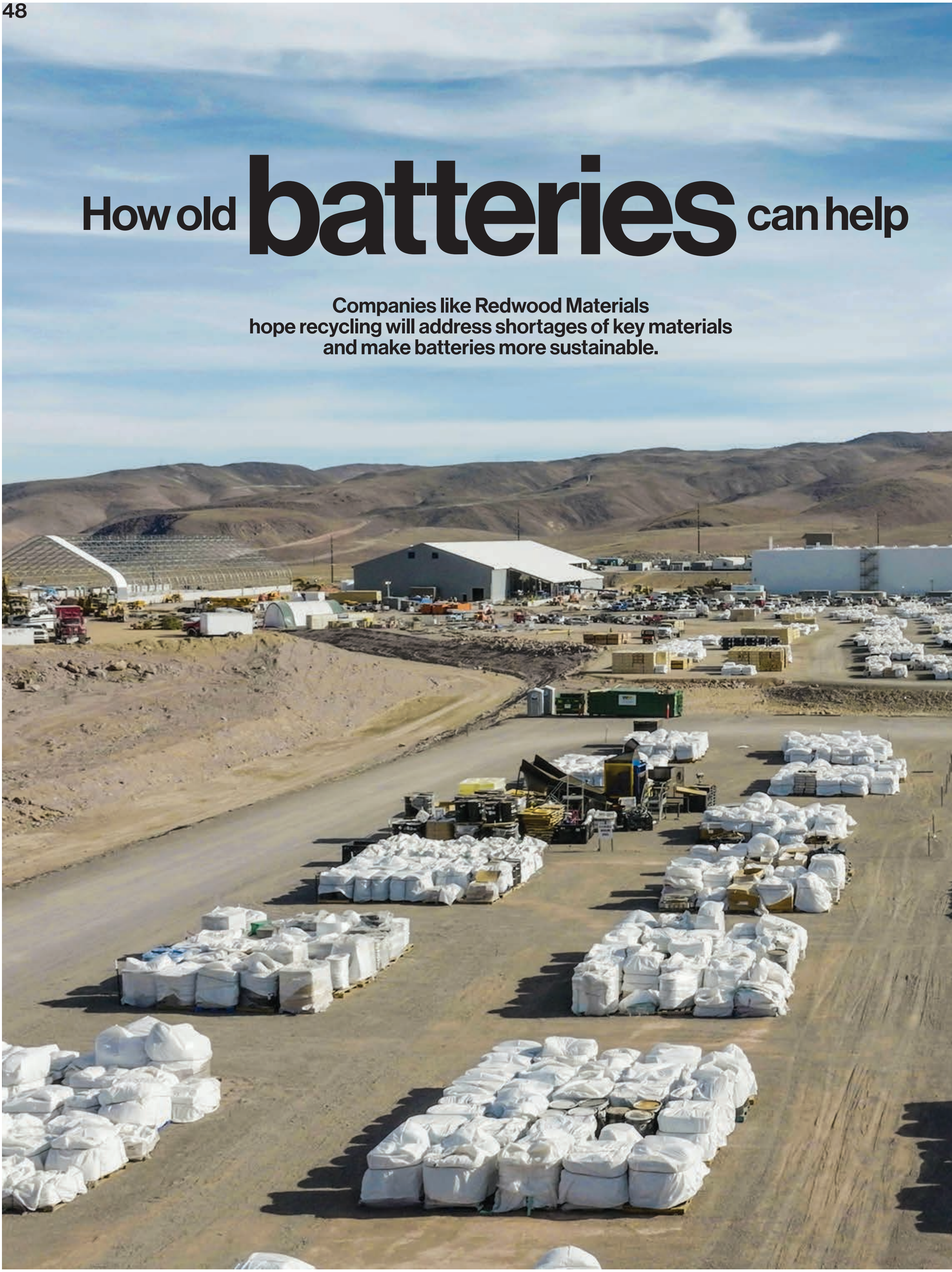
DALL-E 2 accepts either an image or written text as a prompt. The image at right was created by uploading the image from p. 41 back into DALL-E 2 as a prompt.





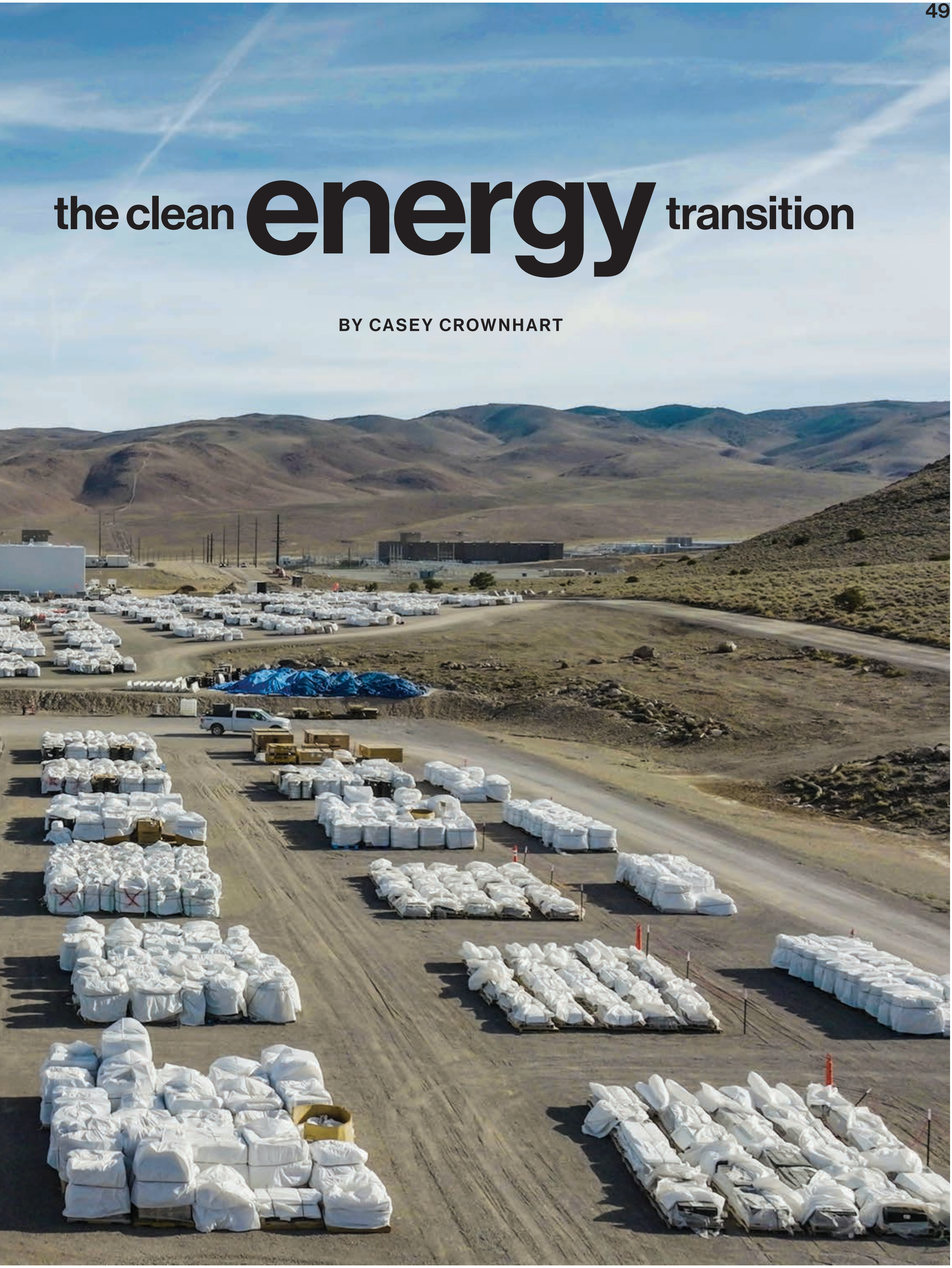
How old batteries can help

Companies like Redwood Materials hope recycling will address shortages of key materials and make batteries more sustainable.



the clean energy transition

BY CASEY CROWNHART



Used batteries and assorted manufacturing scrap from battery producers are stored in one of Redwood's massive warehouses as the company ramps up its recycling process.

To Redwood Materials, the rows of cardboard boxes in its gravel parking lot represent both the past and the future of electric vehicles. The makeshift storage space stretches for over 10 acres at Redwood's new battery recycling site just outside Reno, Nevada. Most of the boxes are about the size of a washing machine and are wrapped in white plastic. But some lie open, revealing their contents: wirelesss keyboards, discarded toys, chunks of used Honda Civic batteries.

Far from trash, the battery materials in all these discarded items are a prize—the metals are valuable ingredients that could be critical to meeting exploding demand for electric vehicles.

Redwood Materials is one of a growing number of recycling companies working to provide an alternative to the landfill for lithium-ion batteries used in electronics and EVs. The company announced its plans for this $3.5 billion plant in Reno in mid-2022. The facility is expected to produce material for 1 million lithium-ion EV batteries by 2025, ramping up to 5 million by 2030. Redwood plans to start construction on an additional facility in the eastern US in 2023.

Meanwhile, the Canadian firm Li-Cycle currently operates four commercial facilities that can together recycle about 30,000 metric tons of batteries annually, with an additional three sites planned. Other US-based startups, like American Battery Technology Company, have also announced large commercial tests, joining an established recycling market in China and Europe.

While these new recycling ventures are better for the environment than burying metals in landfills, they're also spurred by a booming market for electric vehicles. EV adoption is exploding in the US and around the world, bringing new demand for the metals that go into their batteries, especially lithium, nickel, and cobalt. EVs are expected to account for 13% of new vehicle sales in 2022, a number that's expected to climb to about 30% by 2030. Supplying all those cars with batteries will require far more metals than are currently available.

More than 200 new mines could be needed by 2035 to provide enough material for just the cobalt, lithium, and nickel needed for EV batteries. Lithium production will need to grow by 20 times to meet demand for EVs by 2050.

Recycling could represent a major new source of raw materials. Globally, there was over 600,000 metric tons of recyclable lithium-ion batteries and related manufacturing scrap in 2021. That number is expected to top 1.6 million metric tons by 2030, according to the consulting firm Circular Energy Storage. And it could really take off after that, as the first generation of electric cars heads for the junkyards.

New advances in the recycling process for lithium-ion batteries are transforming the industry, allowing recyclers to separate and recover enough of these valuable metals to make the process economical. Recycling can't address material shortages alone, because demand for the metals outstrips the amount circulating in batteries used today. But thanks to these advances, it could account for a significant fraction of supply in the coming decades.

When I visited in September, Redwood was preparing to ship its first product, a small sample of copper foil used in battery anodes. It's sending the foil to the battery maker Panasonic to use in the Nevada Gigafactory, which produces battery cells for Tesla vehicles less than five miles away.

On the way to Redwood's factory, I saw tumbleweeds leap across the highway, and some of the area's wild horses idled on a hillside. Later, I'd spot a coyote skittering across the parking lot.

But down the dirt road at the site, the Old West vibes quickly fell away, replaced by a sense of urgency radiating from nearly everyone there. Several massive buildings were under construction, and engineers and construction workers in safety vests and hard hats hurried around the site, ducking between temporary trailers serving as makeshift offices, labs, and meeting rooms.

When construction is finished, the Redwood site will produce two major products: the copper foil for anodes and a mixture of lithium, nickel, and cobalt known as cathode active material. These components account for over half the cost of battery cells. By 2025, Redwood projects, its facility will produce enough of them to make batteries for more than a million EVs every year.

Redwood runs a collection program for old phones, tablets, and other devices with lithium-ion batteries.

IMAGES COURTESY OF REDWOOD MATERIALS

Redwood began construction on its battery materials campus in late 2021. The facility is expected to produce enough battery materials for 1 million EVs by 2025.

One of Redwood's first products is copper foil, which is used in lithium-ion battery anodes. Here a Redwood technician inspects the product as it rolls off the manufacturing line.

Down the hill from the trailers, the building for copper foil production was the furthest along, with a roof and walls; a machine for making the foil was tucked away in the corner. But the two other major buildings still looked far from completion—one was missing walls, and the other was only a foundation.

Redwood has big plans and plenty of construction ahead.

"A sense of paranoia"

Redwood Materials was founded by JB Straubel, who as Tesla's chief technical officer during the early 2010s led many of the company's battery breakthroughs, including the beginnings of its network of charging stations. But even as Tesla was transforming the way electric cars were manufactured and sold, Straubel was worried about how overwhelming the need for more battery materials would become. He began to think of ways to lower the cost of batteries and help reduce the carbon emissions associated with making them.

Straubel started Redwood while still working at Tesla (he left in 2019); he wanted, as he puts it, to create a sustainable battery materials company. These days he talks about his mission with a breathless excitement coupled with the precision of an engineer, sometimes pausing in the middle of a thought to start over as he explains his vision for the future of battery production.

"It simply can't work unless you have a closed loop for the raw materials," he says. "There aren't enough new raw materials to keep building and throwing them away."

Creating a closed loop of materials, where old batteries become feedstock for new ones, sounds like an obvious idea, but executing it isn't trivial. "It's not just a sorting or a garbage management problem," Straubel says.

Chemically separating the crucial metals locked in batteries is an intricate task. Labs, startups, and established companies alike are all searching for the ideal process to recover the highest possible amounts of valuable materials in the purest possible form.

The details of how Redwood solves this problem are closely held—they're the company's secret sauce. But its process is also very much a work in progress, and the urgency of figuring it out is clear.

"I do have this kind of sense of paranoia and urgency and almost—not exactly—panic, that's not helpful. It really derives from a deep feeling that I don't believe we're appropriately internalizing how bad climate change is going to be," Straubel says.

"I generally don't think we're going fast enough. I don't think anyone is."

Redwood plans to produce copper foil at its new campus outside Reno, Nevada. Delivery to Panasonic was planned for December.

Recycling's role

Most recycling facilities for lithium-ion batteries use a set of chemical processes called hydrometallurgy, where materials in the batteries are dissolved and separated using a range of acids and solvents. In addition to nickel, cobalt, and other materials like graphite and copper, recent developments have allowed hydrometallurgy to recover lithium at high rates as well.

After some additional processing, recovered materials can then be used in new products. Whereas some materials, such as plastics, can degrade over time with recycling, researchers have found that metals recovered from batteries work just as well as mined ones for charging and storing power.

Many batteries arriving at Redwood need to be disassembled by hand before processing. This is the case for batteries coming in full EV battery packs, which are the size of a mattress and too large for Redwood's equipment, as well as batteries still attached to their products, like laptops or power tools. All these battery types generally contain lithium, nickel, and cobalt, though the relative amounts vary; batteries in consumer electronic devices, for example, tend to be more cobalt-heavy than those in EVs.

Large batteries, like these from an energy storage system, often need to be disassembled by hand before recycling.

Hand disassembly won't be ideal once the company starts taking in more materials, says Andy Hamilton, Redwood's VP of manufacturing. Eventually, Redwood hopes to automate more of this sorting process, though building automated systems that can deal with the variety of batteries the company takes in will likely be a challenge.

After sorting and disassembly, the batteries that still hold charge can be loaded onto a conveyor belt and carried up into one of four massive chambers for a process called calcination, where batteries are cooked at high temperatures to discharge them and remove solvents.

The material is then crushed into powder before it enters the hydrometallurgical process to separate individual elements.

Despite recent technical progress, recycling won't meet demand for battery materials anytime soon, says Alissa Kendall, an energy systems researcher at the University of California, Davis. Since demand is still rising exponentially, recycled batteries will at best account for about half the nickel and lithium supply by 2050.

However, as battery chemistries evolve, that percentage could change, as is happening already with cobalt. Batteries in EVs contain less cobalt today than they used to, and cell makers are continuously finding ways to use even less of the expensive metal. As a result, recycled cobalt could make up 85% of the supply needed by 2040, Kendall says.

Even if recycling can't fully supplant mining, cutting the need for more mines could reduce the social and environmental burden of producing new batteries. Many metals for batteries are mined in Africa, Asia, and Central and South America. Mining in these regions is often associated with human rights violations, including forced and child labor, as well as significant air and water pollution, according to the International Energy Agency.

Waiting for the battery tsunami

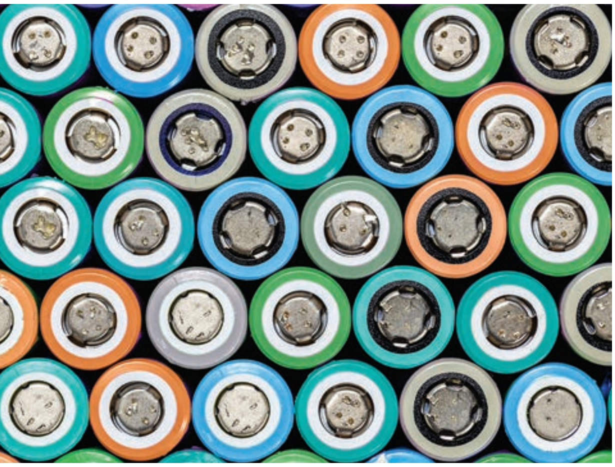
Some in the battery recycling business argue that the industry won't need much policy support, since the materials in batteries will be valuable enough to justify recycling them. But recent policy moves in the US could give recyclers like Redwood a further boost.

Since Redwood's manufacturing plant is in the US, the company could be eligible for production tax credits in the recently passed Inflation Reduction Act. The IRA will also drive demand for raw materials from outfits like Redwood. For cars to qualify for $7,500 tax credits, automakers will need to source their materials and manufacture their batteries in the US or with free-trade partners.

Critics have warned that industry may not be able to meet the timeline for these EV tax credits, especially for material sourcing, since it can take up to a decade to build new mines. A recycling facility, on the other hand, could be built more quickly, and some are pointing to recycling as a possible avenue for battery and car makers hoping to qualify for the credits.

Other governments are considering additional regulations to boost battery recycling. In Europe, recently proposed legislation includes provisions like requiring the original manufacturers of a battery to be responsible for it at its end of life. The EU has also considered requiring new batteries to have a certain fraction of recycled content.

Still, there could be a short-term shortage of batteries for recycling. The wave of old EV batteries expected



Unlike some other recyclers, Redwood plans to make battery components that can be sold directly to battery manufacturers, avoiding the need to send the reclaimed materials to refiners first.

in the coming decades is for now just a trickle, since only a small number of EVs are coming off the roads.

About half of what Redwood accepts these days has never been used in a product. This material ranges from assembled and charged batteries that failed quality checks to what's left of a sheet of metal when the desired pieces are cut out of it. Two semi trucks arrive at the Redwood facilities every day with manufacturing scrap from the Tesla/Panasonic Gigafactory.

Redwood has also made what Straubel calls a "pragmatic" choice to include freshly mined metals in its products for now. The nickel and lithium in its first batch of cathode active material will only be about 30% from recycled sources—the remainder will come from mining.

The goal is to be ready when the battery tsunami arrives, says Straubel, and that means optimizing the recycling process now.

The path forward

While construction continued at the larger site, I walked through Redwood's headquarters in Carson City, where its scientists are still experimenting with the hydrometallurgy process.

Researchers have been working to use chemistry to recover metals from lithium-ion battery materials since the late 1990s. Companies in China have moved fastest, building a widespread network of recycling centers with government support.

But designing a system that can recover high levels of all the most expensive metals in batteries hasn't been easy. Lithium has proved especially difficult. Straubel says that of the four metals Redwood is most focused on, they can reach close to 100% recovery of cobalt, copper, and nickel. For lithium, the figure is about 80%.

Moving from the lab to real-world conditions can also make things even more complicated.

Mary Lou Lindstrom, Redwood's head of hydrometallurgy, showed me around the pilot lab space in Carson City, which resembled a craft beer operation, with stainless-steel equipment distributed around a cavernous room. Researchers were huddled around a computer and one of the large metal tanks.

Lindstrom explained that they were working to produce the feedstock for the first batch of commercial copper foil; production would be starting up in the coming weeks. Delivery to Panasonic was scheduled to take place in December.

A technicality still stands in the way of Straubel's vision for a closed-loop battery ecosystem. So far, the copper Redwood was using to make foil came from industrial copper scrap, not batteries. The company hopes to use at least some battery material in the copper foil that eventually gets delivered to Panasonic for use in new cells. But industrial copper scrap is a more predictable material to work with.

Redwood uses a process called hydrometallurgy to recover valuable metals such as cobalt, lithium, and nickel from the batteries it collects.

This transition speaks to one major potential challenge for battery recyclers moving forward: they'll need to deal with unpredictable inputs while creating predictable, high-quality products. If battery recyclers are competing for material, this challenge will be magnified, since startups may have to accept less-ideal material to survive.

For now, Redwood can supplement its processes with manufacturing scrap, which is generally easier to work with, as well as mined material. But as volumes of old batteries grow and the supply of mined lithium stretches thin, challenges for recyclers will mount.

"Increasingly, the solution to some of these sustainability problems is to electrify it and add a battery to it," Straubel says. "I spent the majority of my career championing that and helping accelerate that."

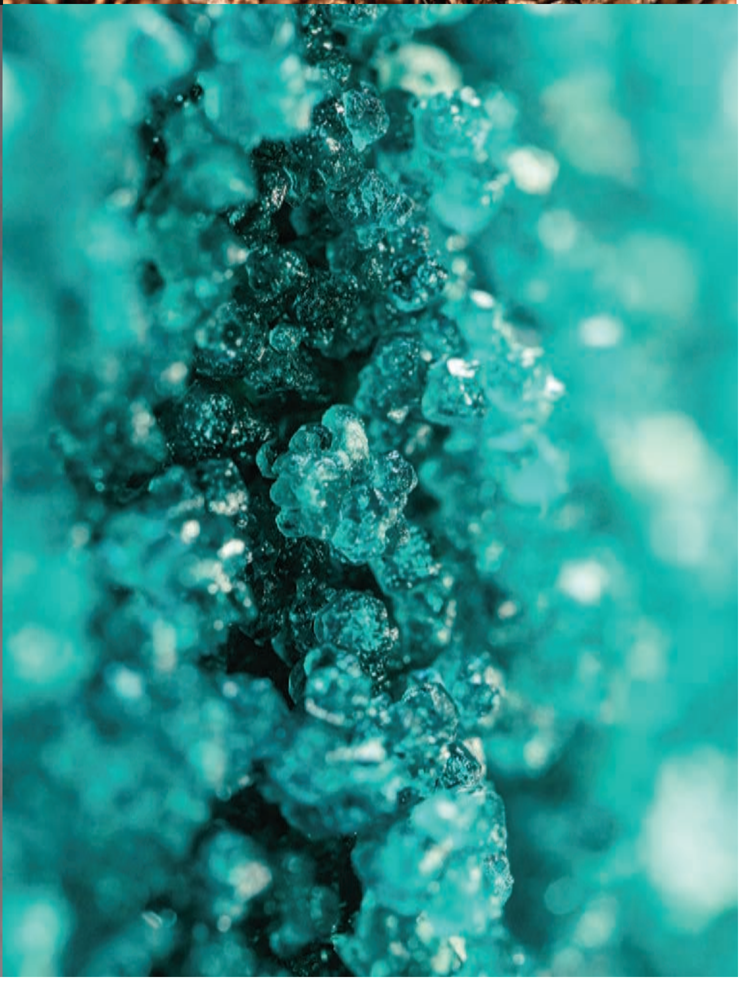
"At the same time," he says, "it's a phenomenal amount of batteries."

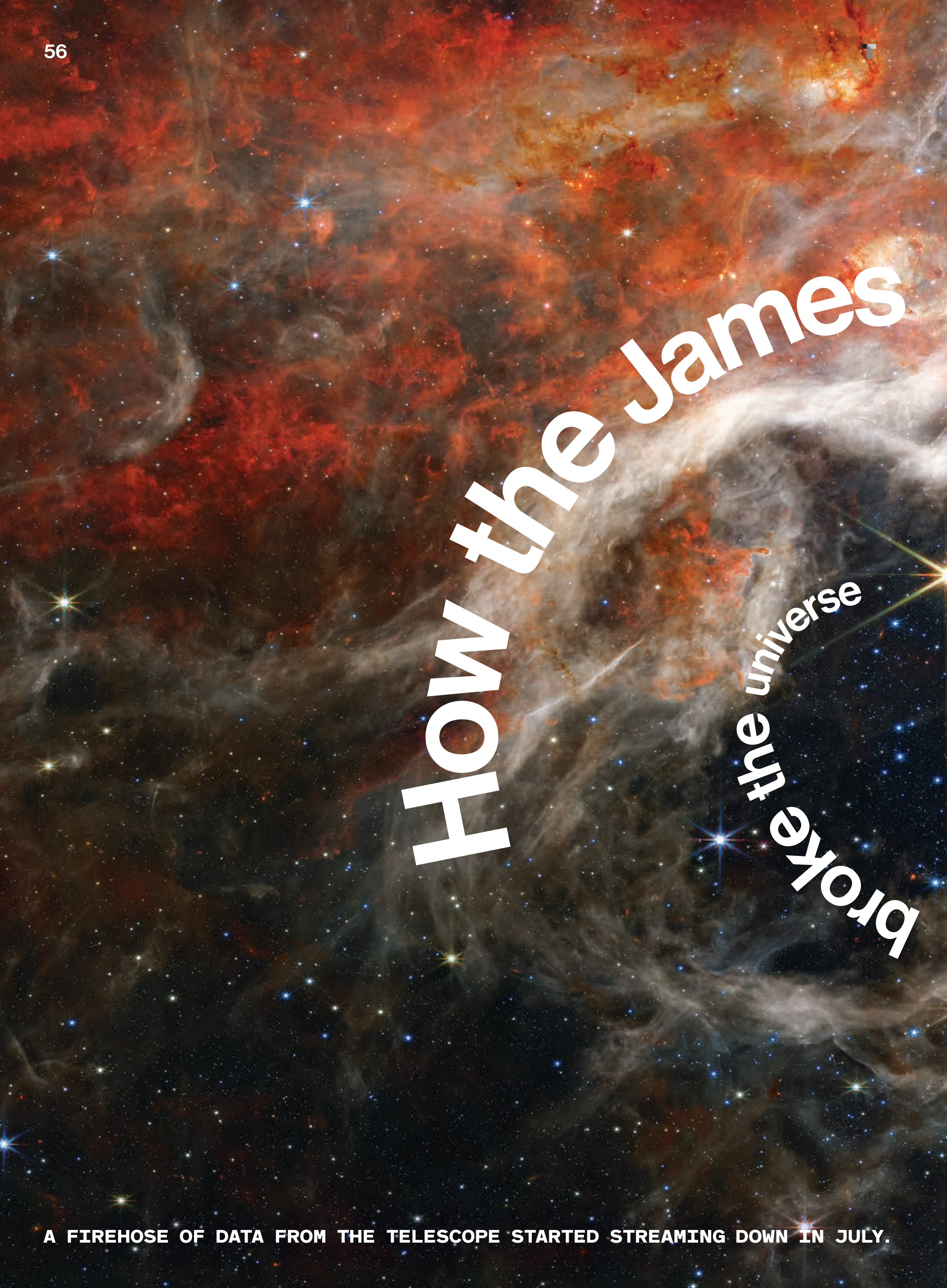
EVs and other electrified transit options are becoming a practical choice. It's already cheaper in many parts of the world to own and drive an EV than a conventional car. And that's good news for the climate: in most cases, EVs will produce less in greenhouse-gas emissions over their lifetime than gas-powered vehicles.

Practical, economical battery recycling is key to fulfilling the promise of EVs. While the wave of dead batteries may be slow to build, the recycling industry is preparing now for what's coming, because executing this new vision will take decades of steady progress and innovation. Redwood's parking lot full of discarded batteries is just the start. ■

Casey Crownhart is the energy and climate reporter for MIT Technology Review.





How the James broke the universe

A FIREHOSE OF DATA FROM THE TELESCOPE STARTED STREAMING DOWN IN JULY.

Webb Space Telescope

Sparkling crowd

A clutch of massive young stars takes center stage in this mosaic image of the Tarantula Nebula, captured with JWST's Near-Infrared Camera. They are surrounded by, and will help sculpt, clouds of gas and dust—the raw material for yet more stars.

ASTRONOMERS WERE READY AND WAITING.

BY JONATHAN O'CALLAGHAN

Galactic gladiators

Galaxies tug and push on one another in this image of Stephan's Quintet, created with data from two of JWST's infrared instruments. The leftmost galaxy appears to be part of the group but sits much closer to Earth.

PREVIOUS SPREAD: NASA, ESA, CSA, STSCI, WEBB ERO PRODUCTION TEAM; NASA, ESA, CSA, STSCI

Natalie Batalha was itching for data from the James Webb Space Telescope. It was a few months after the telescope had reached its final orbit, and her group at the University of California, Santa Cruz, had been granted time to observe a handful of exoplanets—planets that orbit around stars other than our sun.

Among the targets was WASP-39b, a scorching world that orbits a star some 700 light-years from Earth. The planet was discovered years ago. But in mid-July, when Batalha and her team got their hands on the first JWST observations of the distant world, they saw a clear signature of a gas that is common on Earth but had never been spotted before in the atmosphere of an exoplanet: carbon dioxide. On Earth, carbon dioxide is a key indicator of plant and animal life. WASP-39b, which takes just four Earth days to orbit its star, is too hot to be considered habitable. But the discovery could well herald more exciting detections—from more temperate worlds—in the future. And it came just a few days into the lifetime of JWST. "That was a very exciting moment," says Batalha, whose group had gathered to glimpse the data for the first time. "The minute we looked, the carbon dioxide feature was just beautifully drawn out."

This was no accident. JWST, a NASA-led collaboration between the US, Canada, and Europe, is the most powerful space telescope in history and can view objects 100 times fainter than what the Hubble Space Telescope can see. Almost immediately after it started full operations in July of 2022, incredible vistas from across the universe poured down, from images of remote galaxies at the dawn of time to amazing landscapes of nebulae, the dust-filled birthplaces of stars. "It's just as powerful as we had hoped, if not more so," says Gabriel Brammer, an astronomer at the University of Copenhagen in Denmark.

But the speed at which JWST has made discoveries is due to more than its intrinsic capabilities. Astronomers prepared for years for the observations it would make, developing algorithms that can rapidly turn its data into usable information. Much of the data is open access, allowing the astronomical community to comb through it almost as fast as it comes in. Its operators have also built on lessons learned from the telescope's predecessor, Hubble, packing its observational schedule as much as possible.

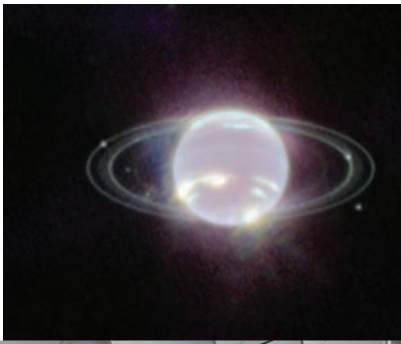
For some, the sheer volume of extraordinary data has been a surprise. "It was more than we expected," says Heidi Hammel, a NASA interdisciplinary scientist for JWST and vice president for science at the Association of Universities for Research in Astronomy in Washington, DC. "Once we went into operational mode, it was just nonstop. Every hour we were looking at a galaxy or an exoplanet or star formation. It was like a firehose."

Now, months later, JWST continues to send down reams of data to astonished astronomers on Earth, and it is expected to transform our understanding of the distant universe, exoplanets, planet formation, galactic structure, and much more. Not all have enjoyed the flurry of activity, which at times has reflected an emphasis on speed over the scientific process, but there's no doubt that JWST is enchanting audiences across the globe at a tremendous pace. The floodgates have opened—and they're not shutting anytime soon.

Opening the pipe

JWST orbits the sun around a stable point 1.5 million kilometers from Earth. Its giant gold-coated primary mirror, which is as tall as a giraffe, is protected from the sun's glare by a tennis-court-size sunshield, allowing unprecedented views of the universe in infrared light.

The aim is to keep the telescope as busy as possible: "The worst thing we could do is have an idle telescope."



The telescope was a long time coming. First conceived in the 1980s, it was once planned for launch around 2007 at a cost of $1 billion. But its complexity caused extensive delays, devouring money until at one point it was dubbed "the telescope that ate astronomy." When JWST finally launched, in December 2021, its estimated cost had ballooned to nearly $10 billion.

Even post-launch, there have been anxious moments. The telescope's journey to its target location beyond the moon's orbit took a month, and hundreds of moving parts were required to deploy its various components, including its enormous sunshield, which is needed to keep the infrared-sensitive instruments cool.

But by now, the delays, the budget overruns, and most of the tensions have been overcome. JWST is hard at work, its activities carefully choreographed by the Space Telescope Science Institute (STScI) in Baltimore. Every week, a team plans out the telescope's upcoming observations, pulling from a long-term schedule of hundreds of approved programs to be run in its first year of science, from July 2022 to June 2023.

The aim is to keep the telescope as busy as possible. "The worst thing we could do is have an idle telescope," says Dave Adler at STScI, the head of long-range planning for JWST. "It's not a cheap thing." In the 1990s Hubble would occasionally find itself twiddling its thumbs in space if programs were altered or canceled; JWST's schedule is deliberately oversubscribed to prevent such issues. Onboard thrusters and reaction wheels, which spin to change the orientation, move the telescope with precision between various targets across the sky. "The goal is always to minimize the amount of time we're not doing science," says Adler.

The result of this packed schedule is that every day, JWST can collect more than 50 gigabytes of data, compared with just one or two gigabytes for Hubble. The data, which contains images and spectroscopic signatures (essentially light broken apart into its elements), is fed through an algorithm run by STScI. Known as a "pipeline," it turns the telescope's raw images and numbers into useful information. Some of this is released immediately on public servers, where it is picked up by eager scientists or even by Twitter bots such as the JWST Photo Bot. Other data is handed to scientists on programs that have proprietary windows, enabling them to take time analyzing their own data before it is released to the masses.

Pipelines are essentially pieces of code, made with programming languages like Python. They have long been used in astronomy but advanced considerably in 2004 after astronomers used Hubble to spend 1 million seconds observing an empty patch of sky. The goal was to look for remote galaxies in the distant universe, but 800 exposures would be taken, so Hubble's planners knew it would be too daunting a task to do by hand.

Instead, they developed a pipeline to turn the exposures into a usable image, a taxing technical challenge given that each image required its own calibration and alignment. "There was no way you could expect the community at that time to combine 800 exposures on their own," says Anton Koekemoer, a research astronomer at STScI. "The goal was to enable science to be done much more quickly." The incredible image resulting from those efforts revealed 10,000 galaxies stretching across the universe, in what came to be known as the Hubble Ultra Deep Field.

With JWST, a single master pipeline developed by STScI takes images and data from all its instruments and makes them science-ready. Many astronomers, both amateur and professional, then use their own pipelines developed in the months and years before launch to further investigate the

Great reflector

—

Segments of JWST's primary mirror are prepped for cryogenic testing in 2011. The full mirror, made of gold-coated beryllium, consists of 18 segments and spans 6.5 meters. It was designed to be folded up for launch.

Fine phasing

—

This image of a star was taken during testing of JWST's optical alignment. But it incidentally showcased the sensitivity of the telescope, with a number of stars and galaxies appearing in the background.

Subtle rings

—

The Near-Infrared Camera aboard JWST captured this snapshot of Neptune in July. Researchers said it was the clearest view of the giant planet's rings since the Voyager 2 flyby in 1989.

NASA, ESA, CSA, STSCI; NASA/MSFC/DAVID HIGGINBOTHAM; ASA/STSCI

data. That's why when JWST's data began streaming down to Earth, astronomers were able to almost immediately understand what they were seeing, turning what would normally be months of analysis time into just hours of processing time.

"We were sitting there ready," says Brammer. "All of a sudden, the pipe was open. We were ready to go."

Galaxies everywhere

Orbiting just a few hundred miles above Earth's surface, the Hubble Space Telescope is close enough for astronauts to visit. And over the years, they did, undertaking a series of missions to repair and upgrade the telescope, starting with a trip to fix its infamously misshapen mirror—a problem discovered shortly after launch in 1990. JWST, which sits farther away than the moon, is on its own.

Lee Feinberg, JWST's optical telescope element manager at NASA's Goddard Space Flight Center, was among those waiting to see whether the telescope would actually deliver. "We spent 20 years simulating the alignment of the telescope," he says—that is, making sure that it could accurately point at targets across the sky.

By March, the wait was over. JWST had reached its target location beyond the moon, and Feinberg and his colleagues were finally ready to start taking test images. As he walked into STScI one morning, one of those images, a test image of a star, was put up on screen. It contained an amazing surprise. "There were literally hundreds of galaxies," says Feinberg. "We were just blown away." So detailed was the image that it revealed galaxies stretching away into the distant universe, even though it hadn't been taken for such a purpose. "Everybody was in disbelief how well it was working," he says.

Following a further process of testing and calibrating instruments to get the telescope up and running, one of JWST's earliest tasks was to look at WASP-39b with its cryogenically cooled Mid-Infrared Instrument (MIRI). This tool is the one aboard the telescope that observes most deeply in the infrared part of the spectrum, where many of the signatures of planetary atmospheres can be readily detected. MIRI's spectrograph allowed scientists to pick apart the light from WASP-39b's atmosphere. Rather than analyzing the observations manually, however, the team used a pipeline called Eureka!, developed by Taylor Bell, an astronomer at the Bay Area Environmental Research Institute at NASA's Ames Research Center in California. "The objective was to go from the raw data that comes down to information about the atmospheric spectrum," says Bell. Analyzing information from an exoplanet like this would usually require months of work. But within hours of the observations, the signature of carbon dioxide leaped out. A host of other details have since been released about the planet, including a detailed analysis of its composition and the presence of patchy clouds.

Others have used pipelines for much more distant targets. In July, studying early images from JWST, a team led by Rohan Naidu at MIT discovered GLASS-z13, a remote galaxy whose light could date from just 300 million years after the Big Bang—earlier than any galaxy known before. The discovery caused a global furor because it suggested that galaxies may have formed earlier than previously expected, perhaps by a few hundred million years—meaning our universe took shape faster than previously believed.

Naidu's discovery was made possible by EAZY, a pipeline Brammer developed to somewhat crudely analyze the light of galaxies in JWST images. "It estimates the distance of the objects using these imaging observations," says Brammer, who posted the tool on the software website GitHub for anybody to use.

Rush hour

Traditionally in science, researchers will submit a scientific paper to a journal, where it is then reviewed by peers in the field and finally approved for publication or rejected. This process can take months, even years, sometimes delaying publication—but always with accuracy and scientific rigor in mind.

There are ways to bypass this process, however. A popular method is to post early

A sculpture in dust

—

The bright star at the center of the Southern Ring Nebula is in a tight orbit with a neighbor, causing it to eject layers of gas and dust. Deeper teal colors in this image indicate areas where the shed material is particularly dense and opaque.

Stellar cradle

JWST captured this new view of the Pillars of Creation, a familiar sight for Hubble fans—a dusty, turbulent region filled with newly forming stars. It sits in the Eagle Nebula, some 6,500 light-years away.

versions of scientific papers on the website arXiv prior to peer review. This means that research can be read or publicized before it is published in a journal. In some cases, the research is never submitted to a journal, instead remaining solely on arXiv and discussed openly by scientists on Twitter and other forums.

Posting on arXiv is popular when there is a new discovery that scientists are keen to publish quickly, sometimes before competing papers come out. In the case of JWST, about a fifth of its first-year programs are open access, meaning the data is immediately released publicly when it is transferred down to Earth. That puts the research team involved with the program in immediate competition with others watching the data stream in. When the telescope's firehose of data was switched on in July, many researchers turned to arXiv to publish early results—for better or worse.

"There was a rush to publish anything as soon as possible," says Emiliano Merlin, an astronomer at the Astronomical Observatory of Rome who was involved in early JWST analysis efforts such as the race to find galaxies in the distant universe after the Big Bang. The discovery of GLASS-z13 and a dozen or so other intriguing candidates was published before follow-up observations could confirm the age of their light. "It was not something I personally really liked," says Merlin. "When you're dealing with something this new and this unknown, things should be checked 10 or 100 times. That's not how things went."

One concern was that early calibration issues with the telescope could have resulted in errors. But so far many of the early results have stood up to scrutiny. One follow-up observation by an Earth-based telescope suggests that GLASS-z13 may indeed be a record-breaking early galaxy. The possible discovery of other galaxies that formed even earlier than GLASS-z13 (now called GLASS-z12 following refinements regarding its distance) suggests that our understanding of how structure emerged in the universe may very likely need to be rethought, perhaps even hinting at more radical models for the early universe.

While many of JWST's programs publicly release data immediately, sometimes resulting in a frantic rush to post results early, about 80% of them have a proprietary period, allowing the researchers running them exclusive access to their data for 12 months. This enables scientists, especially smaller groups that lack the resources of large institutions, to more carefully scrutinize their own data before releasing it to the public.

"Proprietary time evens out the lumps and bumps in resources," says Mark McCaughrean, senior advisor for science and exploration at the European Space Agency and a JWST scientist. "If you take away proprietary periods, you stack it back in the direction of the big teams."

Many scientists do not use their full 12-month allocation, however, which means they will only add to the constant stream of discoveries from JWST. Alongside the open-access observations being taken, there will be more and more proprietary results released to the public. "Now that the firehose is open, we will be seeing papers continuously for the next 10 years and beyond," says Hammel. Perhaps well past that—Feinberg says the telescope may have more than 20 years of fuel, allowing operations to continue far into the 2040s.

"We're cracking open an entirely new window on the universe," says Hammel. "That's just a really exciting moment to be a part of, for us as a species." ■

Jonathan O'Callaghan is a freelance space journalist based in the UK.

"When you're dealing with something this new and this unknown, things should be checked 10 or 100 times. That's not how things went."

PREVIOUS AND OPPOSITE: NASA, ESA, CSA, STSCI

A new US innovation narrative

Legislation investing hundreds of billions into industry and R&D could reset how we think about government's role in the economy.

By David Rotman

It was the perfect political photo op. The occasion was the September groundbreaking for Intel's massive $20 billion chip manufacturing complex in the suburbs of Columbus, Ohio. Backhoes dotted a construction site that stretched across hundreds of flat, empty acres. At a simple podium with the presidential seal, Joe Biden talked about putting an end to the term "Rust Belt," a name popularized in the 1980s in reference to the Midwest's rapidly declining manufacturing sector.

It was a presidential victory lap after the passage of some landmark US legislation, beginning with the infrastructure bill in late 2021. Together, three major bills promise hundreds of billions in federal investments to transform the nation's technology landscape. While ending the Rust Belt might be typical political hyperbole, you get the point: the spending spree is meant to revive the country's economy by rebuilding its industrial base.

The dollar amounts are jaw-dropping. The bills include $550 billion in new spending over the next five years in the Infrastructure Investment and Jobs Act, $280 billion in the CHIPS and Science Act (which prompted Intel to go ahead on the Ohio construction), and another roughly $390 billion for clean energy in the Inflation Reduction Act. Among the investments is the most aggressive federal funding for science and technology in decades. But the greatest long-term impact of the legislative flurry could come from its bold embrace of something that has long been a political third rail in the US: industrial policy.

That means deliberate government interventions, including financial incentives and investments, favoring growth in particular industries or technologies—say, for national security reasons or to address problems such as climate change. Think of US support for semiconductor manufacturing in the 1980s or the creation during the Cold War of the Defense Advanced Research Projects Agency (DARPA), which led to the internet and GPS.

MANUEL BALCE CENETA/AP IMAGES

But for decades now, free-market advocates have disparaged industrial policy as a foolhardy attempt to pick economic winners. Since the early 1980s and the era of Ronald Reagan, US politicians and many mainstream economists have disdained it. In reality, it never completely went away. President Obama toyed with elements of it in trying to revive manufacturing in the US after the 2008 recession; President Trump turned to it in his Operation Warp Speed to mobilize industry around covid vaccine development. But for the most part, it has seemed foreign to US political thinking: it was something China does, something Japan, South Korea, and France used to do (remember the Concorde?).

The US has effective and productive free markets. And, of course, we have Silicon Valley, our own engine of economic growth, propelling the economy forward. All we need to do is unleash that engine by loosening regulations and cutting taxes. Or so the dominant narrative went.

That narrative began crumbling long before the covid-19 pandemic made clear the need for the government to help bolster critical industrial sectors and supply chains. An unblinking faith in free markets has led to globalization, helping to gut many of the country's industries, particularly in manufacturing. For a while, the economic argument was that it didn't matter where you made stuff; cheap commodities were good for living standards, and the country should focus on high-tech growth.

The problem is that high-tech growth has been limited, anemic, and unevenly distributed. Income inequality has climbed to high levels. The Rust Belt and other sections of the middle of the country keep getting rustier. Despite impressive advances in artificial intelligence and other areas of high tech, the nation's prosperity has largely benefited people in only a few regions; notably, experts have begun identifying a handful of superstar cities, including San Francisco, Seattle, and Boston, that are booming while the rest of the country suffers. Perhaps most telling, growth of productivity—particularly the kind related to innovation, called total factor productivity—has been sluggish for several decades now in the US and many other rich countries.

I wrote about the failure of technologies such as social media and artificial intelligence to boost productivity growth in the mid-2010s, in an essay titled "Tech slowdown threatens the American Dream." Since then, the situation hasn't gotten any better, roiling US politics and fueling a mood of economic malaise.

What's changed now is that the new legislation, which passed with some degree of bipartisan support in Congress, signals a strong appetite across the political spectrum for the US government to reengage with the country's industrial base. After decades of declining federal investment in R&D, which dropped from 1.2% of GDP in the late 1970s to below 0.8% in recent years, the CHIPS and Science Act alone authorizes some $174 billion for research at places like the National Science Foundation.

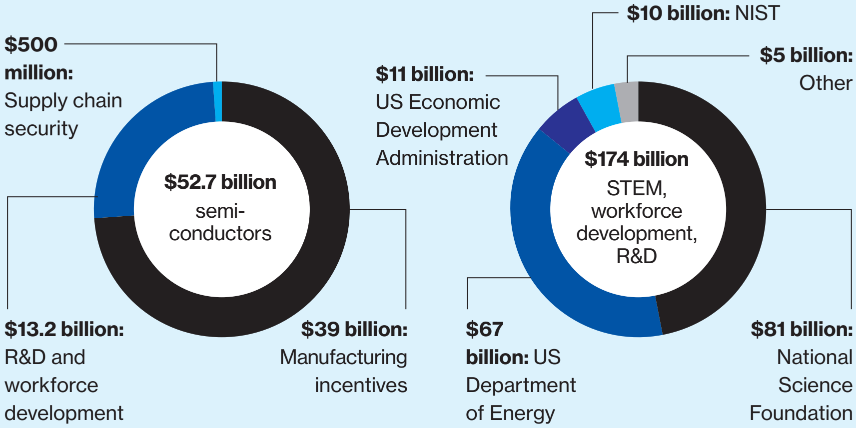
Part of the reason the legislation received such broad support is that the funding provisions are a bit of Rorschach test. Some see measures to defend critical national technology businesses like chip production against the threat from China, and to make sure we don't lose the global race in areas such as AI and quantum computing. Others see green jobs and efforts to address climate change, and a return to the post–World War II recognition that investing in science and research is critical to economic well-being.

Still, despite the differences in motivation, the federal government's willingness to embrace hawkish industrial policy is at least providing a chance to rethink the role the state plays in innovation. "It's not just an opportunity—it's a necessity," says Dan Breznitz, the Peter J. Munk professor of Innovation Studies at the University of Toronto and co-director of its Innovation Policy Lab. After decades, he says, it's time the US government got back in the game of "understanding the importance of merging innovation strategy with industrial policy."

Likewise, the European Union, South Korea and Japan, countries in the Middle East, and various other members of the Organization for Economic Cooperation and Development are all "back on the industrial-policy bandwagon," says Dani Rodrik, an economist at Harvard. "It's not like industrial policy ever went away," says Rodrik, "but now it's at the center of the conversation." Instead of being

CHIPS and Science Act

The bill authorizes nearly $280 billion in spending, including some $52 billion for US semiconductor manufacturing and research, plus $174 billion for scientific R&D and technology commercialization.

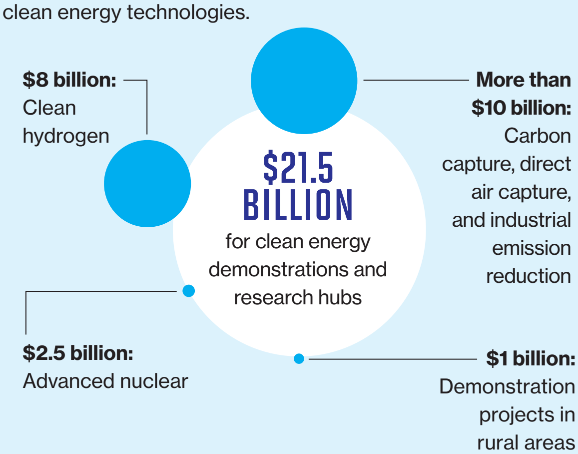


SOURCES: US CONGRESS, MCKINSEY & COMPANY, THE WHITE HOUSE embarrassed by the topic, he says, politicians are now touting it as a strategy.

For economists like Diane Coyle, an expert on productivity and the emerging digital economy, the need for industrial policy to promote targeted growth is obvious at a time when productivity is stagnant, climate change is reaching a crisis point, and the rapid digitalization of the economy is worsening inequality. "We absolutely do need industrial policy in the kind of economy we have now," says Coyle, the co-director of the Bennett Institute for Public Policy at the University of Cambridge. "But the catch, of course, is it's difficult to do, and governments often don't do it well."

Infrastructure Investment and Jobs Act

The legislation passed in late 2021 authorizes $550 billion in new spending for everything from roads to broadband access. Included in the massive bill is generous funding for scaling up clean energy technologies.



SOURCE: US DEPT. OF ENERGY

What about Solyndra?

The well-worn critique that industrial policy asks governments to pick winners, something they aren't particularly good at, doesn't really hold up to scrutiny. For every Solyndra (a solar company that received a half-billion-dollar federal loan guarantee before flaming out, and the favorite example of a disastrous losing pick), there is a Tesla—funded around the same time by a federal loan. But the criticism does have some truth to it; industrial policy requires, well, policies. It requires choices.

The US legislation passed over the last year is really a series of different industrial and innovation strategies. There's a classic industrial policy that singles out support to the chip industry; a green industrial policy in the Inflation Reduction Act (which is often called the climate bill) that broadly favors specific types of companies such as EV manufacturers; and other spending choices and policies scattered throughout the bills that aim to create new jobs. Arguably the most important provisions, at least according to some economists, are those designed to boost federal support for R&D.

There is no obvious, coherent vision tying it all together.

For now, says David Victor, a professor of innovation and public policy at the University of California, San Diego, that's fine. "It's more like industrial policy à la carte," he says. It's based on what is politically possible, appeasing different interests, from labor to industry to climate activists. Now, says Victor, "we need to turn it into as effective industrial policy as possible."

One challenge will be dealing with potentially conflicting priorities. For example, the climate bill's generous tax incentives for electric vehicles come with a few stipulations. The EVs must be assembled in North America. What's more, the battery components must be made or assembled in North America and the critical metals going into the batteries must be mined in the US or by its free-trade partners. That might boost long-term domestic manufacturing, creating jobs and building more reliable supply chains, but it also could create a bottleneck in EV production. If that happens, it could slow down efforts to reduce carbon emissions.

Various other trade-offs and choices loom as the country ramps up its technology investments. To help make better choices, Erica Fuchs, a professor of engineering and public policy at Carnegie Mellon, and her collaborators have started a pilot project, funded by the NSF, that will use advanced data analysis and cross-disciplinary expertise from a team of university researchers to better inform policy makers on technology decisions.

Called the National Network for Critical Technology Assessment, it's meant to provide useful information on different options to meet various geopolitical and economic objectives. For example, given US dependency on China for lithium and the Democratic Republic of the Congo for cobalt, and given the risks of those supply chains, what is the potential value of innovations in battery recycling, alternative battery chemistries (such as ones that don't use cobalt), and alternative extraction technologies? Likewise, there are questions around what parts of domestic battery manufacturing are most important for creating US jobs.

While much analysis has already gone into writing the legislation, says Fuchs, many more questions will come up as the government attempts to spend the allocated funds to best realize legislative goals. She hopes the project will eventually lead to a larger network of experts from academia, industry, and government that provide the tools to clarify and quantify opportunities emerging from US innovation policies.

A new story

Any new narrative that the government can promote innovation and use it to foster economic prosperity is still very much a work in progress. It's not yet clear how the various provisions in the different pieces of legislation will play out. Perhaps most worrisome, the large jumps in funding for R&D in the CHIPS and Science Act are simply authorizations—recommendations that Congress will need to work into the

Inflation Reduction Act

The legislation provides nearly $400 billion for clean energy, much of it in tax credits for consumers and businesses. According to McKinsey, here are a few financial incentives to lower emissions.

$4,000
consumer tax credit for purchase of a used electric vehicle

$3
per kilogram for the production of clean hydrogen

$2,000
consumer tax credit (per year) for the purchase of heat pumps, heat pump water heaters, biomass stoves, and boilers

$15
per megawatt-hour for power produced at a qualifying nuclear facility

SOURCE: MCKINSEY & COMPANY

budget anew every year. A switch in political mood could quickly kill the funding.

But perhaps the greatest unknown is how the federal funding will affect local economies and the welfare of millions of Americans who have suffered decades of lost manufacturing and declining job opportunities. Economists have long argued that technological advances are what drive economic growth. But over the last few decades, the prosperity resulting from such advances has been largely restricted to a few high-tech industries and has mostly benefited a relatively small elite. Can the public once again be convinced that innovation can lead to widespread prosperity?

One worry is that while the recent legislation strongly supports semiconductor manufacturing and assorted clean technologies, the bills do little to create good jobs where they are most needed, says Harvard's Rodrik. "In terms of bang for the buck," he says, investing in advanced manufacturing and semiconductors "is one of the least effective ways of creating good jobs." There is, he says, a "kind of manufacturing nostalgia" and a belief that rebuilding this sector will bring the middle class back. But that's illusory, he says, since today's advanced manufacturing is highly automated, and facilities tend to employ relatively few workers.

Rodrik proposes what he calls an industrial policy for good jobs that would move beyond manufacturing and target the service sector, where by far the most jobs are in the US. His plan calls for investing in new technologies and companies that would improve productivity in jobs long thought of as low-skilled. For example, he points to opportunities to increase the capabilities of people working in long-term care, an area that is exploding as the population ages, by giving them digital tools.

We also need to drop the pretensions around Silicon Valley's role in creating widespread prosperity. A little more than six years ago, I wrote an essay titled "Dear Silicon Valley: Forget flying cars, give us economic growth." Even with the advent of AI and driverless cars, economists were fretting over slow productivity growth. The inability of those in Silicon Valley to develop and commercialize the types of technologies and innovations that produce growth across a broad swath of the economy was clear.

The tech industry gave us Zoom to survive the pandemic, and Amazon went on a hiring spree, but none of this led to a widespread economic expansion. We're still waiting for the long-anticipated economy-wide productivity boom from AI. These days, I would tweak the message: Forget about Silicon Valley and look elsewhere for economic transformation.

If not Silicon Valley and other centers of innovation, where will that transformation come from? Though federal legislation has kick-started the discussion about industrial policy and innovation strategies, any real change will have to happen through efforts by cities and states. Each city, says Breznitz of the University of Toronto, will need to figure things out for itself, creating innovation strategies that work for its people on the basis of its industrial base, educational resources, and type of workforce. And, he admonishes, cities need to stop pinning their hopes on an elusive high-tech strategy modeled on Silicon Valley.

"Two hundred cities in the US are all trying to look like Silicon Valley," Breznitz says, adding, "I don't know why. Maybe they've never been to Silicon Valley?"

A key, he says, is recognizing that inventions are just one stage of innovation. Local governments need to support what he calls continuous innovation by helping local companies and industries offer improved and cheaper products and services. It might not be as glamorous as coming up with a novel idea for a radical new business, but it's how most companies and regions become more productive and localities prosper.

Creating a convincing narrative that large parts of the country buy into will take time. But that, says UCSD's Victor, is precisely the point of industrial policy: "You begin to change the facts on the ground. You create new industries and jobs. And then the politics shift."

Before that happens, of course, lots can go wrong. Successful industrial policy depends on consistent and disciplined choices by politicians. You can decide for yourself whether you think they will manage that.

But one reason for renewed optimism is that today's technologies, especially artificial intelligence, robotics, genomic medicine, and advanced computation, provide vast opportunities to improve our lives, especially in areas like education, health care, and other services. If the government, at the national and local level, can find ways to help turn that innovation into prosperity across the economy, then we will truly have begun to rewrite the prevailing political narrative. ■

David Rotman is editor at large of MIT Technology Review.

Inside the country's long experiment in automating elder care.

By James Wright

Are robots the solution to Japan's care crisis?

Japan is a pioneer in care automation. Well-known devices include the prototype lifting robot Robear (left) and Pepper (right), an interactive humanoid robot.

It's a picture you may have seen before: a large white robot with a cute teddy bear face cradling a smiling woman in its arms. Images of Robear, a prototype lifting robot, have been reproduced endlessly. They still hold a prominent position in Google Image search results for "care robot." The photos seem designed to evoke a sense of how far robots have come—and how we might be able to rely on them in the near future to help care for others. But devices such as Robear, which was developed in Japan in 2015, have yet to be normalized in care facilities or private homes.

Why haven't they taken off? The answer tells us something about the limitations of techno-solutionism and the urgent need to rethink our approach to care.

Japan has been developing robots to care for older people for over two decades, with public and private investment accelerating markedly in the 2010s. By 2018, the national government alone had spent well in excess of $300 million funding research and development for such devices. At first glance, the reason for racing to roboticize care may seem obvious. Almost any news article, presentation, or academic paper on the subject is prefaced by an array of anxiety-inducing facts and figures about Japan's aging population: birth rates are below replacement levels, the population has started to shrink, and though in 2000 there were about four working-age adults for every person over 65, by 2050 the two groups will be near parity. The number of older people requiring care is increasing rapidly, as is the cost of caring for them. At the same time, the already large shortage of care workers is expected to get much worse over the next decade. There's little doubt that many people in Japan see robots as a way to fill in for these missing workers without paying higher wages or confronting difficult questions about importing cheap immigrant labor, which successive conservative Japanese governments have tried to curtail.

KYODO/AP IMAGES (ROBEAR); CHRIS WILLSON/ALAMY

A growing body of evidence is finding that robots tend to end up creating *more* work for caregivers.

Paro, a fuzzy animatronic seal, is intended to provide a robotic form of animal therapy.

KIM KYUNG HOON/REUTERS/ALAMY

Care robots come in various shapes and sizes. Some are meant for physical care, including machines that can help lift older people if they're unable to get up by themselves; assist with mobility and exercise; monitor their physical activity and detect falls; feed them; and help them take a bath or use the toilet. Others are aimed at engaging older people socially and emotionally in order to manage, reduce, and even prevent cognitive decline; they might also provide companionship and therapy for lonely older people, make those with dementia-related conditions easier for care staff to manage, and reduce the number of caregivers required for day-to-day care. These robots tend to be expensive to buy or lease, and so far most have been marketed toward residential care facilities.

In Japan, robots are often assumed to be a natural solution to the "problem" of elder care. The country has extensive expertise in industrial robotics and led the world for decades in humanoid-robot research. At the same time, many Japanese people seem—on the surface, at least—to welcome the idea of interacting with robots in everyday life. Commentators often point to supposed religious and cultural explanations for this apparent affinity—specifically, an animist worldview that encourages people to view robots as having some kind of spirit of their own, and the huge popularity of robot characters in manga and animation. Robotics companies and supportive policy makers have promoted the idea that care robots will relieve the burden on human care workers and become a major new export industry for Japanese manufacturers. The title of not one but two books (published in 2006 and 2011 and written by Nakayama Shin and Kishi Nobuhito, respectively) sums up this belief: *Robots Will Save Japan*.

The reality, of course, is more complex, and the popularity of robots among Japanese people relies in large part on decades of relentless promotion by state, media, and industry. Accepting the idea of robots is one thing; being willing to interact with them in real life is quite another. What's more, their real-life abilities trail far behind the expectations shaped by their hyped-up image. It's something of an inconvenient truth for the robot enthusiasts that despite the publicity, government support, and subsidies—and the real technological achievements of engineers and programmers—robots don't really feature in any major aspect of most people's daily lives in Japan, including elder care.

A major national survey of over 9,000 elder-care institutions in Japan showed that in 2019, only about 10% reported having introduced any care robot, while a 2021 study found that out of a sample of 444 people who provided home care, only 2% had experience with a care robot. There is some evidence to suggest that when robots are purchased, they often end up being used for only a short time before being locked away in a cupboard.

My research has focused on this disconnect between the promise of care robots and their actual introduction and use. Since 2016, I have spent more than 18 months conducting ethnographic fieldwork in Japan, including spending time at a nursing care home that was trialing three of them: Hug, a lifting robot; Paro, a robotic seal; and Pepper, a humanoid robot. Hug was meant to prevent care workers from having to manually lift residents, Paro to offer a robotic form of animal therapy (while also acting as a distraction aid for some people with dementia who made repeated demands of staff throughout the day), and Pepper to run recreational exercise sessions so that staff would be freed for other duties.

But problems quickly became apparent. Staff stopped using Hug after only a few days, saying it was cumbersome and time consuming to wheel from room to room—cutting into the time they had to interact with the residents. And only a small number of them could be lifted comfortably using the machine.

Paro was received more favorably by staff and residents alike. Shaped like a fluffy, soft toy seal, it can make noises, move its head, and wiggle its tail when users pet and talk to it. At first, care workers were quite happy with the robot. However, difficulties soon emerged. One resident kept trying to "skin" Paro by removing its outer layer of synthetic fur, while another developed a very close attachment, refusing to eat meals or go to bed without having it by her side. Staff ended up having to keep a close eye on Paro's interactions with residents, and it didn't seem to reduce the repetitive behavior patterns of those with severe dementia.

Pepper was used to run recreation sessions that were held every afternoon. Instead of leading an activity like karaoke or having a conversation with residents, a care worker would spend some time booting up Pepper and wheeling it to the front of the room. It would then come to life, playing some upbeat music and a prerecorded presentation in its chirpy voice, and launch into a series of upper-body exercises so the residents could follow along. But care workers quickly realized that to get residents to participate in the exercise routine, they had to stand next to the robot, copying its movements and echoing its instructions. Since there was a relatively small set of songs and exercise routines, boredom also started to set in after a few weeks, and they ended up using Pepper less often.

In short, the machines failed to save labor. The care robots themselves required care: they had to be moved around, maintained, cleaned, booted up, operated, repeatedly explained to residents, constantly monitored during use, and stored away afterwards. Indeed, a growing body of evidence from other studies is finding that robots tend to end up creating *more* work for caregivers.

But what was interesting was the type of work that they created. Whereas previously care workers came up with their own recreational activities, now they just had to copy Pepper. Instead of conversing and interacting with residents, now they could give them Paro to play with and monitor the interaction from a distance. And where workers who had to lift a resident had used the occasion to have a chat and build their relationship, those using the Hug machine had to shorten the interaction so they'd have time to wheel the robot back to where it was stored. In each case, existing social and communication-oriented tasks tended to be displaced by new tasks that involved more interaction with the robots than with the residents. Instead of saving time for staff to do more of the human labor of social and emotional care, the robots actually reduced the scope for such work.

What kind of future do such devices point to, and what would it take for them to become a "solution" to the care crisis? Bearing in mind the imperative to control costs, it seems that the most likely scenario for wide-scale use of such robots in residential care would involve—unfortunately—employing more people with fewer skills, who would be paid as little as possible. Care facilities would likely need to be much larger and highly standardized to enable economies of scale that could

Care crises aren't the natural or inevitable result of demographic aging. Instead, they are the result of specific political and economic choices.

The robot Hug is designed to assist care workers in lifting people, a demanding physical job.

make the cost of robotic devices affordable, since they are generally expensive to buy or lease even with government subsidies. Because workers might not have to interact with residents as much and could theoretically get by with less care training, experience, and facility with the Japanese language, they could potentially be brought in more easily from abroad. In fact, such a vision might already be in the works: migration channels in Japan have been rapidly opened up over the past few years as concern has grown about the country's labor shortages, and consolidation in the care industry has been accelerating.

Such a scenario may eventually make some kind of financial sense, but it seems far from many people's understanding of what constitutes good care—or decent work. In the words of roboticist and professor of robot ethics Alan Winfield, talking about the wider application of AI and robots: "The reality is that AI is in fact generating a large number of jobs already. That is the good news. The bad news is that they are mostly crap jobs … It is now clear that working as human assistants to robots and AIs in the 21st century is dull, and both physically and/or psychologically dangerous … these humans are required to behave, in fact, as if they are robots."

Interest in care robots continues. The European Union invested €85 million ($103 million) in a research and development program called "Robotics for Ageing Well" in 2015–2020, and in 2019, the UK government announced an investment of £34 million ($48 million) in robots for adult social care, stating that they could "revolutionize" the care system and highlighting Paro and Pepper as successful examples.

But care is not simply a logistical matter of maintaining bodies. It is a shared social, political, and economic endeavor that ultimately relies on human relationships. Likewise, care crises aren't the natural or inevitable result of demographic aging, as is often suggested by crisis narratives used to explain and promote care robots. Instead, they are the result of specific political and economic choices.

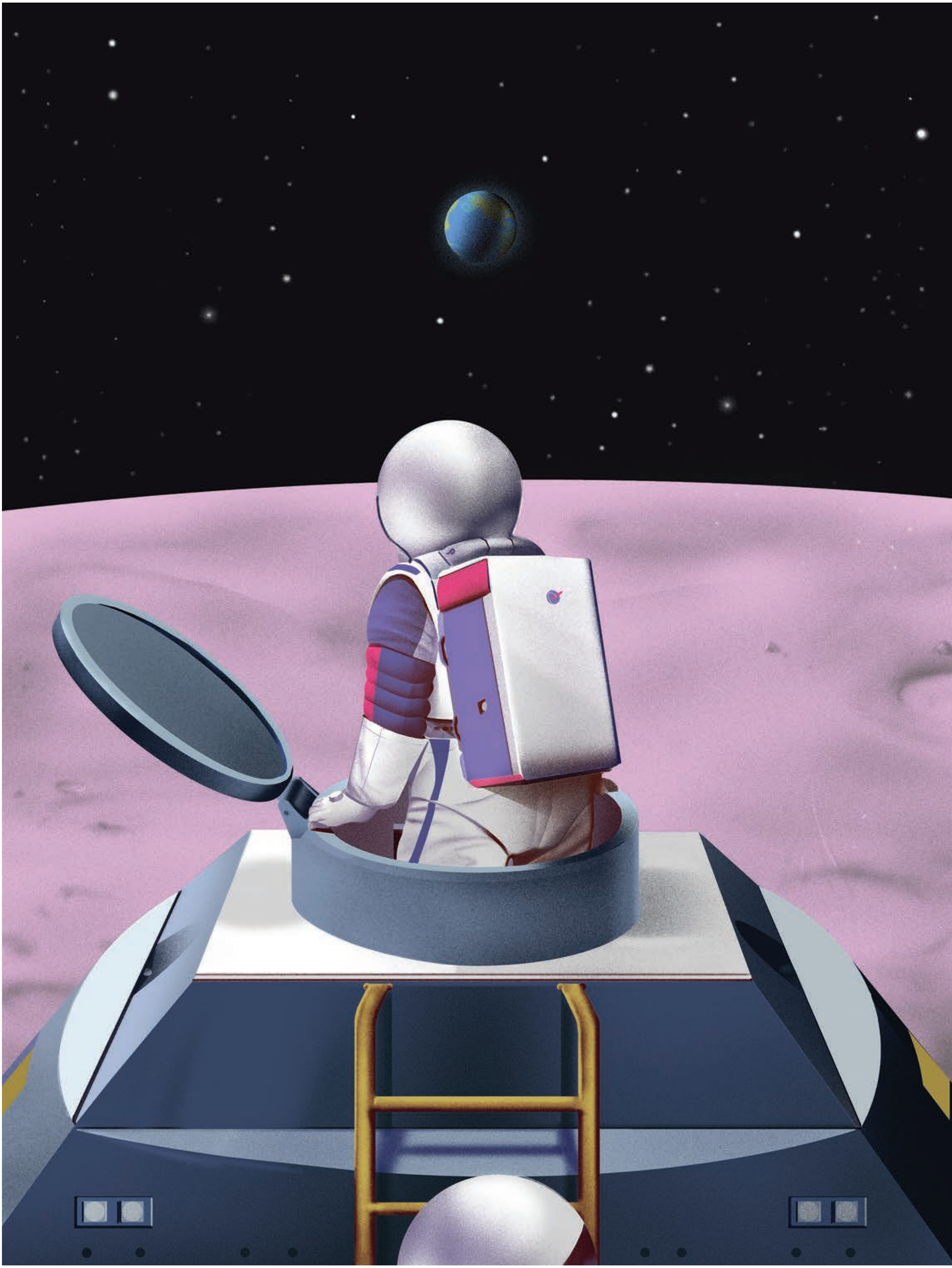
While care robots are technologically sophisticated and those promoting them are (usually) well intentioned, they may act as a shiny, expensive distraction from tough choices about how we value people and allocate resources in our societies, encouraging policy makers to defer difficult decisions in the hope that future technologies will "save" society from the problems of an aging population. And this is not even to mention the potentially toxic and exploitative processes of resource extraction, dumping of e-waste in the Global South, and other negative environmental impacts that massively scaling up robotic care would entail.

Alternative approaches are possible and, indeed, readily available. Most obviously, paying care workers more, improving working conditions, better supporting informal caregivers, providing more effective social support for older people, and educating people across society about the needs of this population could all help build more caring and equitable societies without resorting to techno-fixes. Technology clearly has a role to play, but a growing body of evidence points to the need for far more collaboration across disciplines and the importance of care-led approaches to developing and deploying technology, with the active involvement of the people being cared for as well as the people caring for them.

Like many depictions of robots, the images of Robear conceal as much as they reveal. Robear was an experimental research project never actually used in a care home setting, being too impractical and expensive for real-life deployment. The project has long since been retired, and its inventor has claimed that it was not a solution to the problems facing the care industry in Japan; he said migrant labor was a better answer. Since my fieldwork ended, Pepper too has been discontinued. But such robots continue to have a long afterlife, particularly in online media—projecting and maintaining a techno-orientalist image of a futuristic Japan. This may in fact be their most successful role to date. ■

James Wright is a research associate at the Alan Turing Institute and the author of Robots Won't Save Japan: An Ethnography of Eldercare Automation.

COURTESY OF FUJI CORPORATION



By Rebecca Boyle
Illustration by Richard Chance

Lumbering back to the lunar surface

The US is relying on relics from the shuttle program to get astronauts back to the moon. It's a rough start.

It was December 14, 1972, the final day on the moon for the last Apollo mission. The *Challenger* lander was dusted in a fine coating of gray lunar dirt, called regolith, both inside and out. Geologist Jack Schmitt was packing the sample containers, securing 243 pounds of rocks to bring home. After passing Schmitt the last science instruments, commander Eugene Cernan took a final look at the landscape before climbing into the spacecraft behind him.

"As we leave the moon," Cernan radioed to Houston, "we leave as we came, and God willing as we return, with peace and hope for all mankind." He ascended the ladder, leaving the last set of bootprints on the moon, on a valley between a range of low mountains and soft sculptured hills.

Five decades later, NASA has a plan to send astronauts back to the lunar surface. Called Artemis, after the sister of Apollo in Greek mythology, the project aims to visit a new area of the moon and retrieve new samples, this time with new faces behind the sun visors—including the first woman and first person of color.

Whether this plan will succeed—and whether a fresh moon landing will inspire a new "Artemis generation" in space exploration, as NASA leadership hopes—is a matter of debate. The differences between Artemis and the Apollo program, which itself fizzled out sooner than many had hoped, are certainly stark. Artemis is built on a less exact, less nimble, and much less well-heeled vision of space exploration than the one that launched Cernan and his predecessors. Where Apollo was conceived and executed as a high-priced monument to American ingenuity and the power of capitalism, its sister program is more a reflection of American politics and the power of inertia.

Though the program is officially only three years old, elements of Artemis have been in the works for many years, even decades. Its ancillary projects, spread throughout NASA and at university partners across the US, in many cases existed long before the Trump administration gave the program a name. Its origins were rocky even before fueling problems and two hurricanes delayed its first launch in November.

Artemis has many disparate purposes, serving very different groups. For some space enthusiasts, it's simply a way back to the moon, a destination that will always loom largest in our collective consciousness. For others, it represents a path to Mars. Some see Artemis as a way to reclaim American superiority in space, something that was most visibly lost when the space shuttle retired in 2011. Still others see it as a means to unlock a new era of scientific discovery and invention, first undertaken during Apollo but arguably begun the first time humans looked at the moon and wondered what it was.

The project's first mission, an uncrewed test flight called Artemis 1, thundered to space in the middle of the night on November 16. It was carried into space by the most powerful rocket ever launched, the Space Launch System (SLS). Towering 15 feet taller than the Statue of Liberty, the SLS consists of an orange main tank flanked by white boosters that make it resemble the space shuttle, its progenitor in both propulsion and programmatic style. After multiple missed deadlines and criticism from Congress, multiple White House occupants, and NASA's own auditors, space exploration fans and scientists were amped to go back to the moon.

But overshadowing Artemis is the uncomfortable fact that the rocket, not the moon missions it will carry, has long been the primary goal of NASA's human spaceflight program. Where exactly that rocket is going has always been secondary—and the destination has changed multiple times. If something goes wrong, or if SLS is deemed too expensive or unsustainable, there's a chance the entire moon program will fail or at least be similarly judged. This is a wobbly, uncertain start to an effort to return humans to the lunar surface for the first time in a half-century—and could make that return, if it does happen, a very brief one.

Overshadowing Artemis is the uncomfortable fact that the rocket, not the moon missions it will carry, has long been the primary goal of NASA's human spaceflight program.

On February 1, 2003, the skies over Texas flashed with what appeared to be a daytime meteor shower. The bright objects were pieces of the space shuttle *Columbia*, which had broken apart during its 28th reentry through Earth's atmosphere. As the nation mourned the shuttle's seven crew members, President George W. Bush began work on a new way forward for NASA.

Artemis has its roots in that effort. In January 2004, less than a year after the *Columbia* disaster, Bush announced a Vision for Space Exploration—a reimagining of the space program that called for retiring the shuttle by 2011, scuttling the International Space Station by 2016, and replacing them with a new program called Constellation. Constellation would consist of a new, configurable rocket capable of launching to the moon or even to Mars, named Ares; a new crew vehicle for low Earth orbit, called Orion; and a new lunar lander, named Altair.

But Constellation never coalesced into anything more than a collection of ideas. By the time Barack Obama became president in 2009, the program was already years behind schedule. Obama convened another commission, led by former Lockheed Martin CEO Norman Augustine, to study Constellation. The Augustine Committee judged the project too expensive and underfunded to ever succeed—a fatal combination that watchdogs said would jeopardize other NASA missions. The Obama administration zeroed out the funding for the project, effectively thwarting the nation's moonward trajectory once again.

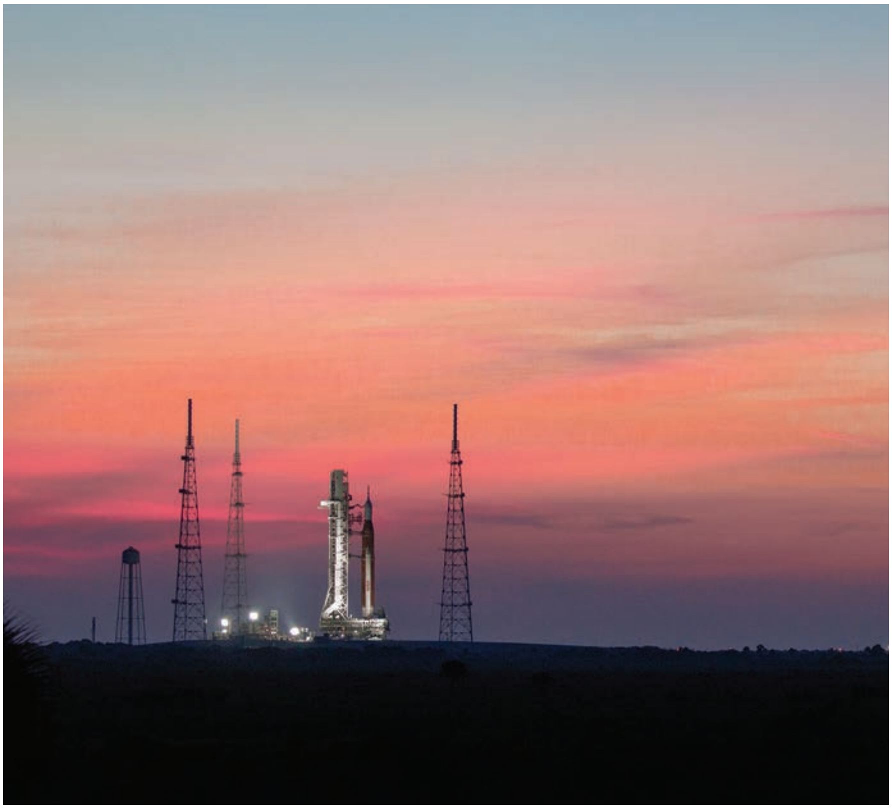
"Everybody who was willing to talk to you about it acknowledged there wasn't any money planned to go into the big rocket or the lunar lander until after the space station was retired," recalls Lori Garver, who was deputy administrator at NASA when Constellation fell on the chopping block. "It was just a shell."

Shortly after the program got the ax, however, members of Congress insisted on funding the rocket anyway, eager to keep the jobs attached to the effort after the shuttle era ended. Though it was not part of the White House's budget request, Congress holds the nation's purse strings and had the power to hand out lucrative contracts to legacy companies like Lockheed and Boeing.

Obama administration officials scrambled to find a place to send the rocket they were given. They decided on an asteroid. The rocket would be used to retrieve one with a robotic spacecraft, which would tug it closer to Earth for a human landing. "It got funded as a rocket to nowhere, and we at NASA had to figure out something to do with it," Garver says. The rocket (which was rebranded as the Space Launch System) and the Asteroid Redirect Mission both chugged along separately for the next few years, though many scientists and engineers criticized the asteroid program. The rocket's first uncrewed launch was initially scheduled for 2016. Launch dates continually slipped in the following six years.

In the meantime, thanks in part to another program supported by President Obama, the space industry was blossoming. Elon Musk's SpaceX developed its reusable Falcon 9 rocket (and later its own large rocket, the Falcon Heavy), launching military and civilian satellites for the government. In 2020, the company began

NASA's Space Launch System (SLS) rocket, with the Orion spacecraft aboard, is seen at sunrise atop the mobile launcher.



NASA/JOEL KOWSKY

carrying up astronauts, restarting the ability to send humans into space from US soil. Other private companies, including Jeff Bezos's Blue Origin, started launching civilians, mainly celebrities and tourists, into space. Meanwhile, NASA engineers continued toiling with space shuttle technology. Legacy contractors like Boeing continued to receive large bonus payments for working on the SLS, despite delays and mushrooming costs—drawing criticism from congressional watchdog groups and NASA auditors.

Shortly after Donald Trump took office in 2017, the much-maligned asteroid program was canceled. Trump's team tried to cancel the rocket too, but the effort was blocked by powerful senators, especially Richard Shelby of Alabama, who chaired the Senate Appropriations Committee and was SLS's chief champion (prompting some to call it the "Senate Launch System"). So the rocket remained—with no destination until 2019, when Trump's NASA administrator, James Bridenstine, announced Artemis, a series of missions to orbit the moon, land on its surface, and begin building a permanent settlement. The first crewed mission is scheduled to loop around the moon in 2024, and the first Artemis landing is currently scheduled for 2025.

The scientific and cultural payoff for a lunar return could be huge. Scientists have many lingering questions about the moon's formation, and Earth's early history, that may be answerable with fresh samples from the lunar far side. Researchers are already preparing a flotilla of instruments and robotic experiments to fly on Artemis-adjacent private landers, funded through the Commercial Lunar Payload Services program, which may pave the way for a return to the moon that distributes risk and reward between NASA and private industry.

NASA's public-facing descriptions of Artemis talk about "going forward" to the moon, not going back. Much of the rhetoric around the moon return includes an eventual trip to Mars as well. Agency officials often say that going back to the moon will teach us how to live and work on another world, paving a path for eventual human exploration of the Red Planet.

Among those preparing for the lunar return is Chris Dreyer, a mechanical engineering professor at the Colorado School of Mines. Dreyer is leading a NASA-funded project studying lunar construction. His team is designing an autonomous moon bulldozer, which would scoop and flatten regolith to prepare a construction site for a landing pad. Artemis landers, which will be built by SpaceX, will be heavier and taller than the spindly Apollo lunar modules, which is why they will need a landing pad; otherwise, the strength of their own exhaust would reshape the ground beneath them, blowing regolith about like the powdered sugar on a doughnut. A landing pad will ensure that landers won't tip over as they set down.

"If you look through all of Apollo, you realize every landing was a bit of an adventure in avoiding boulder fields. Everything was just at the limit of what was possible," Dreyer says. "We could go back and do that again, but it wouldn't advance anything. Part of Artemis is about advancing living and working in space, and I see this construction as part of that."

Artemis will make those advances slowly. The rocket is scheduled to launch once every year and a half; critics argue that momentum and public support could wane with such long waits between launches. Previous exploration programs have faced dwindling interest over time. Apollo's fast and furious pace ensured that the first landing happened within just eight years, but by the sixth Apollo landing, Americans had begun arguing for spending on domestic programs instead. By the 25th shuttle mission, NASA tried to inject new excitement by putting a teacher on board. Christa McAuliffe was killed along with six other crew members when the space shuttle *Challenger* was destroyed just over a minute after it launched in January 1986.

Critics of the Space Launch System argue that the rocket is unsustainable by design, relying on an old and potentially quite expensive way to get to space. Much of SLS is a holdover from the space shuttle.

NASA had 16 leftover shuttle main engines, 14-foot-long cones that were clustered in trefoil arrays on the bottom end of the shuttle orbiters. Those will be repurposed to power SLS. But while the shuttle orbiter, engines, and external tanks were designed to be reusable, SLS and its engines were not. The first Artemis flight used old shuttle engines; the next planned launches will use others. But after that, new engines will be needed. Aerojet Rocketdyne has a $1.79 billion contract to begin building more, starting with the as-yet-unplanned Artemis 5 mission.

"They've designed a rocket that is basically unsustainable, because it's completely throwaway. The only bit that comes back is Orion," says Clive Neal, a lunar geologist at Notre Dame and an outspoken critic of NASA's moon plans. "I get incredibly frustrated."

NASA argues that it is using the most-tested rocket engines in history, and that recycling them for the moon saves money. But not that much money, it turns out. In early 2022, NASA's inspector general told Congress that the first three flights of the SLS would cost $4.1 billion apiece, a level he called "unsustainable." NASA and Boeing later said the price tag would be lower, and outside analysts have said each launch would cost between $876 million and $2 billion, depending on how you break down overhead costs.

"Depending on how you look at it, the SLS is either a product of a broken system that curries favor to wealthy industries or an example of representative democracy working as it should," wrote Casey Dreier, chief advocate and senior space policy advisor at the Planetary Society, in a recent essay.

There is something indefinable and awe-inspiring about sending humans to another world. In some sense we share their experience; they are avatars for us all.

There may be alternative ways to return humans to the moon. Several heavy-launch commercial rockets are in development. SpaceX is building a reusable vehicle called Starship, which includes a configuration that is aimed at taking astronauts all the way to the moon; Blue Origin has a reusable rocket called New Glenn; and even legacy rocket builders United Launch Alliance have a huge rocket called the Vulcan Centaur, which is slated to begin launching science instruments and privately funded landers to the moon early this year. Garver says she was surprised that NASA under President Joe Biden chose a version of Starship to take Artemis astronauts to the lunar surface: "It's an acknowledgment that Starship is going to work. And if Starship is going to work, then you don't need SLS and Orion."

Artemis has created jobs in every state and poured research money into dozens of universities. There's a chance the program may survive in pieces even if the rocket doesn't. Previous human space exploration programs were consolidated under one umbrella within NASA, but for Artemis, agency management under Trump instead established a more distributed method for funding different projects. While NASA's inspector general criticized this approach, some observers believe it may make Artemis more sustainable in the long term, and better able to withstand shifting political winds.

As of now, the rocket is not Artemis's only hurdle in a path toward long-term human habitation on the moon. Space travel is still difficult, even when you do it all the time. And going back to the moon is proving to be hard for NASA. Some observers believe a human landing in 2025 is wildly ambitious.

If Artemis were solely about science, NASA would send robots, as it has done with missions to the sun and out to Mars, Jupiter, Saturn, and beyond the edge of the solar system. But the moon still beckons, and the call is for human visitors like Cernan, not just landers and rovers. China and the European Space Agency have set their sights on this achievement too. Robots just aren't enough. "It is fundamentally changing what it means to be human, on some level," says Teasel Muir-Harmony, the Apollo curator at the Smithsonian Air and Space Museum in Washington.

There is something indefinable and awe-inspiring about sending humans to another world. In some sense we share their experience; they are avatars for us all. That may be why, despite criticism of the rocket, it's difficult to find anyone who will say something negative about Artemis. Returning to the moon is a human imperative for some people. "It is a desire written in the human heart," as Bush said, memorializing the *Columbia* crew. The experience will never cease to be amazing, and for space exploration advocates, it will never cease to be a worthy goal.

Artemis, like America itself, is an experiment begun years ago with good intentions. It was flawed from the outset, in part because of those good intentions and in part for more cynical reasons. It was bequeathed to hardworking people who genuinely want something good to come of it but are hamstrung by problems that predate them and may be too fundamental to ever fully fix, at least in the project's current form. Yet it is all we have, for now. The rocket remains funded. The missions are scheduled. NASA says, "We are going." And the moon will be waiting, indifferent to which vehicle we use to get there. ■

Rebecca Boyle is a science journalist based in Colorado Springs. Her first book, Walking with the Moon, is forthcoming from Random House in 2024.

BLOOM

Bloom is one of Rael San Fratello's many experimental structures. Nine feet tall and composed of 840 customized 3D-printed cement blocks, it was inspired by the traditional mud houses of the Tiebele people.

Printing with purpose

Ronald Rael and Virginia San Fratello question the future of architecture through the lens of 3D printing.

Ronald Rael and Virginia San Fratello may have met as graduate students in architecture at Columbia University, but it quickly became clear that "architecture" would prove an inadequate term to describe their eclectic body of work.

As the pair started working together in 2002, they became increasingly aware that "sometimes the forces that enable architecture, chiefly capitalism, can corrupt the architect's social agenda," Rael says. "This became the impetus to rethink how and why architecture should be created."

But it's the restrictions of the discipline that drive them. "We have to create disruptive situations that bring attention to our work—otherwise, no one would ever know who we are or what we do," they say on their website.

With each passing year and each new project, they seem to add another job title to their respective résumés. They're activists and designers, writers and materials scientists. Both are educators (Rael is chair of the Department of Art Practice at the University of California, Berkeley; San Fratello is chair of the Department of Design at San Jose State University). They design software and create companies. As San Fratello puts it, "We're past the time where we are just putting stuff in the world."

To do the sort of work they were interested in doing, they realized, they had to disrupt what was firmly in place. That started in part by challenging conventional construction methods. Rael describes being intrigued by 3D printing back in 2001: "The allure of the technology was the ability to go directly from a digital model to a physical model relatively quickly and with accuracy."

But the expense and complexity of 3D-printing technology at that time made it inaccessible, so they created a solution: Potterware, a browser-based design application that eliminates the need to learn 3D-modeling software. This lowers the bar to entry "so that a middle school student can be up and 3D printing in a day," San Fratello says. "It all speaks to that accessibility. We're interested in making things simple and affordable rather than more complex."

Early on, they realized they had something unique to bring to 3D technology. "We both come from rural backgrounds, growing up outside in the landscape, literally playing in the dirt," says San Fratello. "We were both able to bring our own lived experiences to that—our own connections to the earth and to agriculture. That lived experience combined with these amazing technologies, and that's why our practice is different. We bring our love of earth and literally put it in the printer."

Whether it's a cabin, a brick, a vessel, or an art installation, a constant of their work is its rethinking of natural materials through the lens of technology. A project might be printed from mud, sawdust, salt, or Chardonnay grape skins—all materials that come from the earth. Everything is about experimentation, about asking "Why not?"

The pair would defy any attempts at categorization, however. As they say on their website, "It would be impossible for us to say we have a studio philosophy. We just try to keep making." ■

Allison Arieff is editorial director of print for MIT Technology Review.

MATTHEW MILLMAN; OPPOSITE: KARA BRODGESELL

In 2010, Ron Rael and Virginia San Fratello launched a 3D-printing “make tank” called Emerging Objects, one of many ventures pushing at the boundaries of what it means to build and make things. The scaffolding system next to Rael uses 3-D printed couplings and glass rods salvaged from former solar cell manufacturer Solyndra. At right, San Fratello shows an assortment of her functional 3D printed ceramics.

CASA COVIDA

Casa Covida, located in Colorado's San Luis Valley, is an experiment in combining 3D printing with indigenous and traditional building materials. The pink orb is a lightweight pneumatic roof that can shelter the oculus (below) from rain or snow and help retain heat in the adobe structure.

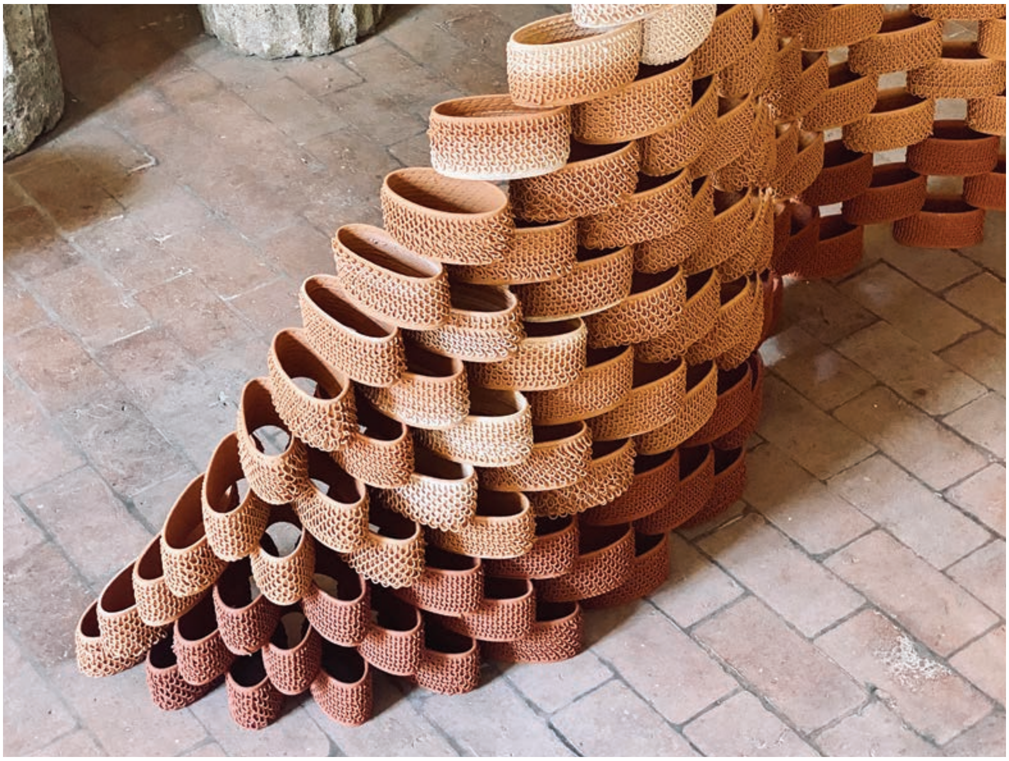
"The biggest reach of the robot arm was to print a circular room," says San Fratello of the form. "It's the most efficient way to print. Turning a corner means you're losing square footage to make straight walls."

TEETER-TOTTER WALL

In 2019, when children were separated from their families at the US-Mexico border, Rael San Fratello installed these pink teeter-totters, allowing residents of El Paso and Juarez to unite through play. It was, they explain, "our form of protest, our way of disrupting the status quo."

FUTURE ARCHAEOLOGY

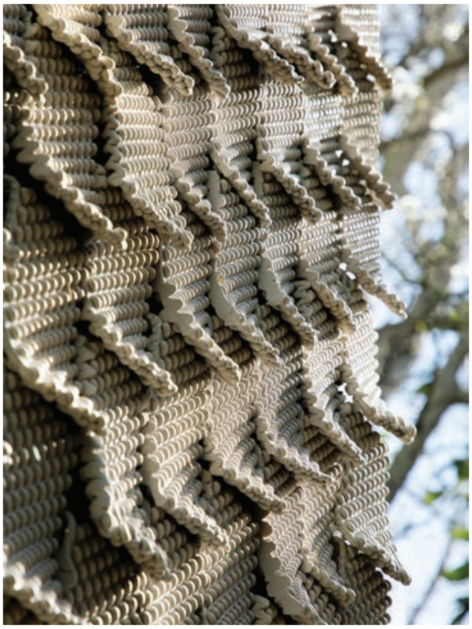
"I imagine this new 3D-printed brick assembly to be a kind of future archaeology or ruin," says San Fratello of her installation in Faenza, Italy, of bricks made from locally sourced clay. It's "already part of something historic but new at the same time."



COURTESY PHOTOS

CABIN OF 3D-PRINTED CURIOSITIES

Emerging Objects' experiments in materials, software, and hardware come together in this prototype dwelling unit. Zoning restrictions were relaxed in response to the Bay Area housing crisis, which inspired the pair to address housing problems at a micro scale.



MATTHEW MILLMAN

What didn't make the list

This year our editors considered more than 50 nominees for our list of 10 Breakthrough Technologies. Here are some we didn't pick.

By Amy Nordrum

GETTY IMAGES

Digital fashion

Fashion brands and designers are now selling digital clothing and accessories in the metaverse and on gaming platforms like Roblox. And people are buying these garments to dress up their virtual avatars, in a new form of online self-expression. The digital fashion market is growing quickly and already influencing real-world trends. But our editors felt other technologies had greater potential to affect more people's lives in a meaningful way.

Next-generation space stations

The International Space Station closes in 2030. What happens after that? NASA will rent space on a private space station, plans for which are now being developed by three separate teams. China has its own space station, and Russia says it will launch one too. But since many of the plans are still preliminary and it's not yet clear what new science might emerge from these next-gen facilities, our editors thought it best to wait.

Chore robots

The dream of a home robot that folds laundry and does the dishes has captivated technologists for decades. Are we getting closer? Amazon has bet big on home robots with its acquisition of iRobot (the maker of Roomba vacuums) and release of Astro, now a roving security bot. The appliance company Dyson recently teased "secret" chore robot prototypes. However, a true general-purpose chore robot is notoriously hard to build. We'll believe it when we see it.

The EV pickup

Electric pickup trucks are starting to hit the US market, including Ford's F-150 Lightning and Chevy's Silverado EV, along with models from Rivian and GMC. Americans buy about as many trucks as cars, so these EVs are an important part of the electrification story. Ultimately, though, this idea felt too US-centric. Our editors worried it ignored important EV progress in China, India, Latin America, and Europe. So you'll see a broader framing of this technology—"The inevitable EV"—on this year's list.

Partial cellular reprogramming

Several new biotech firms aim to slow or even reverse aging by finding ways to coax adult cells to behave more like stem cells found in embryos. Venture capitalists have poured billions into these startups, which have recruited superstar scientists to lead their efforts. But as Antonio Regalado, senior editor for biomedicine, points out in his recent story titled "How scientists want to make you young again," these projects haven't yet delivered the scientific results to back up their claims. ■

What did we miss? Starting January 9 vote online for the 11th breakthrough at technologyreview.com/tr10-2023.

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