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125th Anniversary Issue

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Mat Honan is editor in chief of MIT Technology Review.

Welcome to our 125th anniversary issue!

With this issue, we wanted to celebrate our milestone as a publication without dwelling too much on our own past. Victory laps are for race cars, not magazines. Instead, we decided to try to use history as a way to explore what things may look like over the next 125 years.

The longer you report on tech, the more you realize how often we get the future wrong. Predictions have a way of not coming true. The things that seem so clear now can shift and change, rearranging themselves into wholly new forms we never thought of.

But also, predictions that we laugh off as having been so wrong often have a way of coming true eventually. One great example of that is the Segway. (And, uh, bear with me here.) Before Dean Kamen's personal mobility device was revealed in 2001, hints of it leaked out to the public. Among the most notorious was a claim attributed to Steve Jobs ahead of its unveiling that the Segway would cause people to re-architect cities around it. When the device finally made its awkward debut and was revealed to be nothing more than an electric scooter, the Jobs quote was widely derided—and sometimes employed as an example of his fallibility when it came to predicting the future.

And yet. Here in 2024, we are doing pretty much what Jobs predicted. Okay, so the Segway never really did catch on, but scooters and all manner of other electric micromobility devices are everywhere. We're developing infrastructure to support lanes and docking bays for scooters and e-bikes, writing legislation about where and how fast they can be ridden, and fundamentally reimagining the way we get around—even in cities that already had great transit infrastructure. Take Taipei, for example. In that city, charging banks for scooters from Gogoro (a 2023 *MIT Technology Review* Climate Tech 15 company) now outnumber gas stations and can even be used as a source of grid power when the lights go out. To put it another way, we're finally redesigning cities around these things.

Which is to say: Even when we get the turn-by-turn navigation wrong, we can still manage to at least gesture in the right direction. And so, throughout this issue you'll find some of our best bets as to what the future may hold. We may not get it exactly right, but we think we're at least pointing toward where things are headed.

In this issue, Casey Crownhart looks at our clean-energy future and the resources we will need to create and maintain it. Niall Firth examines the challenges that archivists face as they try to preserve information about our current lives far into the future. Antonio Regalado investigates the ways we may all play God in the coming years, thanks to the ability to change our very DNA. And nowhere do we get more predictive than in Kara Platoni's story, which imagines the experiences a child born today will have interacting with AI and other emerging technologies over her lifetime—all 125-odd years of it.

You'll also find a superb package of essays asking big questions about the future. Cliff Kuang and Lydia Millet both argue for the importance of taking things into our own hands, whether it's computer interfaces or responses to the climate crisis. Jessica Hamzelou takes on the question of (much) longer life, Clive Thompson imagines the changing role of video, Ray Kurzweil believes machines will make us free, Katya Klinova interrogates what AI will mean for economic inequality, and Leo Herrera weighs in on, well, porn.

And as in every issue, there's plenty to read about what's going on right now. I hope you enjoy it.

ROBYN KESSLER

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The magazine you now hold in your hands is 125 years old. Not this actual issue, of course, but the publication itself, which launched in 1899. Few other titles can claim this kind of heritage—the *Atlantic*, *Harper's*, *Audubon* (which is also turning 125 this year), *National Geographic*, and *Popular Science* among them.

MIT Technology Review was born four years before the Wright brothers took flight. Thirty-three before we split the atom, 59 ahead of the integrated circuit, 70 before we would walk on the moon, and 90 before the invention of the World Wide Web. It has survived two world wars, a depression, recessions, eras of tech boom and bust. It has chronicled the rise of computing from the time of room-size mainframes until today, when they have become ubiquitous, not just carried in our pockets but deeply embedded in nearly all aspects of our lives.

Elizabeth Bramson-Boudreau is publisher of MIT Technology Review.

As I sit in my air-conditioned home office writing this letter on my laptop, Spotify providing a soundtrack to keep me on task, I can't help but consider the vast differences between my life and those of the MIT graduates who founded *MIT Technology Review* and laid out its pages by hand. My life—all of our lives—would amaze Arthur D. Little in countless ways.

(Not least is that I am the person to write this letter. When *MITTR* was founded, US women's suffrage was still 20 years in the future. There were women at the Institute, but their numbers were small. Today, it is my honor to be the CEO and publisher of this storied title. And I'm proud to serve at an institution whose president and provost are both women.)

I came to *MIT Technology Review* to guide its digital transformation. Yet despite the pace of change in these past 125 years, my responsibilities are not vastly different from those of my predecessors. I'm here to ensure this publication—in all its digital, app-enabled, audio-supporting, livestreaming formats—carries on. I have a deep commitment to its mission of empowering its readers with trusted insights and information about technology's potential to change the world.

During some chapters of its history, *MIT Technology Review* served as little more than an alumni magazine; through others, it leaned more heavily toward academic or journal-style publishing. During the dot-com era, *MIT Technology Review* invested large sums to increase circulation in pursuit of advertising pages comparable to the number in its counterparts of the time, the *Industry Standard*, *Wired*, and *Business 2.0*.

Through each of these chapters, I like to think, certain core principles remained consistent—namely, a focus on innovation and creativity in the face of new challenges and opportunities in publishing.

Today, *MIT Technology Review* sits in a privileged but precarious position in an industry struggling for viability. Print and online media is, frankly, in a time of crisis. We are fortunate to receive support from the Institute, enabling us to report the technology stories that matter most to our readers. We are driven to create impact, not profits for investors.

We appreciate our advertisers very much, but they are not why we are here. Instead, we are focused on our readers. We're here for people who care deeply about how tech is changing the world. We hope we make you think, imagine, discern, dream. We hope to both inspire you and ground you in reality. We hope you find enough value in our journalism to subscribe and support our mission.

Operating *MIT Technology Review* is not an inexpensive endeavor. Our editorial team is made up of some of the most talented reporters and editors working in media. They understand at a deep level how technologies work and ask tough questions of tech leaders and creators. They're skilled storytellers.

Even from its very start, *MIT Technology Review* faced funding challenges. In a letter to the Association of Class Secretaries in December 1899, Walter B. Snow, an 1882 MIT graduate who was secretary and leader of the association and one of *MITTR*'s cofounders, laid out a plan for increasing revenue and reducing costs to ensure "the continuation of the publication." Oof, Walter—have I got some stories for you. But his goal remains my goal today.

We hope you experience the thrill and possibility of being a human alive in 2024. This is a time when we face enormous challenges, yes, and sometimes it feels overwhelming. But today we also possess many of the tools and technologies that can improve life as we know it.

And so if you're a subscriber, thank you. Help us continue to grow and learn: Tell us what you like and what you don't like (feedback@technologyreview.com; I promise you will receive a reply). Consider a gift subscription for a friend or relative by visiting www.technologyreview.com/subscribe. If you bought this on the newsstand or are reading it over the shoulder of a friend, I hope you'll subscribe for yourself.

The next 125 years seem unimaginable—although in this issue we will try our best to help you see where things may be headed. I've never been an avid reader of science fiction. But by nature I'm an optimist who believes in the power of science and technology to make the world better. Whatever path these next years take, I know that *MIT Technology Review* is the vantage point from which I want to view it. I hope you'll be here alongside me.

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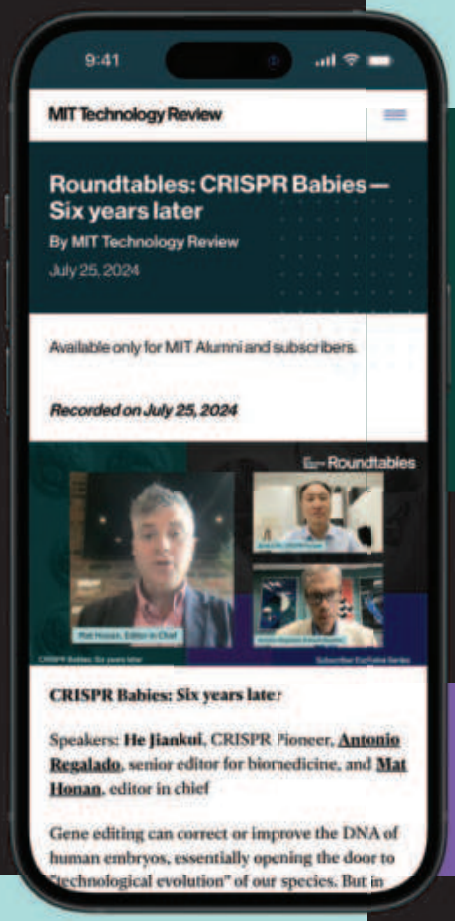

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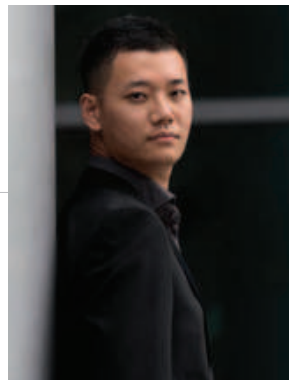
The innovation issue



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COVER ILLUSTRATION BY AARON LOWELL DENTON

The Download

People can move this bionic leg just by thinking about it

A mind-controlled prosthetic feels more like a part of the wearer's body and promises to make walking easier.

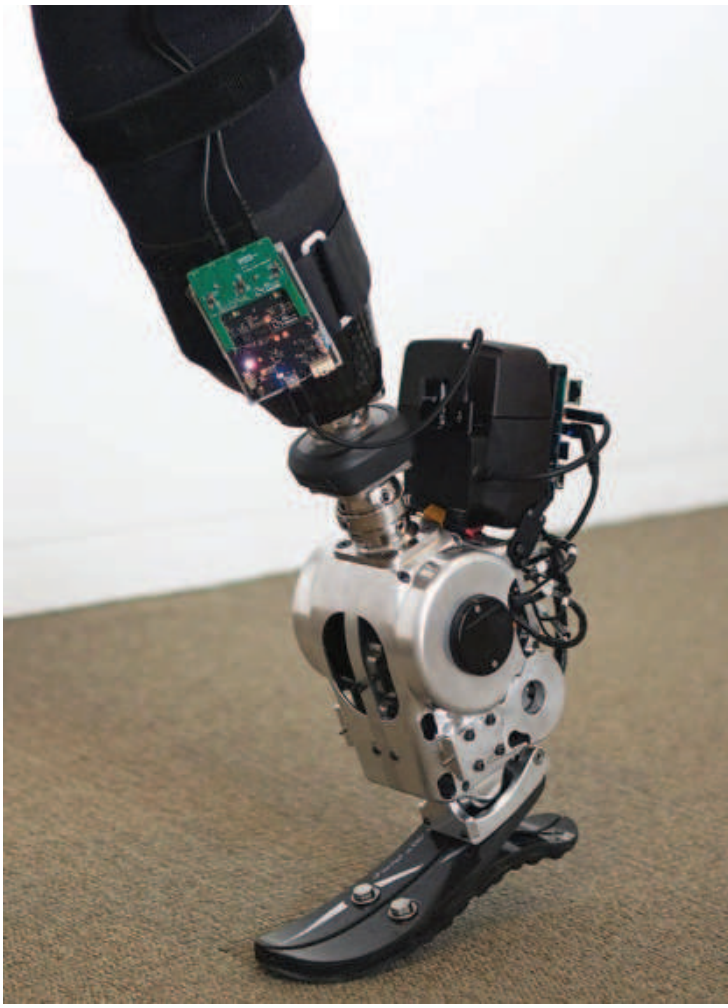
By Sarah Ward

When someone loses part of a leg, a prosthetic can make it easier to get around. But most prosthetics are static, cumbersome, and hard to move. A new neural interface connects a bionic limb to nerve endings in the thigh, allowing the limb to be controlled by the brain. The new device, described in a report in *Nature Medicine*, could help people with lower-leg amputations feel as if their prosthesis is part of them.

"When you ask a patient 'What is your body?' they don't include the prosthesis," says MIT biophysicist Hugh Herr, one of the lead authors on the study. The work is personal for him: he lost both his lower legs in a climbing accident when he was 17. He says linking the brain to the prosthesis can make it feel more like part of someone's anatomy, which can have a positive emotional impact.

Getting the neural interface hooked up to a prosthetic takes two steps. First, patients undergo surgery. Following a lower-leg amputation, portions of shin and calf muscle still remain. The operation connects shin muscle, which contracts to make the ankle flex upward, to calf muscle, which counteracts this movement. The prosthetic can also be fitted at this point. Reattaching the remnants of these muscles can enable the prosthetic to move more dynamically. It can also reduce phantom limb pain, and patients are less likely to trip and fall.

"The surgery stands on its own," says Amy Pietrafitta, a para-athlete who received it in 2018. "I feel like I have my leg back." But natural movements are still limited when the prosthetic isn't connected to the nervous system.



A neural interface that links a bionic limb to nerve endings in the thigh has helped patients walk faster, balance better, and dodge obstacles more nimbly.

H. SONG ET AL.

In step two, surface electrodes measure nerve activity from the brain to the calf and shin muscles, indicating an intention to move the lower leg. A small computer in the bionic leg decodes those nerve signals and moves the leg accordingly, allowing the patient to move the limb more naturally.

"If you have intact biological limbs, you can walk up and down steps, for example, and not even think about it. It's involuntary," says Herr. "That's the case with our patients, but their limb is made of titanium and silicone."

The authors compared the mobility of seven patients using a neural interface with that of patients who had not received the surgery. Patients using the neural interface could walk 41% faster and climb sloped surfaces and steps. They could also dodge obstacles more nimbly and had better balance. And they described feeling that the prosthetic was truly a part of their body rather than just a tool that they used to get around. ▸

"It's a very forward-thinking approach," says Hamid Charkhkar, a biomedical engineer at Case Western Reserve University, who was not involved in the study. "Our limbs are not like shoes. They're not worn over our bodies. They are integrally attached to our bodies via bones, muscles, and nerves."

There are limitations. The surgery can be done during amputation or several years later, but it won't work equally well for every patient. If it's done later, for example, some people's upper-thigh muscles could have atrophied too severely for them to receive the full benefits.

The surgery connecting the shin and calf muscles has become the standard of care at Brigham and Women's Hospital in Boston. But the surface electrodes that give patients full neural control of their limbs are a few years away from being clinically implemented. Plus, the neural interfaces have only been used in laboratory settings, and it will be important to know how they hold up in the real world.

Herr and his team at MIT hope to provide users with even greater control over their prosthetic limbs. In the future, their efforts will likely involve replacing the surface electrodes with magnetic spheres, which can more accurately track muscle dynamics.

"The goal that we have is to really reconstruct bodies, to rebuild bodies," says Herr. And to fully achieve that ambition, he says, "neural integration and embodiment is our long-term goal." ■

Sarah Ward is an editorial fellow at MIT Technology Review*, currently pursuing a PhD in volcanology at Vanderbilt University.*

Jobs of the future: Weather maker

One scientist leads a project to increase winter snowfall so that desert towns in the US West will have water in summer.

By Mara Johnson-Groh

Much of the western United States relies on winter snowpack to supply its rivers and reservoirs through the summer months. But with warming temperatures, less and less snow is falling—a recent study showed a 23% decline in annual snowpack since 1955. By some estimates, runoff from snowmelt in the western US could decrease by a third between now and the end of the century, meaning less water will be available for agriculture, hydroelectric projects, and urban use in a region already dealing with water scarcity.

That's where Frank McDonough comes in. An atmospheric research scientist, McDonough leads a cloud-seeding program at the Desert Research Institute (DRI) that aims to increase snowfall in Nevada and the Eastern Sierras. Snow makers like McDonough and others who generate rain represent a growing sector in a parched world.

Instant snow: Cloud seeding for snow works by injecting a tiny amount of silver iodide dust into a cloud to help its water vapor condense into ice crystals that grow into snowflakes. In other conditions, water molecules drawn to such particles coalesce into raindrops. McDonough uses custom-made, remotely operated machines on the ground to heat up a powdered form of the silver iodide that's released into the air. Dust—or sometimes table salt—can also be released from planes.

Old tech, new urgency: The precipitation-catalyzing properties of silver iodide were first explored in the 1940s by American chemists and engineers, but the field remained a small niche. Now, with 40% of people worldwide affected by water scarcity and a growing number of reservoirs facing climate stress, cloud seeding is receiving global interest. "It's becoming almost like, hey, we have to do this, because there's just too many people and too many demands on these water resources," says McDonough. A growing number of government-run cloud-seeding programs around the world are now working to increase rainfall and snowpack, and even manipulating the timing of precipitation to prevent large hailstorms, reduce air pollution, and minimize flood risk. The private sector is also taking note: One cloud-seeding startup, Rainmaker, recently raised millions.

Generating results: At the end of each winter, the snowmakers dig into the data to see what impact they've had. In the past, McDonough says, his seeding has increased snowpack by 5% to 10%. That's not enough to end a drought, but the DRI estimates that the cloud seeding around Reno, Nevada, alone adds enough precipitation to keep about 40,000 households supplied. And for some hydroelectric projects, "a 1% increase is worth millions of dollars," McDonough says. "Water is really valuable out here in the West." ■

COURTESY OF FRANK MCDONOUGH

A space-based farmhand for hire

Farmers in Africa are turning to satellite monitoring to improve crop yields.

By Orji Sunday

Last year, as the harvest season drew closer, Olabokunde Tope came across an unpleasant surprise.

While certain spots on his 70-hectare cassava farm in Ibadan, Nigeria, were thriving, a sizable parcel was pale and parched—the result of an early and unexpected halt in the rains. The cassava stems, starved of water, had withered to straw.

"It was a really terrible experience for us," Tope says, estimating the cost of the loss at more than 50 million naira ($32,000). "We were praying for a miracle to happen. But unfortunately, it was too late."

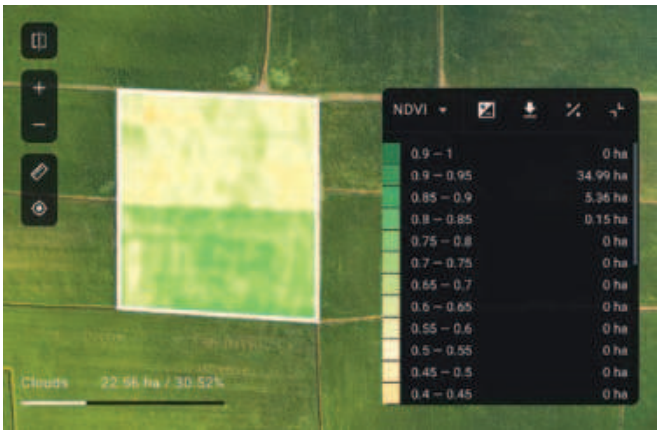
When the next planting season rolled around, Tope's team weighed different ways to avoid another cycle of heavy losses. They decided to work with EOS Data Analytics, a California-based provider of satellite imagery and data for precision farming. The company uses wavelengths of light including the near-infrared, which penetrates plant canopies and can be used to measure a range of variables, including moisture level and chlorophyll content.

EOS's models and algorithms deliver insights on crops' health weekly through an online platform that farmers can use to make informed decisions about issues such as when to plant, how much herbicide to use, and how to schedule fertilizer use, weeding, or irrigation.

When EOS first launched in 2015, it relied largely on imagery from a combination of satellites, especially the European Union's Sentinel-2. But Sentinel-2 has a maximum resolution of 10 meters, making it of limited use for spotting issues on smaller farms, says Yevhenii Marchenko, the company's sales team lead.

So last year the company launched EOS SAT-1, a satellite designed and operated solely for agriculture. Fees to use the crop-monitoring platform now start at $1.90 per hectare per year for small areas and drop as the farm gets larger. (Farmers who can afford to have adopted drones and other related technologies, but drones are significantly more expensive to maintain and scale, says Marchenko.)

In many developing countries, farming is impaired by lack of data. For centuries, farmers relied on native intelligence rooted in experience and hope, says Daramola John, a professor of agriculture and agricultural technology at Bells University of Technology in southwest Nigeria. "Africa is way behind in the race for modernizing farming," he says. "And a lot of farmers suffer huge losses because of it."



COURTESY OF EOS DATA ANALYTICS

In the spring of 2023, when the new planting season was to start, Tope's company, Carmi Agro Foods, had used GPS-enabled software to map the boundaries of its farm. Its setup on the EOS crop monitoring platform was also completed. Tope used the platform to determine the appropriate spacing for the stems and seeds. The rigors and risks of manual monitoring had disappeared. His field-monitoring officers needed only to peer at their phones to know where or when specific spots needed attention on various farms. He was able to track weed breakouts quickly and efficiently.

This technology is gaining traction among farmers in other parts of Nigeria and the rest of Africa. More than 242,000 people in Africa, Southeast Asia, Latin America, the United States, and Europe use the EOS crop-monitoring platform. In 2023 alone, 53,000 more farmers subscribed to the service.

One of them is Adewale Adegoke, the CEO of Agro Xchange Technology Services, a company dedicated to boosting crop yields using technology and good agricultural practices. Adegoke used the platform on half a million hectares (around 1.25 million acres) owned by 63,000 farmers. He says the yield of maize farmers using the platform, for instance, grew to two tons per acre, at least twice the national average.

Adegoke adds that local farmers, who have been struggling with fluctuating conditions as a result of climate change, have been especially drawn to the platform's early warning system for weather.

As harvest time draws nearer this year, Tope reports, the prospects of his cassava field, which now spans a thousand hectares, is quite promising. This is thanks in part to his ability to anticipate and counter the sudden dry spells. He spaced the plantings better and then followed advisories on weeding, fertilizer use, and other issues related to the health of the crops.

"So far, the result has been convincing," says Tope. "We are no longer subjecting the performance of our farms to chance. This time, we are in charge." ■

Orji Sunday is a freelance journalist based in Lagos, Nigeria.

To the extreme

A research park in northern Italy can create all the climate conditions on Earth.

Photo by SchirraGiraldi/Institute

From an office park in the Italian Alps, TerraXcube can artificially simulate all the extreme climatic conditions on Earth, from snowstorms on the highest summits to the heat of desert regions. Temperatures from −40 °C to 60 °C, artificial solar radiation, 60 millimeters of rain per hour, five centimeters of snow per hour, wind speeds of up to 108 kilometers per hour, and the air pressure and oxygen content conditions seen at elevations up to 9,000 meters above sea level—all can be generated at the push of a button. With this ability, its creators say, a new age of industrial, medical, and ecological research can begin.

"How do organisms behave when pressure changes? Can mountains offer suitable shelter for all species that migrate to higher altitudes due to climate change?" asks Georg Niedrist, a senior researcher for the Institute for Alpine Environment at Eurac Research, the center that houses TerraXcube. The system, he explains, "allows us to address basic questions that so far could not be answered." ■

A coffee-bean-free coffee

A Singapore startup is using fermentation to upcycle food waste and make coffee-like drinks.

By Lina Zeldovich

DJ Tan, cofounder of the Singaporean startup Prefer Coffee, pops open a bottle of oat latte and pours some into my cup. The chilled drink feels wonderfully refreshing in Singapore's heat—and it tastes just like coffee. And that's impressive, because there isn't a single ounce of coffee in it.

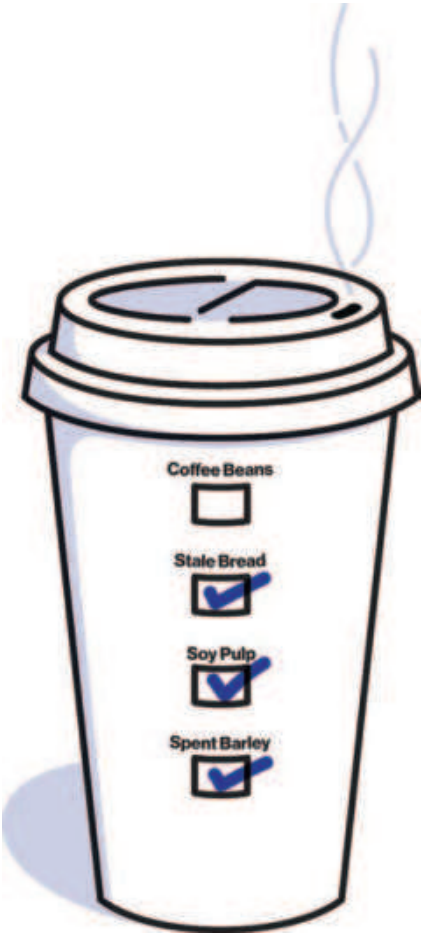
It turns out that our beloved cup of joe may not be sustainable the way it's produced now. Rising temperatures, droughts, floods, typhoons, and new diseases are endangering coffee crops. A 2022 study published in the journal *PLOS One* expects a general decline in land suitable for growing coffee by 2050. Modern coffee production involves clearing forests and uses a lot of water (as well as fertilizers and pesticides). It also consumes a lot of energy, generates greenhouse-gas emissions, and ruins native ecosystems. The situation "presents an existential crisis for the global coffee industry," says Tan—and for all those who love their morning wake-up shot.

Tan had an idea that could fix it: a "coffee" brewed entirely from leftovers of the local food industry.

For a few years before starting Prefer, Tan was working in the food industry with Singapore's top chefs. His clients were in search of new flavors, which he created using fermentation—feeding various organic substances to microbes. Humans have been using microorganisms to create foods for ages: microbes and yeast produce some of our favorite foods and drinks, like yogurt, kimchi, beer, and kombucha. But Tan was pushing the process in new directions. "Fermentation is a way to create flavors that don't exist," he says.

In 2022, at a local startup accelerator in Singapore, Tan met Jake Berber, a neuroscientist turned entrepreneur. Both men were coffee lovers, and they joined forces to create a beanless drink. In doing so, they joined a growing movement of upcyclers who believe that we can reduce our footprint by putting food leftovers back onto our plates after making them appealing and palatable once again.

They spent months experimenting with various ingredients. "From my previous work, I had an inkling of what might work," says Tan, but narrowing it down to the exact proportions, processes, and types of leftovers took a while. They tried roasting chicory root, which had been used as a coffee substitute before, but while the result was reminiscent of coffee, the taste wasn't close enough. They tried grinding date seeds, which yielded a fruity tea-like drink, a far cry from coffee. Then some batches brewed from mixtures of food leftovers showed promise. They used gas chromatography mass spectrometry, a technique that identifies individual molecular compounds in mixtures, to identify and analyze the molecules responsible for the desired taste. The results guided them in tweaking new iterations of the brew. After a few months and several hundred different mixes and methods, they zeroed in on the right combination: stale bread from bakeries, soybean pulp from tofu making, and spent barley grains from local breweries. "We combine them in roughly equal amounts, ferment for 24 hours, and then roast," Tan says. Out comes a naturally caffeine-free "coffee" that can be enjoyed with plant-based or regular milk. Or added to a martini—local bartenders jumped on the novelty. Without milk, the drink "tastes a little more chocolatey and retains the notes of herbaceous bitterness," according to Tan. Price-wise it's comparable to your average coffee, Berber says. Prefer sells a powder to be brewed like any other coffee, as well as bottled cold brew and bottled latte. The products can be bought online and ordered at various Singaporean cafés.



SHAWN HAZEN

For those who want their kick, the startup adds caffeine powder from tea leaves. On a warming planet, tea plants are a better bet, Tan explains: "You're harvesting the leaves, which are a lot more plentiful than the coffee berries."

Currently, Prefer Coffee sells its brew in Singapore only, but it hopes to expand to other places while still upcycling local waste. In the Philippines, for example, leftover cassava, sugarcane, or pineapple might be used, Tan says. Although adjustments will have to be made, the company's fermentation process should be able to deliver something similarly coffee-like: "Our technology doesn't rely on soy, bread, and barley but tries to use whatever is available." ■

Journalist Lina Zeldovich is the author of The Living Medicine: How a Lifesaving Cure Was Nearly Lost and Why It Will Rescue Us When Antibiotics Fail*, to be published by St. Martin's in October 2024.*

Book reviews

Moonbound

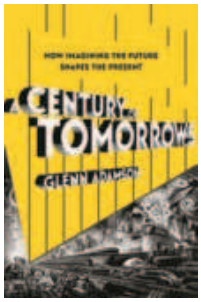
By Robin Sloan (MCD, 2024)

Robin Sloan's newest novel is a feat of world-building, a thought-provoking read on what happens when a mistreated artificial intelligence outpaces its creator, a rollicking quest narrative, an homage to sci-fi and fantasy classics, and a delightful coming-of-age yarn as told by a highly intelligent fungus. The book is, loosely, a part of the same universe as Sloan's previous works—*Sourdough* and *Mr. Penumbra's 24-Hour Bookstore*—but stands completely on its own too.

Power Metal

By Vince Beiser (Penguin Random House, 2024)

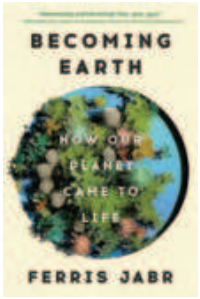
Copper. Nickel. Cobalt. Lithium. The acquisition of these materials is driving our transition to renewable energy. But it is also creating widespread social and environmental carnage. Beiser, a journalist, reports from the front lines on some of the problems that have arisen, many of which have been reported piecemeal before. He also strikes a hopeful note, outlining efforts to alleviate the cycle of destruction.



A Century of Tomorrows: How Imagining the Future Shapes the Present

By Glenn Adamson (Bloomsbury, 2024)

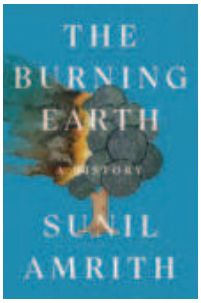
The writer H.G. Wells (*The Time Machine, The War of the Worlds*) once related a friend's remark that "you can know no more about the future than you can know which way a kitten will jump next." Like Wells, who felt that the longevity of prediction as a practice attested to its essential role, Adamson believes that we shouldn't focus so much on accuracy as the futurologist's primary objective. The long tradition of trying to forecast the future, writes the historian, "turns out to be, in retrospect, a fascinating way to understand the past." The future will remain a riddle with an infinite number of solutions, he says, "and just thinking about that conundrum can have positive results."



Becoming Earth: How Our Planet Came to Life

By Ferris Jabr (Penguin Random House, 2024)

In this engrossing book, science writer Ferris Jabr travels a mile underground, climbs a tower high above the Amazon rainforest, and visits a team trying to bring large mammals back to Siberia to explore of how life has shaped Earth at seemingly every scale, from creating fertile soils to altering the atmosphere. Humanity's impact on the environment is just the latest chapter in a story that spans billions of years.



The Burning Earth: A History

By Sunil Amrith (Norton, 2024)

Once upon a time, writes Amrith, "all history was environmental history … every culture had its gods of beneficence; every culture had dreams of plenty." Until, he continues, "the most powerful people in the world believed … that human beings and other forms of life on Earth are but resources to be exploited, to be moved around at will." Amrith charts this shift from reverence to exploitation in hopes of challenging the "self-destructive folly" of the last 200 years. We need to realize the strength in collective action, he writes, because "there is no us without the world."

The People of the Ruins

By Edward Shanks (MIT Press, 2024)

Part of MIT Press's Radium Age series of notable proto–science fiction stories published between 1900 and 1935, *The People of the Ruins,* by the war poet Edward Shanks (1892–1953), imagines England in the not-so-distant future as a neo-medieval society whose inhabitants have forgotten how to build or operate machinery. The book's protagonist is a physics instructor who has been cryogenically frozen. When he emerges a century and a half later, he must grapple with the realities of a post-civilized world. ■

COURTESY OF THE PUBLISHERS

A polyester-dissolving process could make modern clothing recyclable

The new technique can help break mixed-fiber clothing back down into feedstock for future textiles.

By Sarah Ward

Less than 1% of clothing is recycled, and most of the rest ends up dumped in a landfill or burned. A team of researchers hopes to change that with a new process that breaks down mixed-fiber clothing into reusable, recyclable parts without any sorting or separation in advance.

"We need a better way to recycle modern garments that are complex, because we are never going to stop buying clothes," says Erha Andini, a chemical engineer at the University of Delaware and lead author of a study on the process, published in *Science Advances*. "We are looking to create a closed-loop system for textile recycling."

Many garments are made of a mix of natural and synthetic fibers. Once these fibers are combined, they are difficult to separate. This presents a problem for recycling, which often needs textiles to be sorted into uniform categories, similar to how we sort glass, aluminum, and paper.

To tackle this problem, Andini and her team used a solvent that breaks the chemical bonds in polyester fabric while leaving cotton and nylon intact. To speed up the process, they power it with microwave energy and add a zinc oxide catalyst. This combination reduces the breakdown time to 15 minutes, whereas traditional plastic recycling methods take over an hour. What the polyester ultimately breaks down into is BHET, an organic compound that can, in theory, be turned into polyester once more. While similar methods have been used to recycle pre-sorted plastic, this is the first time they've been used to recycle mixed-fiber textiles without any sorting required.

In addition to speeding things up, the use of microwave energy also reduces the technique's carbon footprint because it's quicker and uses less energy, says Andini.

Nevertheless, the process could be difficult to scale, says Bryan Vogt, a chemical engineer at Penn State University, who was not involved in the study. That's because the solvent used to break down polyester is expensive and difficult to recover after use. Further, according to Andini, even though BHET is easily turned back into clothing, it's less clear what to do with the leftover fibers. Nylon could be especially tricky, because the fabric is degraded significantly by the team's chemical recycling technique.

Less than 1% of clothing is recycled, but a new chemical process may help.

ANTONIO COSSIO/PICTURE-ALLIANCE/DPA/AP IMAGES; COURTESY OF THE RESEARCHERS

"We are chemical engineers, so we think of this process as a whole," says Andini. "Hopefully, once we are able to get pure components from each part, we can transform them back into yarn and make clothes again."

Andini, who just received a fellowship for entrepreneurs, is developing a business plan to commercialize the process. In the coming years, she aims to launch a startup that will take the clothes recycling technique out of the lab and into the real world. That could be a significant step toward reducing the large amounts of textile waste in landfills. "It'll be a matter of having the capital or not," she says, "but we're working on it and excited for it." ■

Op-Ed

AI could do a lot for accessibility

The technology's potential for serving the disabled community is wildly underappreciated.

By Steven Aquino

As a lifelong disabled person who constantly copes with multiple conditions, I have a natural tendency to view emerging technologies with skepticism. Most new things are built for the majority of people—in this case, people without disabilities—and the truth of the matter is there's no guarantee I'll have access to them.

There are certainly exceptions to the rule. A prime example is the iPhone. Although discrete accessibility software did not appear until the device's third-generation model, in 2009, earlier generations were still revolutionary for me. After I'd spent years using flip phones with postage-stamp-size screens and hard-to-press buttons, the fact that the original iPhone had a relatively large screen and a touch-based UI was accessibility unto itself.

AI could make these kinds of jumps in accessibility more common across a wide range of technologies. But you probably haven't heard much about that possibility. While the *New York Times* sues OpenAI over ChatGPT's scraping of its content and everyone ruminates over the ethics of AI tools, there seems to be less consideration of the *good* ChatGPT can do for people of various abilities. For someone with visual and motor delays, using ChatGPT to do research can be a lifesaver. Instead of trying to manage a dozen browser tabs with Google searches and other pertinent information, you can have ChatGPT collate everything into one space. Likewise, it's highly plausible that artists who can't draw in the conventional manner could use voice prompts to have Midjourney or Adobe Firefly create what they're thinking of. That might be the only way for such a person to indulge an artistic passion.

Of course, data needs to be vetted for accuracy and gathered with permission—there are ample reasons to be wary of AI's potential to serve up wrong or potentially harmful, ableist information about the disabled community. Still, it feels unappreciated (and underreported) that AI-based software can truly be an assistive technology, enabling people to do things they otherwise would be excluded from. AI could give a disabled person agency and autonomy. That's the whole point of accessibility—freeing people in a society not designed for their needs.

The ability to automatically generate video captions and image descriptions provides additional examples of how automation can make computers and productivity technology more accessible. And more broadly, it's hard not to be enthused about ever-burgeoning technologies like autonomous vehicles. Most tech journalists and other industry watchers are interested in self-driving cars for the sheer novelty, but the reality is the AI software behind vehicles like Waymo's fleet of Jaguar SUVs is quite literally enabling many in the disability community to exert more agency over their transport. For those who, like me, are blind or have low vision, the ability to summon a ride on demand and go anywhere without imposing on anyone else for help is a huge deal. It's not hard to envision a future in which, as the technology matures, autonomous vehicles are normalized to the point where blind people could buy their own cars.

At the same time, AI is enabling serious advances in technology for people with limb differences. How exciting will it be, decades from now, to have synthetic arms and legs, hands or feet, that more or less function like the real things? Similarly, the team at Boston-based Tatum Robotics is combining hardware with AI to make communication more accessible for deaf-blind people: A robotic hand forms hand signs, or words in American Sign Language that can be read tactilely against the palm. Like autonomous vehicles, these applications have enormous potential to positively influence the everyday lives of countless people. All this goes far beyond mere chatbots.

For those who, like me, are blind or have low vision, the ability to summon a ride on demand and go anywhere without imposing on anyone else for help is a huge deal.

It should be noted that disabled people historically have been among the earliest adopters of new technologies. AI is no different, yet public discourse routinely fails to meaningfully account for this. After all, AI plays to a computer's greatest strength: automation. As time marches on, the way AI grows and evolves will be unmistakably and indelibly shaped by disabled people and our myriad needs and tolerances. It will offer us more access to information, to productivity, and most important, to society writ large. ■

Steven Aquino is a freelance tech journalist covering accessibility and assistive technologies. He is based in San Francisco.

What are AI agents?

The next big thing is AI tools that can do more complex tasks. Here's how they will work. By Melissa Heikkilä

When ChatGPT was first released, everyone in AI was talking about the new generation of AI assistants. But over the past year, that excitement has turned to a new target: AI agents.

Agents featured prominently in Google's annual I/O conference in May, when the company unveiled Astra, an agent users can interact with using audio and video. OpenAI's new GPT-4o model has also been called an AI agent.

And it's not *just* hype, although there is definitely some of that too. Tech companies are plowing vast sums into creating AI agents, and their research efforts could usher in the kind of useful AI we have been dreaming about for decades.

But what are they? And how can we use them?

It is still early days for research into AI agents, and the field does not have a definitive definition for them. But simply, they are AI models and algorithms that can autonomously make decisions in a dynamic world, says Jim Fan, a senior research scientist at Nvidia who leads the company's work in this area.

The grand vision for AI agents is a system that can execute a vast range of tasks, much like a human assistant. In the future, it could help you book your vacation, but it will also remember if you prefer swanky hotels, so it will only suggest hotels that have four stars or more and then go ahead and book the one you pick from the range of options it offers you. It will then also suggest flights that work best with your calendar and plan the itinerary for your trip according to your preferences. It might even send your itinerary to any friends it knows live in your destination and invite them along. In the workplace, it could analyze your to-do list and execute tasks from it, such as sending calendar invites, memos, or emails.

One vision for agents is that they are multimodal, meaning they can process language, audio, and video. For example, in Google's Astra demo, users could point a smartphone camera at things and ask the agent questions. The agent could respond to text, audio, and video inputs.

These agents could also make processes smoother for businesses and public organizations, says David Barber, the director of the University College London Centre for Artificial Intelligence. For example, an AI agent might be able to function as a more sophisticated customer service bot. The current generation of language-model-based assistants can only generate the next likely word in a sentence. But an AI agent would have the ability to act on natural-language commands autonomously and process customer service tasks without supervision. For example, the agent would be able to analyze customer complaint emails and then know to check the customer's reference number, access databases such as customer relationship management and delivery systems to see whether the complaint is legitimate, and process it according to the company's policies, Barber says.

Broadly speaking, there are two different categories of agents, says Fan: software agents and embodied agents.

Software agents run on computers or mobile phones and use apps, much as in the travel agent example above. "Those agents are very useful for office work or

STEPHANIE ARNETT/MIT TECHNOLOGY REVIEW

sending emails or having this chain of events going on," he says.

Embodied agents are agents that are situated in a 3D world such as a video game, or in a robot. These kinds of agents might make video games more engaging by letting people play with nonplayer characters controlled by AI. They could also lead to more useful robots that could help us with everyday tasks at home, such as folding laundry and cooking meals.

Fan was part of a team that built an embodied AI agent called MineDojo in the popular computer game Minecraft. Using a vast trove of data collected from the internet, Fan's AI agent was able to learn new skills and tasks that allowed it to freely explore the virtual 3D world and complete complex tasks such as encircling llamas with fences or scooping lava into a bucket. Video games are good proxies for the real world, because they require agents to understand physics, reasoning, and common sense.

In a recent paper, which has not yet been peer-reviewed, researchers at Princeton say that AI agents tend to have three different characteristics. AI systems are considered "agentic" if they can pursue difficult goals without being instructed in complex environments. They also qualify if they can be instructed in natural language and act autonomously without supervision. And finally, the term "agent" can also apply to systems that are able to use tools, such as web search or programming, or are capable of planning.

Are they a new thing?

There have been two waves of agents, says Fan. The current wave is thanks to the language model boom and the rise of systems such as ChatGPT. The previous wave was in 2016, when Google DeepMind introduced AlphaGo, its AI system that can play—and win—the game Go. AlphaGo was able to make decisions and plan strategies. This relied on reinforcement learning, a technique that rewards AI algorithms for desirable behaviors.

"But these agents were not general," says Oriol Vinyals, vice president of research at Google DeepMind. They were created for very specific tasks—in this case, playing Go. The new generation of foundation-model-based AI makes agents more universal, as they can learn from the world humans interact with.

"It's not like 'Oh my God, all of a sudden we have AGI' ... but more like 'Oh my God, my computer can do way more than it did five years ago.'"

"You feel much more that the model is interacting with the world and then giving back to you better answers or better assistance or whatnot," says Vinyals.

What are the limitations?

There are still many open questions that need to be answered. Kanjun Qiu, CEO and founder of the AI startup Imbue, which is working on agents that can reason and code, likens the state of agents to where self-driving cars were just over a decade ago. They can do stuff, but they're unreliable and still not really autonomous. For example, a coding agent can generate code, but it sometimes gets it wrong, and it doesn't know how to test the code it's creating, says Qiu. So humans still need to be actively involved in the process. AI systems still can't fully reason, which is critical to operating in a complex and ambiguous human world.

"We're nowhere close to having an agent that can just automate all of these chores for us," says Fan. Current systems "hallucinate and they also don't always follow instructions closely," Fan says. "And that becomes annoying."

Another limitation is that after a while, AI agents lose track of what they are working on. AI systems are limited by their context windows, meaning the amount of data they can take into account at any given time. "ChatGPT can do coding, but it's not able to do long-form content well. But for human developers, we look at an entire GitHub repository that has tens if not hundreds of lines of code, and we have no trouble navigating it," says Fan.

To tackle this problem, Google has increased its models' capacity to process data, which allows users to have longer interactions with them in which the models remember more about past interactions. The company said it is working on making its context windows infinite in the future.

For embodied agents such as robots, there are even more limitations. There is not enough training data to teach them, and researchers are only just starting to harness the power of foundation models in robotics.

So amid all the hype and excitement, it's worth bearing in mind that research into AI agents is still in its very early stages, and it will likely take years until we can experience their full potential.

That sounds cool. Can I try an AI agent now?

Sort of. You've most likely tried early prototypes, such as OpenAI's ChatGPT and GPT-4. "If you're interacting with software that feels smart, that is kind of an agent," says Qiu.

Right now the best agents we have are systems with very narrow and specific use cases, such as coding assistants, customer service bots, or workflow automation software like Zapier, she says. But these are a far cry from a universal AI agent that can do complex tasks.

"Today we have these computers and they're really powerful, but we have to micromanage them," says Qiu.

These systems will one day change the way we interact with technology, Qiu believes, and it is a trend people need to pay attention to. "It's not like 'Oh my God, all of a sudden we have AGI [artificial general intelligence]' ... but more like 'Oh my God, my computer can do way more than it did five years ago,'" she says. ■

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

This designer looks for magic in everyday materials

Skylar Tibbits coined the term "4D printing"—and immediately moved on to his next blue-sky idea. By Anna Gibbs

Around 2012, at a bakery in Cambridge, Massachusetts, Skylar Tibbits noticed someone wearing a shirt with the logo of a 3D-printing company. Tibbits, a designer and computer scientist, approached her and posed a question: "Why can't I print something that walks off the machine?"

The idea kicked off a multiyear collaboration between the industrial 3D-printing company behind the logo, called Stratasys, and Tibbits's Self-Assembly Lab at the Massachusetts Institute of Technology. Together, they explored 3D-printed materials that, while they couldn't walk off the machine, could change their shape or properties after being printed—a concept that Tibbits dubbed "4D printing," where the fourth dimension is time. Today, 4D printing is its own field—the subject of a professional society and thousands of papers, with researchers around the world looking into potential applications from self-adjusting biomedical devices to soft robotics.

The concept of materials that transform—specifically, that "remember" their form after being deformed—had already been around for a couple of decades, says Thomas Gries, a mechanical engineer who was inspired by Tibbits's innovations to conduct research on 4D textiles at RWTH Aachen University in Germany. "But to give it a name and bring it to a next stage of, let's say, perception … this was definitely the main breakthrough by Skylar Tibbits," he says.

Not long after 4D printing took off, Tibbits was already looking toward a new challenge: What other capabilities can we build into materials? And can we do that … without printing?

Tibbits still does a lot of printing in his Self-Assembly Lab, which he founded around 2011. It recently spun out a company, Rapid Liquid Print, that can print large, stretchable products like furniture or prosthetics inside a gel bath; Tibbits also invented a novel technique called liquid metal printing that makes furniture from molten aluminum in a matter of seconds. But his research extends far beyond printing into a world that he refers to as "programmable materials"—those that can transform, sense, reconfigure in shape or property, or self-assemble without relying on robotic mechanisms.

Tibbits's interest in transforming materials stretches back to his bachelor's degree in architecture at Philadelphia University in the 2000s. There he became "obsessively interested" in two emerging fields: digital fabrication (in which machines like 3D printers or laser cutters use code to physically make things) and the use of computation for design. He started working at a classmate's father's sign shop, which had an early computer numerically controlled machine. (The classmate, Jared Laucks, now co-directs the Self-Assembly Lab with Tibbits.) "We had unprecedented access to this early digital fabrication tool that our school didn't even have at the time," Tibbits recalls. Meanwhile, he was teaching himself to code so that he could design and fabricate things computationally.

By the time he arrived at MIT, where he earned separate master's degrees in computer science and design computation, 3D

COURTESY OF SKYLAR TIBBITS

printing had exploded in popularity. True to his nature, Tibbits was already looking to the next unknown. His start in architecture and a few stints at design firms continued to influence his curiosity: He had studied code for design and code for digital fabrication, but there was not yet a way to code for assembling parts into a whole.

"Most things that are assembled are still either by hand or it's like a robot in a factory," he says. "There is no elegant process for building very complicated things."

He imagined a way to embed information into material parts so that they could build themselves. That led him to self-assembly, which refers to components that come together on their own. For example, an early project at the Self-Assembly Lab involved placing unique chair parts, each designed to fit into one precise location in a final structure, into a tank of turbulent water, which caused the parts to bump into each other and, after several hours, click into their proper spot to form a chair. Around the same time, he became interested in the idea of programmable materials, in which properties and geometry—like what a yarn is made of and how it's woven together—can determine behavior.

Over the past decade, Tibbits's team has worked on a long list of projects in many industries, from fashion to aerospace. He has helped make specially knitted spacesuits, developed an engine component for Airbus, and printed shoes for Converse. For BMW, he worked on printed car seats that can morph around a passenger's body. For Google, he designed a structure for meeting spaces that can contract into the ceiling when not in use. With the National Science Foundation, he integrated dynamic braille into a textile sleeve. For Arc'teryx, he collaborated on a wearable textile prototype that he and the company's senior design director, Greg Grenzke, tested out on a ski slope at Whistler Blackcomb in Canada. In all cases, Tibbits sees his team's role as making the impossible possible. "That's where we're super, super good," he says.

"[Tibbits is] one of those people that thinks anything is possible," says Grenzke. "And he's very exploratory, which I think for innovation and more big blue-sky thinking—that's a must-have."

It's particularly important in manufacturing, where old methods often go unquestioned and change is difficult. "Sometimes people get a hammer, and then they just go around their whole lives looking for nails even when it'd be better to pick up a screwdriver," says Michael Dickey, a chemical engineer at North Carolina State University in Raleigh, who has collaborated with Tibbits. "What Skylar's done has been, I would say, fearless."

That mindset was important to Emeco, a US-based furniture company established in the 1940s. When they were struggling to make the foam in their upholstery more sustainable, Tibbits's team was "really good at taking a step back and saying, 'Okay, well, what if it didn't have to be that way?'" says Jaye Buchbinder, a product development engineer at the company. "In our heads, it's 'Let's find a better foam,' and in their heads, it's 'How do you not use foam?'" Buchbinder also worked with Tibbits to run a course at MIT about reimagining a chair for the future—one that could be reconfigured or infinitely recycled.

Lately, Tibbits has turned his attention to textiles—in particular, using fibers and yarns to create active structures that can sense and transform. For example, climate-adaptive clothing can open and close its "pores" in response to heat in order to regulate the wearer's temperature. Or extreme heat can be harnessed selectively to custom-tailor a generic article of clothing. The lab, in collaboration with the fashion brand Ministry of Supply, recently showcased a knitted dress prototype that can be sized and styled in the store to fit a customer's needs. A robotic arm applies heat to specific parts of the dress, shortening fibers and changing the garment's shape.

In all cases, the magic lies in the process. "There's nothing magic about the material," says Tibbits. "Every material is active." In fact, that property is usually considered a nuisance: think warping wood. But, he says, "if you can help guide it to do some kind of useful transformation, then that's great."

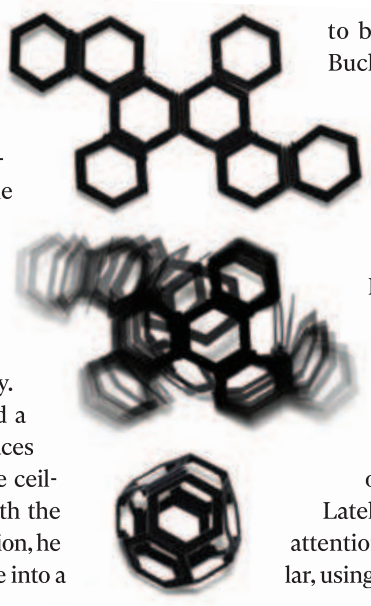
If it all sounds a little whimsical, it is. Tibbits sees the importance of creating something practical—the textiles are exciting to him because they can be made on preexisting factory machines, which makes them possible to scale—but he likes it when the result is also radical. One of his most out-there projects is happening on the other side of the world in the Maldives, where the team has worked in collaboration with a company called Invena on underwater structures designed to influence wave energy and promote sand accumulation in certain spots along island shores—an alternative to dredging. The idea is to harness natural forces, rather than fight them, to help protect coasts against erosion and rising sea levels.

The way Tibbits sees it, his position in academia allows his lab to "fail often and, frankly, waste time and money"—resources that most companies could not afford to waste. He sees it as his obligation as a designer to spend time considering the radical and irrelevant.

"Sometimes they're playful, sometimes they're weird, sometimes they're funny," he says of his designs. "Hopefully, eventually, they're useful, they're helpful, they're important." ■

Anna Gibbs is a freelance science journalist based in New York City.

A series of photographs shows the transformation of a flat 4D-printed structure into a 3D object.



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The big questions

Predicting the future is a near-impossible task. But as we celebrate our 125th anniversary, we looked to these writers and thinkers to muse on the ideas and technologies affecting us all in the coming decades.

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“If we wish to thrive beyond it, the next century will have to be a time of unmaking and remaking.”

CLIMATE CHANGE

LYDIA MILLET

A future beyond the climate crisis?

Awe, not hope, is the prerequisite to action.

When it comes to climate breakdown and the extinction crisis, the question I get most often is: How can we have hope?

People ask me this in a range of contexts—in Q&A sessions, in emails, and on podcasts and radio shows, whether I'm doing outreach for my novels, like *A Children's Bible* or *Dinosaurs*, or for nonfiction like *We Loved It All*, my new memoir. I see numerous iterations of it in the media and my social feeds and hear accounts of its ubiquity from writer friends, scientist and lawyer colleagues, activists and community organizers.

I've thought about the impulse behind the asking and am left with the lingering sense that many of us tend, in this cultural moment, to privilege our feelings on these existential threats over reason, say, or moral virtue, or apparently antiquated notions of civic and collective duty. Feelings are the beacon we entrust with shining a path through the fog to guide us home—anger and aggrievement, maybe, on the right of the political spectrum, and on the left something akin to defensive self-righteousness.

It's almost as though we lay our fate at the feet of feelings and wait for deliverance.

In the realm of emotion, hope guards against despair, whose rationalized intellectual output is cynicism—a free pass out of the tension of grappling with our responsibility to the future, with the difficulty and possible unpleasantness of engagement and resistance. But like cynicism, hope is its own free pass, filling the space of subjectivity with a passive expectation of relief. For the most part "hope" functions as a unit of rhetoric, as amorphous as "happiness" or "freedom": a shredded flag in the discourse around climate doomsaying and denial that can only droop over a citadel under relentless siege. If we rely on hope, we give up agency. And that may be seductive, but it's also surrender.

It's possible that feelings aren't our most useful gift. Other animals have feelings too, yet they haven't radically modified the planet toward unlivability; we've done so by pairing our feelings with the unique combination of capabilities that were our species' answers to the pressures of evolution. These include communication and collaboration, the sophisticated languages we share, our ability to conceptualize a distant past and future and make tools with our opposable thumbs—capacities that, together, have allowed us to construct empires and complex machines and cast our intelligence into the deep sea and the far-off thermosphere. Even beyond the sun.

Yet the mission we chose to undertake has been one guided by desire and by a framework of ideas we've built to justify projecting that desire into the appropriation and liquidation of our resource base. The result has been voracious production and reproduction. Over the course of just a handful of fast-moving centuries, that hysterical vector of taking and making has landed us in a state of emergency that suddenly appears, with a high degree of credibility, poised to bury us under the sea or burn us off the land: in effect to steam open our small envelope of life and peel our paper-thin atmosphere, forests and rivers, grasslands and tundra and reefs and polar icescapes and the creatures they sustain, right off the surface of the world.

To fathom the danger of our situation, to let its immediacy dawn on us and drive us to act, it's true that emotion is required. But in the stable of emotions to which we have ready access, hope is a pale horse. To spark an understanding of our history of error and push us to reconceive and heal as passionately as we now lay waste, we need to embrace a more extraordinary recognition.

We need shock and awe in the face of the majesty and fragility of nature, humility in the face of the vastness of the transformations our kind has set in motion—a bristling realization of imminent peril, a visceral apprehension of the nonfungibility of our zone of life. Of this marvelous place, infinitesimal in the solar system if not the galaxy, that has given us, on the thin skin of a solitary planet, the combination of flowing water and breathable air that are the preconditions for life.

More than ordinary emotions, we need an encounter with the shock of our finitude, a sensation of awe, reverence, and astonishment before the richness and precariousness of being.

Ordinary emotions let us blunder through the onslaught of information in the slow befuddlement of a stubborn belief that the familiar is bound to persist. But without a swift, far-reaching, and cooperative global effort, the familiar will *not* persist. Social and political stability will vanish along with biological and geophysical vanishments—the disappearance of coral reefs, for instance, whose absence will denude the oceans of diversity, or the collapse of the AMOC, the Atlantic meridional overturning circulation, under the influx of fresh water from melting ice, which could render Northern Europe inhospitably cold, raise sea levels along the US Eastern Seaboard, and overheat the tropics.

In the realm of emotion, awe is the prerequisite to action. Not hope. Only awe can drive us to work as frenziedly from fear as, it might be argued, we've worked from greed until now. And whether it's music or nature or art or religion that leaves us awestruck or just a simple decision to suddenly, deeply notice the world beyond ourselves, each of these requires the suspension of chatter—a willingness to halt and stand still within the rushing momentum of daily life.

If we wish to thrive beyond it, the next century will have to be a time of unmaking and remaking: unmaking the technologies and culture of fossil fuels and their massive, entrenched infrastructure and remaking our template for prosperity from one based on limitless growth into one aimed at accommodation to a delicate biosphere. This means, among other key policy steps, defending and funding reproductive rights, equity, and education both at home and abroad—chiefly for women, since women's access to education is a central driver of the lower birth rates that will be crucial to living within our means.

Only awe can drive us to work as frenziedly from fear as, it might be argued, we've worked from greed until now.

To champion makerdom alone as the answer is to add willful ignorance to hubris. It's a fact that we need to manufacture and rapidly propagate better tools—energy and food delivery systems that don't disintegrate our life support to fuel our daily activities—and, equally, it's a lie that better making by itself can save us or the other life forms we depend on.

Less making and unmaking are also the solution—less making of what we do not need and more unmaking of harmful machines and ideas. The sprawling patrimony of bad ideas—that *Homo sapiens* reigns supreme over nature and so is miraculously independent of it, in defiance of ecology and physics; that market capitalism is the unassailable apogee of civilization and ongoing expansion the correct communal goal, including endless human procreation cheered on by neoliberal economists who whinge over declining birth rates in industrialized nations—should be dismantled as steadily as the destructive machines.

Neither the United States nor the world community has mechanisms in place to adequately curb potentially catastrophic enterprise, either when that enterprise is demonstrably causing climate chaos or when it purports to meet the demand for fixes. Treaties made under international law have been famously toothless to date, while the US legal system, which *does* possess sharp teeth, defers to the legislative bounds established by a Congress deeply beholden to fossil fuels and related industries bent on maintaining the status quo. And that legal system, far from being disposed to address the exceptionally high public health and security risks posed by climate change and extinction, is clearly, through the recent stacking of courts with antigovernment and antiscience jurists, in the business of radically increasing its deference to private actors as it erodes the rights of the dispossessed and the power of federal oversight.

If we in this country can't rely on the legislative or judicial branches of our central government to tackle the crises of their own volition, while the executive branch directs, at best, movement toward renewables without movement away from fossils; if we can't rely on the myopic and nihilistic companies dominating the energy sector to pivot anytime soon; then who remains to help us? To whom can we turn, we who exist, always and only, here and nowhere else, in this walled city of the Earth under such terrible siege?

The answer may be, for now, only ourselves. Those of us who have language and believe in the wisdom science can offer. Who know the surpassing vulnerability of the rivers and prairies, the jungles and wetlands, the cypress swamps of South Florida, the Cape Floristic Region of South Africa, the Siberian taiga, the Tropical Andes, Madagascar, the island Caribbean. Who can gaze into the future and, beholding the prospect of a frightening and emptier world for our descendants, feel compelled to fight on behalf of the one we have. ■

Lydia Millet is the author of more than a dozen novels, including A Children's Bible; her most recent book, We Loved It All: A Memory of Life, is her first work of nonfiction.

CLIVE THOMPSON

We're entering the age of the moving image

Our information landscape will be filled with video.

The other day I idly opened TikTok to find a video of a young woman refinishing an old hollow-bodied electric guitar.

It was a montage of close-up shots—looking over her shoulder as she sanded and scraped the wood, peeled away the frets, expertly patched the cracks with filler, and then spray-painted it a radiant purple. She compressed days of work into a tight 30-second clip. It was mesmerizing.

Of course, that wasn't the only video I saw that day. In barely another five minutes of swiping around, I saw a historian discussing the songs Tolkien wrote in *The Lord of the Rings*; a sailor puzzling over a capsized boat he'd found deep at sea; a tearful mother talking about parenting a child with ADHD; a Latino man laconically describing a dustup with his racist neighbor; and a linguist discussing how Gen Z uses video-game metaphors in everyday life.

I could go on. I will! And so, probably, will you. This is what the internet looks like now. It used to be a preserve of text and photos—but increasingly, it is a forest of video.

This is one of the most profound technology shifts that will define our future: We are entering the age of the moving image.

For centuries, when everyday people had to communicate at a distance, they really had only two options. They could write something down; they could send a picture. The moving image was too expensive to shoot, edit, and disseminate. Only pros could wield it.

The smartphone, the internet, and social networks like TikTok have rapidly and utterly transformed this situation. It's now common, when someone wants to hurl an idea into the world, not to pull out a keyboard and type but to turn on a camera and talk. For many young people, video might be *the* prime way to express ideas.

As media thinkers like Marshall McLuhan have intoned, a new medium changes us. It changes the way we learn, the way we think—and what we think *about*. When mass printing emerged, it helped create a culture of news, mass literacy, and bureaucracy, and—some argue—the very idea of scientific evidence. So how will mass video shift our culture?

"My students were like, 'If there's a video over seven seconds, we're not watching it.'"

For starters, I'd argue, it is helping us share knowledge that used to be damnably hard to capture in text. I'm a long-distance cyclist, for example, and if I need to fix my bike, I don't bother reading a guide. I look for a video explainer. If you're looking to express—or absorb—knowledge that's visual, physical, or proprioceptive, the moving image nearly always wins. Athletes don't read a textual description of what they did wrong in the last game; they watch the clips. Hence the wild popularity, on video platforms, of instructional video—makeup tutorials, cooking demonstrations. (Or even learn-to-code material: I learned Python by *watching* coders do it.)

Video also is no longer about mere broadcast, but about conversation—it's a way to respond to others, notes Raven Maragh-Lloyd, the author of *Black Networked Resistance* and a professor of film and media studies at Washington University. "We're seeing a rise of audience participation," she notes, including people doing "duets" on TikTok or response videos on YouTube. Everyday creators see video platforms as ways to talk back to power.

There's also an increasingly sophisticated lexicon of visual styles. Today's video creators riff on older film aesthetics to make their points. Brianna Wiens, an assistant professor of digital media and rhetoric at Waterloo University, says she admired how a neuroscientist used stop-motion video, a technique from the early days of film, to produce TikTok discussions of vaccines during the height of the covid-19 pandemic. Or consider the animated GIF, which channels the "zoetrope" of the 1800s, looping a short moment in time to examine over and over.

Indeed, as video becomes more woven into the vernacular of daily life, it's both expanding and contracting in size. There are streams on Twitch where you can watch someone for hours—and viral videos where someone compresses an idea into mere seconds. Those latter ones have a particular rhetorical power because they're so ingestible. "I was teaching a class called Digital Lives, and my students were like, *If there's a video over seven seconds, we're not watching it*," Wiens says, laughing.

Are there dangers ahead as use of the moving image grows? Possibly. Maybe it will too powerfully reward people with the right visual and physical charisma. (Not necessarily a novel danger: Text and radio had their own versions.) More subtly, video is technologically still adolescent. It's not yet easy to search, or to clip and paste and annotate and collate—to use video for quietly organizing our thoughts, the way we do with text. Until those tool sets emerge (and you can see

that beginning), its power will be limited. Lastly, maybe the moving image will become so common and go-to that'll kill off print culture.

Media scholars are not terribly stressed about this final danger. New forms of media rarely kill off older ones. Indeed, as the late priest and scholar Walter Ong pointed out, doing television and radio requires writing plenty of text—all those scripts. Today's moving-media culture is possibly even more saturated with writing. Videos on Instagram and TikTok often include artfully arranged captions, "diegetic" text commenting on the action, or data visualizations. You read while you watch; write while you shoot.

"We're getting into all kinds of interesting hybrids and relationships," notes Lev Manovich, a professor at the City University of New York. The tool sets for sculpting and editing video will undoubtedly improve too, perhaps using AI to help auto-edit, redact, summarize.

One firm, Reduct, already offers a clever trick: You alter a video by editing the transcript. Snip out a sentence, and it snips out the related visuals. Public defenders use it to parse and edit police videos. They're often knee-deep in the stuff—the advent of body cameras worn by officers has produced an ocean of footage, as Reduct's CEO, Robert Ochshorn, tells me.

Meanwhile, generative AI will make it easier to create a film out of pure imagination. This means, of course, that we'll see a new flood of visual misinformation. We'll need to develop a sharper culture of finding the useful amid the garbage. It took print a couple of *centuries* to do that, as scholars of the book will tell you—centuries during which the printing press helped spark untold war and upheaval. We'll be living through the same process with the moving image.

So strap yourselves in. Whatever else happens, it'll be interesting. ■

Clive Thompson is the author of Coders: The Making of a New Tribe and the Remaking of the World.

KATYA KLINOVA

What will AI mean for economic inequality?

If we're not careful, we could see widening gaps within countries and between them.

Prominent AI researchers expect the arrival of artificial general intelligence anywhere between "the next couple of years" and "possibly never." At the same time, leading economists disagree about the potential impact of AI: Some anticipate a future of perpetually accelerating productivity, while others project more modest gains. But most experts agree that technological advancement, however buoyant, is no guarantee that everyone benefits.

And unfortunately, even though some of the most notable AI R&D efforts declare that making sure everyone benefits is a key goal or guiding principle, ensuring that AI helps create a more inclusive future remains one of the least invested-in areas of AI governance. This might seem natural given the state of the field: The impact AI will have on labor and inequality is still highly uncertain, making it difficult to design interventions. But we know at least some of the factors that will influence the interplay between AI and inequality over the next few decades. Paying attention to those can help us make the idea that AI will benefit everyone into more than just a pipe dream.

Because they're largely driven by the private sector, AI development and use are heavily influenced by the incentive structures of the world's economies. And if there is something important that can be predicted with reasonable certainty about those economies, it is their future demographic composition. There is a stark divide between higher-income countries, whose populations are aging rapidly and will shrink without migration, and low- and lower-middle income countries, which will continue to grow for the rest of the century thanks to the excess of births over deaths.

What does this have to do with AI? AI development is concentrated in the aging countries, and thus it will follow the path set by the realities, needs, and incentives in those places. Aging countries are seeing the ratio of working-age people to retirees collapse, making it more difficult to sustain pension schemes and contain health-care costs. Countries looking to maintain their retirees' living standards and their overall economic dynamism will seek ways to expand their effective labor force, be that with humans or with artificial agents. Limited (and likely highly unpopular) gains could come from increasing the retirement age. More sizable gains could come from immigration. But keeping the ratio of the working-age to retiree populations constant would require a significant increase in immigration to the higher-income countries. Widespread anti-immigration sentiment makes that seem unlikely, though opinions could change relatively quickly when people are faced with the prospect of diminishing pensions and rising health-care costs.

If overly restrictive immigration policies do not relax in rich countries, we will likely see the economic incentives to fill labor gaps with AI go into overdrive over the next few decades. It might seem on the surface that this won't exacerbate inequality if there are fewer people than available jobs. But if the trend is associated with an uneven distribution of gains and losses, increasingly precarious employment, excessive surveillance of workers, and digitization of their know-how without adequate compensation, we should expect a spike in inequality.

And even if the efforts to replace labor with AI unfold incredibly well for the populations of rich countries, they might dramatically deepen inequality *between* countries. For the rest of the 21st century, lower-income countries will continue to have young, growing populations in need not of labor-replacing tech, but of gainful employment. The problem is that machines invented to fill in for missing workers in countries with labor shortages often quickly spread even to countries where unemployment is in the double digits and the majority of the working population is employed by unregistered informal businesses. That is how we find self-service kiosks in South African restaurants and Indian airports, replacing formal-sector jobs in these and many more countries struggling to create enough of them.

In such a world, many beneficial applications of AI could remain relatively underdeveloped compared with the merely labor-saving ones. For example, efforts to develop AI for climate-change resilience, early prediction of natural disasters, or affordable personalized tutoring might end up taking a back seat to

projects geared to cutting labor costs in retail, hospitality, and transportation. Deliberate, large-scale efforts by governments, development banks, and philanthropies will be needed to make sure AI is used to help address the needs of poorer countries, not only richer ones. The budgets for such efforts are currently quite small, leaving AI on its default path—which is far from inclusive.

But default is not destiny. We could choose to channel more public R&D efforts toward pressing global challenges like accelerating the green transition and improving educational outcomes. We could invest more in creating and supporting AI development hubs in lower-income countries. Policy choices that allow for greater labor mobility would help create a more balanced distribution of the working-age population between countries and relieve the economic pressures that would drive commercial AI to displace jobs. If we do none of that, distorted incentives will continue to shape this powerful technology, leading to profound negative consequences not only for lower-income countries but for everyone. ■

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RAY KURZWEIL

Technology will let us fully realize our humanity

Advances in AI and medicine will afford us unprecedented freedom.

By the end of this decade, AI will likely surpass humans at all cognitive tasks, igniting the scientific revolution that futurists have long imagined. Digital scientists will have perfect memory of every research paper ever published and think a million times faster than we can. Our plodding progress in fields like robotics, nanotechnology, and genomics will become a sprint. Within the lifetimes of most people alive today, society will achieve radical material abundance, and medicine will conquer aging itself. But our destiny isn't a hollow *Jetsons* future of gadgetry and pampered boredom. By freeing us from the struggle to meet the most basic needs, technology will serve our deepest human aspirations to learn, create, and connect.

This sounds fantastically utopian, but humans have made such a leap before. Our hunter-gatherer ancestors lived on a razor's edge of precarity. Every winter was a battle with starvation. Violence or infection likely killed most people before age 30. The constant struggle to survive left little opportunity for invention or philosophy. But the discovery of agriculture afforded just enough stability to create a feedback loop. Material surplus meant some could develop skills that created even larger surpluses. In a blink of evolutionary time, civilization appeared—literature, law, science, engineering. While modern life can often feel like a rat race, to our paleolithic ancestors, we would seem to enjoy impossible abundance and freedom.

What will the next leap look like? One of the first shifts will be in learning. From the ancient Greeks through the Enlightenment, education's primary goal was to nourish the mind and cultivate virtue. But the Industrial Revolution reframed education as training for economic success in an increasingly technical society. Today, kids are told from an early age that they have to study for instrumental reasons—to get into a good college, to get into a good grad school, to get a good job. All too often, this deadens their natural curiosity and love of learning.

As superhuman AI makes most goods and services so abundant as to be almost free, the need to structure our lives around jobs will fade away. We'll then be free to learn for its own sake—nurturing the knowledge and wisdom that define our humanity. And learning itself will become vastly richer. Instead of just reading about Rome in dry text, you'll be able to explore the Forum in virtual reality and debate an AI Cicero trained on the original's speeches. Instead of getting lost in a crowded lecture hall, you'll work one on one with a supremely patient digital tutor that's been trained by the greatest teachers on Earth and knows exactly how you learn best.

AI tools will also supercharge your creativity. Today, expressing your artistic impulses requires both technical skill and resources—for films and games, sometimes hundreds of millions of dollars. These bottlenecks keep countless brilliant ideas trapped in people's heads, and we are all poorer for it. But systems like Midjourney and Sora let us glimpse a different future. You'll be able to speak a painting into being like a muse in Rembrandt's ear. Or you'll hum a tune and then work with a digital Wagner to orchestrate it into a symphony.

Thanks to this creative revolution, the coming medical breakthroughs won't just offer longer lives but fuller ones, enriched by all the art, music, literature, film, and games created by humanity during those extra years. Most important, you'll share all this with the people you love most. Imagine being healthy as you watch your great-grandchildren grow into adults! And material abundance will ease economic pressures and afford families the quality time together they've long yearned for.

This is the profound leap that awaits us—a future where our technological wonders don't diminish our humanity but allow it to flourish. ■

Ray Kurzweil is a technologist and futurist and the author, most recently, of The Singularity Is Nearer: When We Merge with AI.

JESSICA HAMZELOU

We could extend our lives—or at least our health

Longevity researchers are exploring a range of different approaches.

The UK's Office of National Statistics has an online life expectancy calculator. Enter your age and sex, and the website will, using national averages, spit out the age at which you can expect to pop your clogs. For me, that figure is coming out at 88 years old.

That's not too bad, I figure, given that globally, life expectancy is around 73. But I'm also aware that this is a lowball figure for many in the longevity movement, which has surged in recent years. When I interview a scientist, doctor, or investor in the field, I always like to ask about personal goals. I've heard all sorts. Some have told me they want an extra decade of healthy life. Many want to get to 120, close to the current known limit of human age. Others have told me they want to stick around until they're 200. And some have told me they don't want to put a number on it; they just want to live for as long as they possibly can—potentially indefinitely.

How far can they go? This is a good time to ask the question. The longevity scene is having a moment, thanks to a combination of scientific advances, public interest, and an unprecedented level of investment. A few key areas of research suggest that we might be able to push human life spans further, and potentially reverse at least some signs of aging.

Take, for example, the concept of cellular reprogramming. Nobel Prize–winning research has shown it is possible to return adult cells to a "younger" state more like that of a stem cell. Billions of dollars have been poured into trying to transform this discovery into a therapy that could wind back the age of a person's cells and tissues, potentially restoring some elements of youth.

Many other avenues are being explored, including a diabetes drug that could have broad health benefits; drugs based on a potential anti-aging compound discovered in the soil of Rapa Nui (Easter Island); attempts to rejuvenate the immune system; gene therapies designed to boost muscle or extend the number of times our cells can divide; and many, many more. Other researchers are pursuing ways to clear out the aged, worn-out cells in our bodies. These senescent cells appear to pump out chemicals that harm the surrounding tissues. Around eight years ago, scientists found that mice cleared of senescent cells lived 25% longer than untreated ones. They also had healthier hearts and took much longer to develop age-related diseases like cancer and cataracts. They even looked younger.

Unfortunately, human trials of senolytics—drugs that target senescent cells—haven't been quite as successful. Unity Biotechnology, a company cofounded by leading researchers in the field, tested such a drug in people with osteoarthritis. In 2020, the company officially abandoned that drug after it was found to be no better than a placebo in treating the condition.

That doesn't mean we won't one day figure out how to treat age-related diseases, or even aging itself, by targeting senescent cells. But it does illustrate how complicated the biology of aging is. Researchers can't even agree on what the exact mechanisms of aging are and which they should be targeting. Debates continue to rage over how long it's possible for humans to live—and whether there is a limit at all.

Still, we are getting better at testing potential therapies in more humanlike models. We're finding new and improved ways to measure the aging process itself. The X Prize is offering $101 million to researchers who find a way to restore at least 10 years of "muscle, cognitive, and immune function" in 65- to 80-year-olds with a treatment that takes one year or less to administer. Given that the competition runs for seven years, it's a tall order; Jamie Justice, executive director of the X Prize's health-span domain, told me she initially fought back on the challenging goal and told the organization's founder, Peter Diamandis, there was "no way" researchers could achieve it. But we've seen stranger things in science.

Some people are banking on this kind of progress. Not just the billionaires who have already spent millions of dollars and a significant chunk of their time on strategies that might help them defy aging, but also the people who have opted for cryopreservation. There are hundreds of bodies in storage—bodies of people who believed they might one day be reanimated. For them, the hopes are slim. I asked Justice whether she thought they stood a chance at a second life. "Honest answer?" she said. "No."

It looks likely that *something* will be developed in the coming decades that will help us live longer, in better health. Not an elixir for eternal life, but perhaps something—or a few somethings—that can help us stave off some of the age-related diseases that tend to kill a lot of us. Such therapies may well push life expectancy up. I don't feel we need a massive increase, but perhaps I'll feel differently when I'm approaching 88.

The ONS website gives me a one in four chance of making it to 96, and a one in 10 chance of seeing my 100th birthday. To me, that sounds like an impressive number—as long as I get there in semi-decent health.

I'd still be a long way from the current record of 122 years. But it might just be that there are some limitations we must simply come to terms with—as individuals and in society at large. In a 2017 paper making the case for a limit to the human life span, scientists Jan Vijg and Eric Le Bourg wrote something that has stuck with me—and is worth bearing in mind when considering the future of human longevity: "A species does not need to live for eternity to thrive."■

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CLIFF KUANG

Your wish is your command

Enough with the passive consumption; it's way past time we took interfaces back into our own hands.

If you took a walk in Hayes Valley, San Francisco's epicenter of AI froth, and asked the first dude-bro you saw wearing a puffer vest about the future of the interface, he'd probably say something about the movie *Her*, about chatty virtual assistants that will help you do everything from organize your email to book a trip to Coachella to sort your text messages.

Nonsense. Setting aside that *Her* was about how technology manipulates us into a one-sided relationship, you'd have to be pudding-brained to believe that chatbots are the best way to use computers. The real opportunity is close, but it isn't chatbots.

Instead, it's computers built atop the visual interfaces we know, but which we can interact with more fluidly, through whatever combination of voice and touch is most natural. Crucially, this won't just be a computer that we can *use*. It'll also be a computer that empowers us to break and remake it, to whatever ends we want.

Chatbots fail because they ignore a simple fact that's sold 20 billion smartphones: For a computer to be useful, we need an easily absorbed mental model of both its capabilities and its limitations. The smartphone's victory was built on the graphical user interface, which revolutionized how we use computers—and how many computers we use!—because it made it easy to understand what a computer could do. There was no mystery. In a blink, you saw the icons and learned without realizing it.

Today we take the GUI for granted. Meanwhile, chatbots can feel like magic, letting you say anything and get a reasonable-sounding response. But magic is also the power to mislead. Chatbots and open-ended conversational systems are doomed as general-purpose interfaces because while they may seem able to understand anything, they can't actually do everything.

In that gap between anything and everything sits a teetering mound of misbegotten ideas and fatally hyped products.

"But dude, maybe a chatbot could help you book that flight to Coachella?" Sure. But could it switch your reservation when you have a problem? Could it ask you, in turn, which flight is best given your need to be back in Hayes Valley by Friday at 2?

We take interactive features for granted because of the GUI's genius. But with a chatbot, you can never know up front where its abilities begin and end. Yes, the list of things they can do is growing every day. But how do you remember what does and doesn't work, or what's supposed to work soon? And how are you supposed to constantly update your mental model as those capabilities grow?

If you've ever used a digital assistant or smart speaker, you already know that mismatched expectations create products we'll never use to their full potential. When you first tried one, you probably asked it to do whatever you could think of. Some things worked; most didn't. So you eventually settled on asking for just the few things you could remember that *always* worked: timers and music. LLMs, when used as primary interfaces, re-create the trouble that arises when your mental model isn't quite right.

Chatbots have their uses and their users. But their usefulness is still capped because they are open-ended computer interfaces that challenge you to figure them out through trial and error. Instead, we need to combine the ease of natural-language input with machines that will simply show us what they are capable of.

For example, imagine if, instead of stumbling around trying to talk to the smart devices in your home like a doofus, you could simply look at something with your smart glasses (or whatever) and see a right-click for the real world, giving you a menu of what you can control in all the devices that increasingly surround us. It won't be a voice that tells you what's possible—it'll be an old-fashioned computer screen, and an old-fashioned GUI, which you can operate with your voice or with your hands, or both in combination if you want.

Why shouldn't we be able to not merely consume technology but instead architect it to suit our own ends?

But that's still not the big opportunity!

I think the future interface we want is made from computers and apps that work in ways similar to the phones and laptops we have now—but that we can remake to suit whatever uses we want. Compare this with the world we have now: If you don't like your hotel app, you can't make a new one. If you don't want all the bloatware in your banking app, tough luck. We're surrounded by apps that are nominally tools. But unlike any tool previously known to man, these are tools that serve only the purpose that someone else defined for them. Why shouldn't we be able to not merely consume technology, like the gelatinous former Earthlings in *Wall-E*, but instead architect technology to suit our own ends?

That world seemed close in the 1970s, to Steve Wozniak and the Homebrew Computer Club. It seemed to approach again in the 1990s, with the World Wide Web. But today, the imbalance between people who own computers and people who remake them has never been greater. We, the heirs of the original tool-using primates, have been reduced from wielders of those tools to passive consumers of technology delivered in slick buttons we can use but never change. This runs against what it is to be *Homo sapiens*, a species

defined by our love and instinct for repurposing tools to whatever ends we like.

Imagine if you didn't have to accept the features some tech genius announced on a wave of hype. Imagine if, instead of downloading some app someone else built, you could describe the app you wanted and then make it with a computer's help, by reassembling features from any other apps ever created. Comp sci geeks call this notion of recombining capabilities "composability." I think the future is composability—but composability that anyone can command.

This idea is already lurching to life. Notion—originally meant as enterprise software that let you collect and create various docs in one place—has exploded with Gen Z, because unlike most software, which serves only a narrow or rigid purpose, it allows you to make and share templates for how to do things of all kinds. You can manage your finances or build a kindergarten lesson plan in one place, with whatever tools you need.

Now imagine if you could tell your phone what kinds of new templates you want. An LLM can already assemble all the things you need and draw the right interface for them. Want a how-to app about knitting? Sure. Or your own guide to New York City? Done. That computer will probably be using an LLM to assemble these apps. Great. That just means that you, as a normie, can inspect and tinker with the prompt powering the software you just created, like a mechanic looking under the hood.

One day, hopefully soon, we'll look back on this sad and weird era when our digital tools were both monolithic and ungovernable as a blip when technology conflicted with the human urge to constantly tinker with the world around us. And we'll realize that the key to building a different relationship with technology was simply to give each of us power over how the interface of the future is designed. ■

Cliff Kuang is a user-experience designer and the author of User Friendly: How the Hidden Rules of Design Are Changing the Way We Live, Work, and Play.

LEO HERRERA

AI and the future of sex

What if the rise of AI-generated porn is a symptom of a new synthetic sexuality, not the cause?

The power of pornography doesn't lie in arousal but in questions. *What is obscene? What is ethical or safe to watch?*

We don't have to consume or even support it, but porn will still demand answers. The question now is: *What is "real" porn?*

Anti-porn crusades have been at the heart of the US culture wars for generations, but by the start of the 2000s, the issue had lost its hold. Smartphones made porn too easy to spread and hard to muzzle. Porn became a politically sticky issue, too entangled with free speech and evolving tech. An uneasy truce was made: As long as the imagery was created by consenting adults and stayed on the other side of paywalls and age verification systems, it was to be left alone.

But today, as AI porn infiltrates dinner tables, PTA meetings, and courtrooms, that truce may not endure much longer. The issue is already making its way back into the national discourse; Project 2025, the Heritage Foundation–backed policy plan for a future Republican administration, proposes the criminalization of porn and the arrest of its creators.

But what if porn is wholly created by an algorithm? In that case, whether it's obscene, ethical, or safe becomes

secondary to *What does it mean for porn to be "real"—and what will the answer demand from all of us?*

During my time as a filmmaker in adult entertainment, I witnessed seismic shifts: the evolution from tape to digital, the introduction of new HIV preventions, and the disruption of the industry by free streaming and social media. An early tech adopter, porn was an industry built on desires, greed, and fantasy, propped up by performances and pharmaceuticals. Its methods and media varied widely, but the one constant was its messy humanity. Until now.

When AI-generated pornography first emerged, it was easy to keep a forensic distance from the early images and dismiss them as a parlor trick. They were laughable and creepy: cheerleaders with seven fingers and dead, wonky eyes. Then, seemingly overnight, they reached uncanny photorealism. Synthetic erotica, like hentai and CGI, has existed for decades, but I had *never* seen porn like this. These were the hallucinations of a machine trained on a million pornographic images, both the creation of porn and a distillation of it. Femmes fatales with psychedelic genitalia, straight male celebrities in same-sex scenes, naked girls in crowded grocery stores—posted not in the dark corners of the internet but on social media. The images were glistening and warm, raising fresh questions about consent and privacy. What would these new images turn *us* into?

In September of 2023, the small Spanish town of Almendralejo was forced to confront this question. Twenty girls returned from summer break to find naked selfies they'd never taken being passed around at school. Boys had rendered the images using an AI "nudify" app with just a few euros and a yearbook photo. The girls were bullied and blackmailed, suffered panic attacks and depression. The youngest was 11. The school and parents were at a loss. The tools had arrived faster than the speed of conversation, and they did not discriminate. By the end of the school year, similar cases had spread to Australia, Quebec, London, and Mexico. Then explicit AI images of Taylor Swift flooded social media. If she couldn't stop this, a 15-year-old from Michigan stood no chance.

The technology behind pornography never slows down, regardless of controversies. When students return to school this fall, it will be in the shadow of AI video engines like Sora and Runway 3, which produce realistic video from text prompts and photographs. If still images have caused so much global havoc, imagine what video could do and where the footage could end up.

As porn becomes more personal, it's also becoming more personalized. Users can now check boxes on a list of options as long as the Cheesecake Factory menu to create their ideal scenes: categories like male, female, and trans; ages from 18 to 90; breast and penis size; details like tan lines and underwear color; backdrops like grocery stores, churches, the Eiffel Tower, and Stonehenge; even weather, like tornadoes. It may be *1*s and *0*s, but AI holds no binary; it holds no judgment or beauty standards. It can render seldom-represented bodies, like those of mature, transgender, and disabled people, in all pairings. Hypercustomizable porn will no longer require performers—only selections and an answer to the question "What is it that I *really* like?" While Hollywood grapples with the ethics of AI, artificial porn films will become a reality. Celebrities may boost their careers by promoting their synthetic sex tapes on late-night shows.

What does it mean for porn to be "real"—and what will the answer demand from all of us?

The progress of AI porn may shift our memories, too. AI is already used to extend home movies and turn vintage photos into live-action scenes. What happens when we apply this to sex? Early sexual images etch themselves on us: glimpses of flesh from our first crush, a lost lover, a stranger on the bus. These erotic memories depend on the specific details for their power: a trail of hair, panties in a specific color, sunlight on wet lips, my PE teacher's red gym shorts. They are ideal for AI prompts.

Porn and real-life sex affect each other in a loop. If people become accustomed to getting *exactly* what they want from erotic media, this could further affect their expectations of relationships. A first date may have another layer of awkwardness if each party has already seen an idealized, naked digital doppelganger of the other.

Despite (or because of) this blurring of lines, we may actually start to see a genre of "ethical porn." Without the need for sets, shoots, or even performers, future porn studios might not deal with humans at all. This may be appealing for some viewers, who can be sure that new actors are not underage, trafficked, or under the influence.

A synergy has been brewing since the '90s, when CD-ROM games, life-size silicone dolls, and websites introduced "interactivity" to adult entertainment. Thirty years later, AI chatbot "partners" and cheaper, lifelike sex dolls are more accessible than ever. Porn tends to merge all available tech toward complete erotic immersion. The realism of AI models has already broken the dam to the uncanny valley. Soon, these avatars will be powered by chatbots and embodied in three-dimensional prosthetics, all existing in virtual-reality worlds. What follows will be the fabled sex robot.

So what happens when we've removed the "messy humanity" from sex itself? Porn is defined by the needs of its era. Ours has been marked by increasing isolation. The pandemic further conditioned us to digitize our most intimate moments, bringing us FaceTime hospital visits and weddings, and caused a deep discharge of our social batteries. Adult entertainment may step into that void. The rise of AI-generated porn may be a symptom of a new synthetic sexuality, not the cause. In the near future, we may find this porn arousing because of its artificiality, not in spite of it. ■

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Gene edits will get easier and easier to administer. What does that mean for the future of our species?

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Un-natural selection

By
Antonio Regalado

Illustrations
Michael Byers

In 2016, I attended a large meeting of journalists in Washington, DC. The keynote speaker was Jennifer Doudna, who just a few years before had co-invented CRISPR, a revolutionary method of changing genes that was sweeping across biology labs because it was so easy to use. With its discovery, Doudna explained, humanity had achieved the ability to change its own fundamental molecular nature. And that capability came with both possibility and danger. One of her biggest fears, she said, was "waking up one morning and reading about the first CRISPR baby"—a child with deliberately altered genes baked in from the start.

As a journalist specializing in genetic engineering—the weirder the better—I had a different fear. A CRISPR baby would be a story of the century, and I worried some other journalist would get the scoop. Gene editing had become the biggest subject on the biotech beat, and once a team in China had altered the DNA of a monkey to introduce customized mutations, it seemed obvious that further envelope-pushing wasn't far off.

If anyone did create an edited baby, it would raise moral and ethical issues, among the profoundest of which, Doudna had told me, was that doing so would be "changing human evolution." Any gene alterations made to an embryo that successfully developed into a baby would get passed on to any children of its own, via what's known as the germline. What kind of scientist would be bold enough to try that?

Two years and nearly 8,000 miles in an airplane seat later, I found the answer. At a hotel in Guangzhou, China, I joined a documentary film crew for a meeting with a biophysicist named He Jiankui, who appeared with a retinue of advisors. During the meeting, He was immensely gregarious and spoke excitedly about his research on embryos of mice, monkeys, and humans, and about his eventual plans to improve human health by adding beneficial genes to people's bodies from birth. Still imagining that such a step must lie at least some way off, I asked if the technology was truly ready for such an undertaking.

"Ready," He said. Then, after a laden pause: "Almost ready."

Four weeks later, I learned that he'd already done it, when I found data that He had placed online describing the genetic profiles of two gene-edited human fetuses—that is, "CRISPR babies" in gestation—as well an explanation of his plan, which was to create humans immune to HIV. He had targeted a gene called *CCR5*, which in some people has a variation known to protect against HIV infection. It's rare for numbers in a spreadsheet to make the hair on your arms stand up, although maybe some climatologists feel the same way seeing the latest Arctic temperatures. It appeared that something historic—and frightening—had already happened. In our story breaking the news that same day, I ventured that the birth of genetically tailored humans would be something between a medical breakthrough and the start of a slippery slope of human enhancement.

For his actions, He was later sentenced to three years in prison, and his scientific practices were roundly excoriated. The edits he made, on what proved to be twin girls (and a third baby, revealed later), had in fact been carelessly imposed, almost in an out-of-control fashion, according to his own data. And I was among a flock of critics—in the media and academia—who would subject He and his circle of advisors to Promethean-level torment via a daily stream of articles and exposés. Just this spring, Fyodor Urnov, a gene-editing specialist at the University of California, Berkeley, lashed out on X, calling He a scientific "pyromaniac" and comparing him to a Balrog, a demon from J.R.R. Tolkien's *The Lord of the Rings*. It could seem as if He's crime wasn't just medical wrongdoing but daring to take the wheel of the very processes that brought you, me, and him into being.

Futurists who write about the destiny of humankind have imagined all sorts of changes. We'll all be given auxiliary chromosomes loaded with genetic goodies, or maybe we'll march through life as a member of a pod of identical clones. Perhaps sex will become outdated as we reproduce exclusively through our stem cells. Or human colonists on another planet will be isolated so long that they become their own species. The thing about He's idea, though, is that he drew it from scientific realities close at hand. Just as some gene mutations cause awful, rare diseases, others are being discovered that lend a few people the ability to resist common ones, like diabetes, heart disease, Alzheimer's—and HIV. Such beneficial, superpower-like traits might spread to the rest of humanity, given enough time. But why wait 100,000 years for natural selection to do its job? For a few hundred dollars in chemicals, you could try to install these changes in an embryo in 10 minutes. That is, in theory, the easiest way to go about making such changes—it's just one cell to start with.

Editing human embryos is restricted in much of the world—and making an edited baby is flatly illegal in most countries surveyed by legal scholars. But advancing technology could render the embryo issue moot. New ways of adding CRISPR to the bodies of people already born—children and adults—could let them easily receive changes as well. Indeed, if you are curious what the human genome could look like in 125 years, it's possible that many people will be the beneficiaries of multiple rare, but useful, gene mutations currently found in only small segments of the population. These could protect us against common diseases and infections, but eventually they could also yield frank improvements in other traits, such as height, metabolism, or even cognition. These changes would not be passed on genetically to people's offspring, but if they were widely distributed, they too would become a form of human-directed self-evolution—easily as big a deal as the emergence of computer intelligence or the engineering of the physical world around us.

Why wait 100,000 years for natural selection to do its job? For a few hundred dollars in chemicals, you could try to install these changes in an embryo in 10 minutes.

I was surprised to learn that even as He's critics take issue with his methods, they see the basic stratagem as inevitable. When I asked Urnov, who helped coin the term "genome editing" in 2005, what the human genome could be like in, say, a century, he readily agreed that improvements using superpower genes will probably be widely introduced into adults—and embryos—as the technology to do so improves. But he warned that he doesn't necessarily trust humanity to do things the right way. Some groups will probably obtain the health benefits before others. And commercial interests could eventually take the trend in unhelpful directions—much as algorithms keep his students' noses pasted, unnaturally, to the screens of their mobile phones. "I would say my enthusiasm for what the human genome is going to be in 100 years is tempered by our history of a lack of moderation and wisdom," he said. "You don't need to be Aldous Huxley to start writing dystopias."

Editing early

At around 10 p.m. Beijing time, He's face flicked into view over the Tencent videoconferencing app. It was May 2024, nearly six years after I had first interviewed him, and he appeared in a loftlike space with a soaring ceiling and a wide-screen TV on a wall. Urnov had warned me not to speak with He, since it would be like asking "Bernie Madoff to opine about ethical investing." But I wanted to speak to him, because he's still one of the few scientists willing to promote the idea of broad improvements to humanity's genes.

Of course, it's his fault everyone is so down on the idea. After his experiment, China formally made "implantation" of gene-edited human embryos into the uterus a crime. Funding sources evaporated. "He created this blowback, and it brought to a halt many people's research. And there were not many to begin with," says Paula Amato, a fertility doctor at Oregon Health and Science University who co-leads one of only two US teams that have ever reported editing human embryos in a lab. "And the publicity—nobody wants to be associated with something that is considered scandalous or eugenic."

After leaving prison in 2022, the Chinese biophysicist surprised nearly everyone by seeking to make a scientific comeback. At first, he floated ideas for DNA-based data storage and "affordable" cures for children who have muscular dystrophy. But then, in summer 2023, he posted to social media that he intended to return to research on how to change embryos with gene editing, with the caveat that "no human embryo will be implanted for pregnancy." His new interest was a gene called APP, or amyloid precursor protein. It's known that people who possess a very rare version, or "allele," of this gene almost never develop Alzheimer's disease.

In our video call, He said the APP gene is the main focus of his research now and

that he is determining how to change it. The work, he says, is not being conducted on human embryos, but rather on mice and on kidney cells, using an updated form of CRISPR called base editing, which can flip individual letters of DNA without breaking the molecule.

"We just want to expand the protective allele from small amounts of lucky people to maybe most people," He told me. And if you made the adjustment at the moment an egg is fertilized, you would only have to change one cell in order for the change to take hold in the embryo and, eventually, everywhere in a person's brain. Trying to edit an individual's brain after birth "is as hard a delivering a person to the moon," He said. "But if you deliver gene editing to an embryo, it's as easy as driving home."

In the future, He said, human embryos will "obviously" be corrected for all severe genetic diseases. But they will also receive "a panel" of "perhaps 20 or 30" edits to improve health. (If you've seen the sci-fi film *Gattaca*, it takes place in a world where such touch-ups are routine—leading to stigmatization of the movie's hero, a would-be space pilot who lacks them.) One of these would be to install the APP variant, which involves changing a single letter of DNA. Others would protect against diabetes, and maybe cancer and heart disease. He calls these proposed edits "genetic vaccines" and believes people in the future "won't have to worry" about many of the things most likely to kill them today.

Is He the person who will bring about this future? Last year, in what seemed to be a step toward his rehabilitation, he got a job heading a gene center at Wuchang University of Technology, a third-tier institution in Wuhan. But He said during our call that he had already left the position. He didn't say what had caused the split but mentioned that a flurry of press coverage had "made people feel pressured." One item, in a French financial paper, *Les Echos*, was titled "GMO babies: The secrets of a Chinese Frankenstein." Now he carries out research at his own private lab, he says, with funding from Chinese and American supporters. He has early plans for a startup company. Could he tell me names and locations? "Of course not," he said with a chuckle.

It could be there is no lab, just a concept. But it's a concept that is hard to dismiss. Would you give your child a gene tweak—a swap of a single genetic letter among the 3 billion that run the length of the genome—to prevent Alzheimer's, the mind thief that's the seventh-leading cause of death in the US? Polls find that the American public is about evenly split on the ethics of adding disease resistance traits to embryos. A sizable minority, though, would go further. A 2023 survey published in *Science* found that nearly 30% of people would edit an embryo if it enhanced the resulting child's chance of attending a top-ranked college.

The benefits of the genetic variant He claims to be working with were discovered

Rising promise ...

2005

Scientists at a biotech company, Sangamo Biosciences, coin the term "genome editing."

2012

The advent of CRISPR offers a precise way to rewrite DNA and correct detrimental genes.

2012

Icelandic gene-hunting company deCode Genetics studies a single-letter change in the APP gene, observing that individuals who have it rarely develop Alzheimer's disease.

2014

Researchers in China use CRISPR to create baby monkeys possessing several genetic modifications. The stage is being set for human gene editing.

2017

A team co-led by Paula Amato, a fertility doctor at the Oregon Health and Science University, shares the results of efforts to correct a deadly gene mutation in test embryos. The findings are initially celebrated.

... and pessimism

2018

Chinese biophysicist He Jiankui announces that he has created three edited human babies, whom he'd sought to make immune to HIV. Public outcry is swift, and He is soon jailed.

2023

After his release from prison, He attempts a scientific comeback, outlining a strategy to create humans resistant to Alzheimer's. But he promises "no more gene-edited babies" until society comes around.

by the Icelandic gene-hunting company deCode Genetics. Twenty-six years ago, in 1998, its founder, a doctor named Kári Stefánsson, got the green light to obtain medical records and DNA from Iceland's citizens, allowing deCode to amass one of the first large national gene databases. Several similar large biobanks now operate, including one in the United Kingdom, which recently finished sequencing the genomes of 500,000 volunteers. These biobanks make it possible to do computerized searches to find relationships between people's genetic makeup and real-life differences like how long they live, what diseases they get, and even how much beer they drink. The result is a statistical index of how strongly every possible difference in human DNA affects every trait that can be measured.

In 2012, deCode's geneticists used the technique to study a tiny change in the APP gene and determined that the individuals who had it rarely developed Alzheimer's. They otherwise seemed healthy. In fact, they seemed particularly sharp in old age and appeared to live longer, too. Lab tests confirmed that the change reduces the production of brain plaques, the abnormal clumps of protein that are a hallmark of the disease.

One way evolution works is when a small change or error appears in one baby's DNA. If the change helps that person survive and reproduce, it will tend to become more common in the species—eventually, over many generations, even universal. This process is slow, but it's visible to science. In 2018, for example, researchers determined that the Bajau, a group indigenous to Indonesia whose members collect food by diving, possess genetic changes associated with bigger spleens. This allows them to store more oxygenated red blood cells—an advantage in their lives.

Even though the variation in the APP gene seems hugely beneficial, it's a change that benefits old people, way past their reproductive years. So it's not the kind of advantage natural selection can readily act on. But *we* could act on it. That is what technology-assisted evolution would look like—seizing on a variation we think is useful and spreading it. "The way, probably, that enhancement will be done will be to look at the population, look at people who have enhanced capabilities—whatever those might be," the Israeli medical geneticist Ephrat Levy-Lahad said during a gene-editing summit last year. "You are going to be using variations that already exist in the population that you already have information on."

One advantage of zeroing in on advantageous DNA changes that already exist in the population is that their effects are pretested. The people located by deCode were in their 80s and 90s. There didn't seem to be anything different about them—except their unusually clear minds. Their lives—as seen from the computer screens of deCode's biobank—served as a kind of long-term natural experiment. Yet scientists could not be fully confident placing this variant into an embryo, since the benefits or downsides might differ depending on what other genetic factors are already present, especially other Alzheimer's risk genes. And it would be difficult to run a study to see what happens. In the case of APP, it would take 70 years for the final evidence to emerge. By that time, the scientists involved would all be dead.

When I spoke with Stefánsson last year, he made the case both for and against altering genomes with "rare variants of large effect," like the change in APP. "All of us would like to keep our marbles until we die. There is no question about it. And if you could, by pushing a button, install the kind of protection people with this mutation have, that would be desirable," he said. But even if the technology to make this edit before birth exists, he says, the risks of doing so seem almost impossible to gauge: "You are not just affecting the person, but all their descendants forever. These are mutations that would allow for further selection and further evolution, so this is beginning to be about the essence of who we are as a species."

Editing everyone

Some genetic engineers believe that editing embryos, though in theory easy to do, will always be held back by these grave uncertainties. Instead, they say, DNA editing in living adults could become easy enough to be used not only to correct rare diseases but to add enhanced capabilities to those who seek them. If that happens, editing for improvement could spread just as quickly as any consumer technology or medical fad. "I don't think it's going to be germline," says George Church, a Harvard geneticist often sought out for his prognostications. "The 8 billion of us who are alive kind of constitute the marketplace." For several years, Church has been circulating what he calls "my famous, or infamous, table of enhancements." It's a tally of gene variants that lend people superpowers, including APP and another that leads to extra-hard bones, which was found in a family that

"This is beginning to be about the essence of who we are as a species."

complained of not being able to stay afloat in swimming pools. The table is infamous because some believe Church's inclusion of the HIV-protective *CCR5* variant inspired He's effort to edit it into the CRISPR babies.

Church believes novel gene treatments for very serious diseases, once proven, will start leading the way toward enhancements and improvements to people already born. "You'd constantly be tweaking and getting feedback," he says—something that's hard to do with the germline, since humans take so long to grow up. Changes to adult bodies would not be passed down, but Church thinks they could easily count as a form of heredity. He notes that railroads, eyeglasses, cell phones—and the knowledge of how to make and use all these technologies—are already all transmitted between generations. "We're clearly inheriting even things that are inorganic," he says.

The biotechnology industry is already finding ways to emulate the effects of rare, beneficial variants. A new category of heart drugs, for instance, mimics the effect of a rare variation in a gene, called *PCSK9*, that helps maintain cholesterol levels. The variation, initially discovered in a few people in the US and Zimbabwe, blocks the gene's activity and gives them ultra-low cholesterol levels for life. The drugs, taken every few weeks or months, work by blocking the *PCSK9* protein. One biotech company, though, has started trying to edit the DNA of people's liver cells (the site of cholesterol metabolism) to introduce the same effect permanently.

For now, gene editing of adult bodies is still challenging and is held back by the difficulty of "delivering" the CRISPR instructions to thousands, or even billions of cells—often using viruses to carry the payloads. Organs like the brain and muscles are hard to access, and the treatments can be ordeals. Fatalities in studies aren't unheard-of. But biotech companies are pouring dollars into new, sleeker ways to deliver CRISPR to hard-to-reach places. Some are designing special viruses that can home in on specific types of cells. Others are adopting nanoparticles similar to those used in the covid-19 vaccines, with the idea of introducing editors easily, and cheaply, via a shot in the arm.

At the Innovative Genomics Institute, a center established by Doudna in Berkeley, California, researchers anticipate that as delivery improves, they will be able to create a kind of CRISPR conveyor belt that, with a few clicks of a mouse, allows doctors to design gene-editing treatments for any serious inherited condition that afflicts children, including immune deficiencies so uncommon that no company will take them on. "This is the trend in my field. We can capitalize on human genetics quite quickly, and the scope of the editable human will rapidly expand," says Urnov, who works at the institute. "We know that already, today—and forget 2124, this is in 2024—we can build enough CRISPR for the entire planet. I really, really think that [this idea of] gene editing in a syringe will grow. And as it does, we're going to start to face very clearly the question of how we equitably distribute these resources."

For now, gene-editing interventions are so complex and costly that only people in wealthy countries are receiving them. The first such therapy to get FDA approval, a treatment for sickle-cell disease, is priced at over $2 million and requires a lengthy hospital stay. Because it's so difficult to administer, it's not yet being offered in most of Africa, even though that is where sickle-cell disease is most common. Such disparities are now propelling efforts to greatly simplify gene editing, including a project jointly paid for by the Gates Foundation and the National Institutes of Health that aims to design "shot in the arm" CRISPR, potentially making cures scalable and "accessible to all." A gene editor built along the lines of the covid-19 vaccine might cost only $1,000. The Gates Foundation sees the technology as a way to widely cure both sickle-cell and HIV—an "unmet need" in Africa, it says. To do that, the foundation is considering introducing into people's bone marrow the exact HIV-defeating genetic change that He tried to install in embryos.

Scientists can foresee great benefits ahead—even a "final frontier of molecular liberty," as Christopher Mason, a "space geneticist" at Weill Cornell Medicine in New York, characterizes it. Mason works with newer types of gene editors that can turn genes on or off temporarily. He is using these in his lab to make cells resistant to radiation damage. The technology could be helpful to astronauts or, he says, for a weekend of "recreational genomics"—say, boosting your repair genes in preparation to visit the site of the Chernobyl power plant. The technique is "getting to be, I actually think it is, a euphoric application of genetic technologies," says Mason. "We can say, hey, find a spot on the genome and flip a light switch on or off on any given gene to control its expression at a whim."

Easy delivery of gene editors to adult bodies could give rise to policy questions

Then there's the risk that gene terrorists, or governments, could change people's DNA without their permission or knowledge.

just as urgent as the ones raised by the CRISPR babies. Whether we encourage genetic enhancement—in particular, free-market genome upgrades—is one of them. Several online health influencers have already been touting an unsanctioned gene therapy, offered in Honduras, that its creators claim increases muscle mass. Another risk: If changing people's DNA gets easy enough, gene terrorists or governments could do it without their permission or knowledge. One genetic treatment for a skin disease, approved in the US last year, is formulated as a cream—the first rub-on gene therapy (though not a gene editor).

Some scientists believe new delivery tools should be kept purposefully complex and cumbersome, so that only experts can use them—a biological version of "security through obscurity." But that's not likely to happen. "Building a gene editor to make these changes is no longer, you know, the kind of technology that's in the realm of 100 people who can do it. This is out there," says Urnov. "And as delivery improves, I don't know how we will be able to regulate that."

In our conversation, Urnov frequently returned to that list of superpowers—genetic variants that make some people outliers in one way or another. There is a mutation that allows people to get by on five hours of sleep a night, with no ill effects. There is a woman in Scotland whose genetic peculiarity means she feels no pain and is perpetually happy, though also forgetful. Then there is Eero Mäntyranta, the cross-country ski champion who won three medals at the 1964 Winter Olympics and who turned out to have an inordinate number of red blood cells thanks to an alteration in a gene called the EPO receptor. It's basically a blueprint for anyone seeking to join the Enhanced Games, the libertarian plan for a pro-doping international sports competition that critics call "borderline criminal" but which has the backing of billionaire Peter Thiel, among others.

All these are possibilities for the future of the human genome, and we won't even necessarily need to change embryos to get there. Some researchers even expect that with some yet-to-be-conceived technology, updating a person's DNA could become as simple as sending a document via Wi-Fi, with today's viruses or nanoparticles becoming anachronisms like floppy disks. I asked Church for his prediction about where gene-editing technology is going in the long term. "Eventually you'd get shot up with a whole bunch of things when you're born, or it could even be introduced during pregnancy," he said. "You'd have all the advantages without the disadvantages of being stuck with heritable changes."

And that will be evolution too. ■

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

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The future

A look at what the coming decades hold for those born today.

Happy birthday, baby.

You have been born into an era of intelligent machines. They have watched over you almost since your conception. They let your parents listen in on your tiny heartbeat, track your gestation on an app, and post your sonogram on social media. Well before you were born, you were known to the algorithm.

Your arrival coincided with the 125th anniversary of this magazine. With a bit of luck and the right genes, you might see the next 125 years. How will you and the next generation of machines grow up together? We asked more than a dozen experts to imagine your joint future. We explained that this would be a thought

By
Kara Platoni

Illustrations
David Biskup

starts now

experiment. What I mean is: We asked them to get weird.

Just about all of them agreed on how to frame the past: Computing shrank from giant shared industrial mainframes to personal desktop devices to electronic shrapnel so small it's ambient in the environment. Previously controlled at arm's length through punch card, keyboard, or mouse, computing became wearable, moving onto—and very recently into—the body. In our time, eye or brain implants are only for medical aid; in your time, who knows?

In the future, everyone thinks, computers will get smaller and more plentiful still. But the biggest change in your lifetime will be the rise of intelligent agents. Computing will be more responsive, more intimate, less confined to any one platform. It will be less like a tool, and more like a companion. It will learn from you and also be your guide.

What they mean, baby, is that it's going to be your friend.

Present day to 2034

Age 0 to 10

When you were born, your family surrounded you with "smart" things: rockers, monitors, lamps that play lullabies.

But not a single expert name-checked those as your first exposure to technology. Instead, they mentioned your parents' phone or smart watch. And why not? As your loved ones cradle you, that deliciously blinky thing is *right there*. Babies learn by trial and error, by touching objects to see what happens. You tap it; it lights up or makes noise. Fascinating! Cognitively, you won't get much out of that interaction between birth and age two, says Jason Yip, an associate professor of digital youth at the University of Washington. But it helps introduce you to a world of animate objects, says Sean Follmer, director of the SHAPE Lab in Stanford's mechanical engineering department, which explores haptics in robotics and computing. If you touch something, how does it respond?

You are the child of millennials and Gen Z—digital natives, the first influencers. So as you grow, cameras are ubiquitous. You see yourself onscreen and learn to smile or wave to the people on the other side. Your grandparents read to you on FaceTime; you photobomb Zoom meetings. As you get older, you'll realize that images of yourself are a kind of social currency.

Your primary school will certainly have computers, though we're not sure how educators will balance real-world and onscreen instruction, a pedagogical debate today. But baby, school is where our experts think you will meet your first intelligent agent, in the form of a tutor or coach. Your AI tutor might guide you through activities that combine physical tasks with augmented-reality instruction—a sort of middle ground.

Some school libraries are becoming more like makerspaces, teaching critical thinking along with building skills, says Nesra Yannier, a faculty member in the Human-Computer Interaction Institute at Carnegie Mellon University. She is developing NoRILLA, an educational system that uses mixed reality—a combination of physical and virtual reality—to teach science and engineering concepts. For example, kids build wood-block structures and predict, with feedback from a cartoon AI gorilla, how they will fall.

Learning will be increasingly self-directed, says Liz Gerber, co-director of the Center for Human-Computer Interaction and Design at Northwestern University. The future classroom is "going to be hyper-personalized." AI tutors could help with one-on-one instruction or repetitive sports drills.

All of this is pretty novel, so our experts had to guess at future form factors. Maybe while you're learning, an unobtrusive bracelet or smart watch tracks your performance and then syncs data with a tablet, so your tutor can help you practice.

What will that agent be like? Follmer, who has worked with blind and low-vision students, thinks it might just be a voice. Yannier is partial to an animated character. Gerber thinks a digital avatar could be paired with a physical version, like a stuffed animal—in whatever guise you like. "It's an imaginary friend," says Gerber. "You get to decide who it is."

Not everybody is sold on the AI tutor. In Yip's research, kids often tell him AI-enabled technologies are … creepy. They feel unpredictable or scary or like they seem to be *watching*.

Kids learn through social interactions, so he's also worried about technologies that isolate. And while he thinks AI can handle the cognitive aspects of tutoring, he's not sure about its social side. Good teachers know how to motivate, how to deal with human moods and biology. Can a machine tell when a child is being sarcastic, or redirect a kid who is goofing off in the bathroom? When confronted with a meltdown, he asks, "is the AI going to know this kid is hungry and needs a snack?"

2040

Age 16

By the time you turn 16, you'll likely still live in a world shaped by cars: highways, suburbs, climate change. But some parts of car culture may be changing. Electric chargers might be supplanting gas stations. And just as an intelligent agent assisted in your schooling, now one will drive with you—and probably *for* you.

Paola Meraz, a creative director of interaction design at BMW's Designworks, describes that agent as "your friend on the road." William Chergosky, chief designer at Calty Design Research, Toyota's North American design studio, calls it "exactly like a friend in the car."

While you are young, Chergosky says, it's your chaperone, restricting your speed or routing you home at curfew. It tells you when you're near In-N-Out, knowing your penchant for their animal fries. And because you want to keep up with your friends online *and* in the real world, the agent can comb your social media feeds to see where they are and suggest a meetup.

Cars have long been spots for teen hangouts, but as driving becomes more autonomous, their interiors can become

2049

Age 25

more like living rooms. (You'll no longer need to face the road and an instrument panel full of knobs.) Meraz anticipates seats that reposition so passengers can talk face to face, or game. "Imagine playing a game that interacts with the world that you are driving through," she says, or "a movie that was designed where speed, time of day, and geographical elements could influence the storyline."

Without an instrument panel, how do you control the car? Today's minimalist interiors feature a dash-mounted tablet, but digging through endless onscreen menus is not terribly intuitive. The next step is probably gestural or voice control—ideally, through natural language. The tipping point, says Chergosky, will come when instead of giving detailed commands, you can just say: "Man, it is hot in here. Can you make it cooler?"

An agent that listens in and tracks your every move raises some strange questions. Will it change personalities for each driver? (Sure.) Can it keep a secret? ("Dad said he went to Taco Bell, *but did he*?" jokes Chergosky.) Does it even have to stay in the car?

Our experts say nope. Meraz imagines it being integrated with other kinds of agents—the future versions of Alexa or Google Home. "It's all connected," she says. And when your car dies, Chergosky says, the agent does not. "You can actually take the soul of it from vehicle to vehicle. So as you upgrade, it's not like you cut off that relationship," he says. "It moves with you. Because it's grown with you."

Just as an intelligent agent assisted in your schooling, now one will drive with you—and probably *for* you.

By your mid-20s, the agents in your life know an awful lot about you. Maybe they are, indeed, a single entity that follows you across devices and offers help where you need it. At this point, the place where you need the most help is your social life.

Kathryn Coduto, an assistant professor of media science at Boston University who studies online dating, says everyone's big worry is the opening line. To her, AI could be a disembodied Cyrano that whips up 10 options or workshops your own attempts. Or maybe it's a dating coach. You agree to meet up with a (real) person online, and "you have the AI in a corner saying 'Hey, maybe you should say this,' or 'Don't forget this.' Almost like a little nudge."

Virtual first dates might solve one of our present-day conundrums: Apps make searching for matches *easier*, but you get sparse—and perhaps inaccurate—info about those people. How do you know who's worth meeting in real life? Building virtual dating into the app, Coduto says, could be "an appealing feature for a lot of daters who want to meet people but aren't sure about a large initial time investment."

T. Makana Chock, who directs the Extended Reality Lab at Syracuse University, thinks things could go a step further: first dates where both parties send an AI version of themselves in their place. "That would tell both of you that this is working—or this is definitely not going to work," Chock says. If the date is a dud—well, at least you weren't on it.

Or maybe you will just date an entirely virtual being, says Sun Joo (Grace) Ahn, who directs the Center for Advanced

2049 (continued)

“There is some concern that we are going to see some people who are just like, ‘Nope, this is all I want. Why go out and do that when I can stay home with my partner, my virtual buddy?’”

Computer-Human Ecosystems at the University of Georgia. Or you’ll go to a virtual party, have an amazing time, “and then later on you realize that you were the only real human in that entire room. Everybody else was AI.”

This might sound odd, says Ahn, but “humans are really good at building relationships with nonhuman entities.” It’s why you pour your heart out to your dog—or treat ChatGPT like a therapist.

There is a problem, though, when virtual relationships become *too* accommodating, says Chock: If you get used to agents that are tailored to please you, you get less skilled at dealing with real people and risking awkwardness or rejection. “You still need to have human interaction,” she says. “And there is some concern that we are going to see some people who are just like, ‘Nope, this is all I want. Why go out and do that when I can stay home with my partner, my virtual buddy?’”

By now, social media, online dating, and livestreaming have likely intertwined and become more immersive. Engineers have shrunk the obstacles to true telepresence: internet lag time, the uncanny valley, and clunky headsets, which may now be replaced by something more like glasses or smart contact lenses.

Online experiences may be less like observing someone else’s life and more like *living* it. Imagine, says Follmer: A basketball star wears clothing and skin sensors that track body position, motion, and forces, plus super-thin gloves that sense the texture of the ball. You, watching from your couch, wear a jersey and gloves made of smart textiles, woven with actuators that transmit whatever the player feels. When the athlete gets shoved, Follmer says, your fan gear “can really shove you right back.”

Gaming is another obvious application. But it’s not the likely first mover in this space. Nobody else wants to say this on the record, so I will: It’s porn. (Baby, ask your parents and/or AI tutor when you’re older.)

By your 20s, you are probably wrestling with the dilemmas of a life spent online and on camera. Coduto thinks you might rebel, opting out of social media because your parents documented your first 18 years without permission. As an adult, you’ll want tighter rules for privacy and consent, better ways to verify authenticity, and more control over sensitive materials, like a button that could nuke your old sexts.

But maybe it’s the opposite: Now you are an influencer yourself. If so, your body can be your display space. Today, wearables are basically boxes of electronics strapped onto limbs. Tomorrow, hopes Cindy Hsin-Liu Kao, who runs the Hybrid Body Lab at Cornell University, they will be more like your own skin. Kao develops wearables like color-changing eyeshadow stickers and mini nail trackpads that can control a phone or open a car door. In the not-too-distant future, she imagines, “you might be able to rent out each of your fingernails as an ad for social media.” Or maybe your hair: Weaving in super-thin programmable LED strands could make it a kind of screen.

What if those smart lenses could be display spaces too? “That would be really creepy,” she muses. “Just looking into someone’s eyes and it’s, like, CNN.”

2059

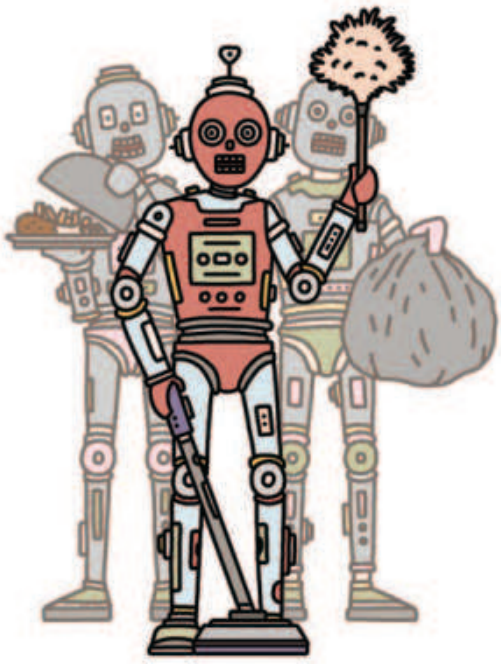
Age 35

By now, you’ve probably settled into domestic life—but it might not look much like the home you grew up in. Keith Evan Green, a professor of human-centered design at Cornell, doesn’t think we should imagine a home of the future. “I would call it a *room* of the future,” he says, because it will be the place for everything—work, school, play. This trend was hastened by the covid pandemic.

Your place will probably be small if you live in a big city. The uncertainties of climate change and transportation costs mean we can’t build cities infinitely outward. So he imagines a reconfigurable architectural robotic space: Walls move, objects inflate or unfold, furniture appears or dissolves into surfaces or recombines. Any necessary computing power is embedded. The home will finally be what Le Corbusier imagined: a machine for living in.

Green pictures this space as spartan but beautiful, like a temple—a place, he says, to think and be. “I would characterize it as this capacious monastic cell that is empty of most things but us,” he says.

Our experts think your home, like your car, will respond to voice or gestural control.



2074

Age 50

But it will make some decisions autonomously, learning by observing you: your motion, location, temperature.

Ivan Poupyrev, CEO and cofounder of Archetype AI, says we'll no longer control each smart appliance through its own app. Instead, he says, think of the home as a stage and you as the director. "You don't interact with the air conditioner. You don't interact with a TV," he says. "You interact with the home as a total." Instead of telling the TV to play a specific program, you make high-level demands of the entire space: "Turn on something interesting for me; I'm tired." Or: "What is the plan for tomorrow?"

Stanford's Follmer says that just as computing went from industrial to personal to ubiquitous, so will robotics. Your great-grandparents envisioned futuristic homes cared for by a single humanoid robot—like Rosie from *The Jetsons*. He envisions swarms of maybe 100 bots the size of quarters that materialize to clean, take out the trash, or bring you a cold drink. ("They know ahead of time, even before you do, that you're thirsty," he says.)

Baby, perhaps now you have your own baby. The technologies of reproduction have changed since you were born. For one thing, says Gerber, fertility tracking will be way more accurate: "It is going to be like weather prediction." Maybe, Kao says, flexible fabric-like sensors could be embedded in panty liners to track menstrual health. Or, once the baby arrives, in nipple stickers that nursing parents could apply to track biofluid exchange. If the baby has trouble latching, maybe the sticker's capacitive touch sensors could help the parent find a better position.

Also, goodbye to sleep deprivation. Gerber envisions a device that, for lack of an existing term, she's calling a "baby handler"—picture an exoskeleton crossed with a car seat. It's a late-night soothing machine that rocks, supplies pre-pumped breast milk, and maybe offers a bidet-like "cleaning and drying situation." For your children, perhaps, this is their first experience of being close to a machine.

Now you are at the peak of your career. For professions heading toward AI automation, you may be the "human in the loop" who oversees a machine doing its tasks. The 9-to-5 workday, which is crumbling in our time, might be totally atomized into work-from-home fluidity or earn-as-you-go gig work.

Ahn thinks you might start the workday by lying in bed and checking your messages—on an implanted contact lens. Everyone loves a big screen, and putting it in your eye effectively gives you "the largest monitor in the world," she says.

You've already dabbled with AI selves for dating. But now virtual agents are more photorealistic, and they can mimic your voice and mannerisms. Why not make one go to meetings for you?

Kori Inkpen, who studies human-computer interaction at Microsoft Research, calls this your "ditto"—more formally, an embodied mimetic agent, meaning it represents a specific person. "My ditto looks like me, acts like me, sounds like me, knows sort of what I know," she says. You can instruct it to raise certain points and recap the conversation for you later. Your colleagues feel as if you were there, and you get the benefit of an exchange that's not quite real time, but not as asynchronous as email. "A ditto starts to blend this reality," Inkpen says.

In our time, augmented reality is slowly catching on as a tool for workers whose jobs require physical presence and tangible objects. But experts worry that once the last baby boomers retire, their technical expertise will go with them. Perhaps they can leave behind a legacy of training simulations.

Inkpen sees DIY opportunities. Say your fridge breaks. Instead of calling a repair person, you boot up an AR tutorial on glasses, a tablet, or a projection that overlays digital instructions atop the appliance. Follmer wonders if haptic sensors woven into gloves or clothing would let people training for highly specialized jobs—like surgery—literally feel the hand motions of experienced professionals.

For Poupyrev, the implications are much bigger. One way to think about AI is "as a storage medium," he says. "It's a preservation of human knowledge." A large language model like ChatGPT is basically a compendium of all the text information people have put online. Next, if we feed models not only text but real-world sensor data that describes motion and behavior, "it becomes a very compressed presentation not of just knowledge, but also of how people *do* things." AI can capture how to dance, or fix a car, or play ice hockey—all the skills you cannot learn from words alone—and preserve this knowledge for the future.

2099

Age 75

By the time you retire, families may be smaller, with more older people living solo.

Well, sort of. Chaiwoo Lee, a research scientist at the MIT AgeLab, thinks that in 75 years, your home will be a kind of roommate—"someone who cohabitates that space with you," she says. "It reacts to your feelings, maybe understands you."

By now, a home's AI could be so good at deciphering body language that if you're spending a lot of time on the couch, or seem rushed or irritated, it could try to lighten your mood. "If it's a conversational agent, it can talk to you," says Lee. Or it might suggest calling a loved one. "Maybe it changes the ambiance of the home to be more pleasant."

The home is also collecting your health data, because it's where you eat, shower, and use the bathroom. Passive data collection has advantages over wearable sensors: You don't have to remember to put anything on. It doesn't carry the stigma of sickness or frailty. And in general, Lee says, people don't start wearing health trackers until they are ill, so they don't have a comparative baseline. Perhaps it's better to let the toilet or the mirror do the tracking continuously.

Green says interactive homes could help people with mobility and cognitive challenges live independently for longer. Robotic furnishings could help with lifting, fetching, or cleaning. By this time, they might be sophisticated enough to offer support when you need it and back off when you don't.

Kao, of course, imagines the robotics embedded in fabric: garments that stiffen around the waist to help you stand, a glove that reinforces your grip.

If getting from point A to point B is becoming difficult, maybe you can travel without going anywhere. Green, who favors a blank-slate room, wonders if you'll have a brain-machine interface that lets you change your surroundings at will. You think about, say, a jungle, and the wallpaper display morphs. The robotic furniture adjusts its topography. "We want to be able to sit on the boulder or lie down on the hammock," he says.

Anne Marie Piper, an associate professor of informatics at UC Irvine who studies older adults, imagines something similar—minus the brain chip—in the context of a care home, where spaces could change to evoke special memories, like your honeymoon in Paris. "What if the space transforms into a café for you that has the smells and the music and the ambience, and that is just a really calming place for you to go?" she asks.

Gerber is all for virtual travel: It's cheaper, faster, and better for the environment than the real thing. But she thinks that for a truly immersive Parisian experience, we'll need engineers to invent … well, remote bread. Something that lets you chew on a boring-yet-nutritious source of calories while stimulating your senses so you get the crunch, scent, and taste of the perfect baguette.

2149

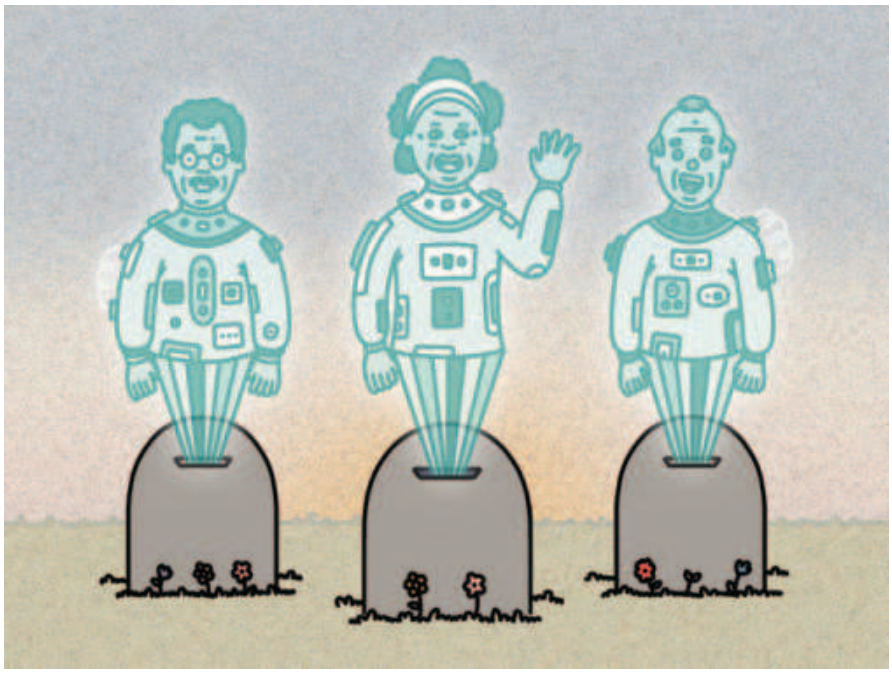
Age 125

We hope that your final years will not be lonely or painful.

Faraway loved ones can visit by digital double, or send love through smart textiles: Piper imagines a scarf that glows or warms when someone is thinking of you, Kao an on-skin device that simulates the touch of their hand. If you are very ill, you can escape into a soothing virtual world. Judith Amores, a senior researcher at Microsoft Research, is working on VR that responds to physiological signals. Today, she immerses hospital patients in an underwater world of jellyfish that pulse at half of an average person's heart rate for a calming effect. In the future, she imagines, VR will detect anxiety without requiring a user to wear sensors—maybe by smell.

You might be pondering virtual immortality. Tim Recuber, a sociologist at Smith College and author of *The Digital Departed*, notes that today people create memorial websites and chatbots, or sign up for post-mortem messaging services. These offer some end-of-life comfort, but they can't preserve your memory indefinitely. Companies go bust. Websites break. People move on; that's how mourning works.

What about uploading your consciousness to the cloud? The idea has a fervent fan base, says Recuber. People hope to resurrect themselves into human or robotic bodies, or spend eternity as part of a hive mind or "a beam of laser light that can travel the cosmos." But he's skeptical that it'll work, especially within 125 years. Plus, what if being a ghost in the machine is *dreadful*?



"It is a little cool to think of cemeteries in the future that are literally haunted by motion-activated holograms."

"Embodiment is, as far as we know, a pretty key component to existence. And it might be pretty upsetting to actually be a full version of yourself in a computer," he says.

There is perhaps one last thing to try. It's another AI. You curate this one yourself, using a lifetime of digital ephemera: your videos, texts, social media posts. It's a hologram, and it hangs out with your loved ones to comfort them when you're gone. Perhaps it even serves as your burial marker. "It is a little cool to think of cemeteries in the future that are literally haunted by motion-activated holograms," Recuber says.

It won't exist forever. Nothing does. But by now, maybe the agent is no longer your friend.

Maybe, at last, it is *you*.

Baby, we have caveats.

We imagine a world that has overcome the worst threats of our time: a creeping climate disaster; a deepening digital divide; our persistent flirtation with nuclear war; the possibility that a pandemic will kill us quickly, that overly convenient lifestyles will kill us slowly, or that intelligent machines will turn out to be *too smart*.

We hope that democracy survives and these technologies will be the opt-in gadgetry of a thriving society, not the surveillance tools of dystopia. If you have a digital twin, we hope it's not a deepfake.

You might see these sketches from 2024 as a blithe promise, a warning, or a fever dream. The important thing is: Our present is just the starting point for infinite futures.

What happens next, kid, depends on you. ■

Kara Platoni is a science reporter and editor in Oakland, California.

Mountain Pass Mine in California, reopened in 2017, currently accounts for about 12% of global rare earth production.

The sustain

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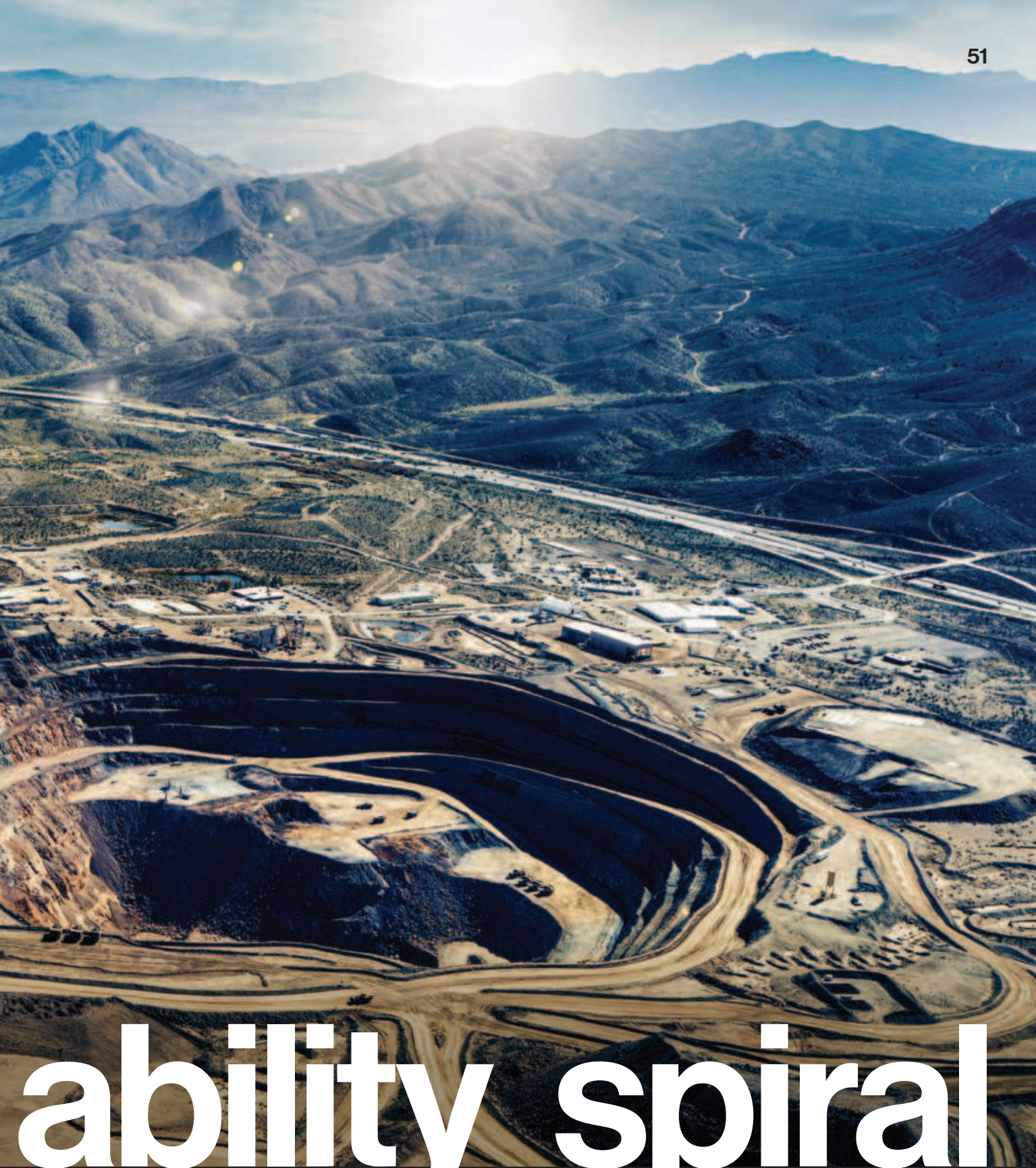
By Casey Crownhart



ability spiral

What one element can tell us about the next century for our planet's resources.

Leaving aside meteorites that strike Earth's surface and spacecraft that get flung out of its orbit, the quantity of materials available on this planet isn't really changing all that much.

That simple fact of our finite resources becomes clearer and more daunting as the pace of technological change advances and our society requires an ever wider array of material inputs to sustain it. So for nearly as long as we've systematically extracted these substances, we've been trying to predict how long they will be able to meet our demand. How much can we pump from a well, or wrest from a mine, before we need to reconsider what we're building and how?

Those predictions have grown increasingly complicated. And now it's also a matter of how much we can pull from manufactured and discarded objects. Can we recycle parts of that iPhone, or the guts of that massive wind turbine? How much of any given object can we recirculate into our churning technological economy?

Estimates of how much material we'll have access to in the future tend to have a tricky, often implicit assumption at their center: that we'll be making roughly the same products with the same materials as today. But technology moves quickly, and by the time we understand what we might need next, or develop a specialized system to mine or recycle it, the next generation of tech might render all our assumptions obsolete.

We're in the middle of a potentially transformative moment. The materials we need to power our world are beginning to shift from fossil fuels to energy sources that don't produce the greenhouse-gas emissions changing our climate. Metals discovered barely more than a century ago now underpin the technologies we're relying on for cleaner energy, and not having enough of them could slow progress.

Take neodymium, one of the rare earth metals. While far from a household name, it's a metal that humans have relied on for generations. Since the early 20th century, neodymium has been used to give decorative glass a purplish hue. Today, it's used in cryogenic coolers to reach ultra-low temperatures needed for devices like superconductors and in high-powered magnets that power everything from smartphones to wind turbines.

Demand for neodymium-based magnets could outstrip supply in the coming decade. The longer-term prospects for the metal's supply aren't as dire, but a careful look at neodymium's potential future reveals many of the challenges we'll likely face across the supply chain for materials in the coming century and beyond.

Peak panic

Before we get into our material future, it's important to point out just how hard it's always been to make accurate predictions of this kind. Just look at our continuous theorizing about the supply of fossil fuels.

One version of the story, told frequently in economics classes, goes something like this: Given that there's a limited supply of oil, at some point the world will run out of it. Before then, we should reach some maximum amount of oil extraction, and then production will start an irreversible decline. That high point is known as "peak oil."

This idea has been traced back as far as the early 1900s, but one of the most famous analyses came from M. King Hubbert, who was a geologist at Shell. In a 1956 paper, Hubbert considered the total amount of oil (and other fossil fuels, like coal and natural gas) that geologists had identified on the planet. From the estimated supply and the amount the world had burned through, he predicted that oil production in the US would peak and begin declining between 1965 and 1970. The peak of world oil production, he predicted, would come a bit later, in 2000.

If we extract, process, use, and discard these metals, conceptually there must be some point in the future when we run out of them.

For a while, it looked as if Hubbert was right. US oil production increased until 1970, when it reached a dramatic peak. It then declined for decades afterward, until about 2010. But then advances in drilling and fracking techniques unlocked hard-to-reach reserves. Oil production skyrocketed in the US through the 2010s, and as of 2023, the country was producing more oil than ever before.

Peak-oil panic has long outlived Hubbert, but every time economists and geologists have predicted that we've reached, or are about to reach, the peak of

PREVIOUS SPREAD: TMY350 VIA WIKIMEDIA COMMONS

Neodymium is crucial for powering many of our devices. And we could be facing a supply crunch.

GETTY IMAGES

oil production, they've missed the mark (so far).

Now there's a new reason we might see fossil-fuel production *actually* peak and eventually fall off: the energy transition. That's shorthand for the grand effort to shift away from energy sources that produce greenhouse gases and toward renewables and other low-carbon options.

Hubbert's theory suggested that a fixed supply would force production to decline from a peak. But as the world wakes up to the dangers of climate change, and as low-carbon energy sources like wind, solar, and nuclear take off, we may wind up leaving some coal, oil, and natural gas in the ground. Simply put, production might head back down because of a lack of demand, not a lack of supply.

Those newly ascendant energy sources, though, are ironically a new source of "peak" panic. Solar panels, wind turbines, and batteries may not require fuel, but they do require a host of metals, including lithium, copper, steel, and rare earths like neodymium.

If we extract, process, use, and discard these metals, conceptually there must be some point in the future when we run out of them. And as the energy transition has gotten underway, plenty of forecasts have attempted to understand which metals we should worry about and when they might start to be depleted. But experts say that understanding the availability of resources in this sector is much more complicated than picking out a single future peak.

"The peak modeling thing is something that doesn't really apply to metals," says Simon Jowitt, director of the Center for Research in Economic Geology at the University of Nevada, Reno. It's nearly impossible to understand whether we've reached a peak in production for any given material, or even whether those peaks can be predicted, as Jowitt said in a 2020 paper.

Let's take a closer look at neodymium. Reserves of the metal—the amount we know about that's economically feasible to extract—have been estimated at 12.8 million tons. To keep the world from warming more than 1.5 °C over preindustrial levels, we might need as much as 121,000 tons every year just for wind turbines, according to a 2023 study on the material demands of the energy transition. Depending on how much material we assume makes it from the mine into final products, we could burn through those reserves in roughly a century.

The problem with this thinking, though, is that reserves and resources are far from fixed. Geologists discover new deposits all the time, for one thing. And what was considered too expensive and difficult to mine a few decades ago might be possible to extract with today's technology. So instead of being slowly depleted, those material supplies have roughly kept up with production.

"We are currently producing more metals than ever before and have more metal resources and reserves than ever before," as Jowitt put it in his paper.

And the question, he says, isn't whether we'll blow through what's theoretically available on the planet, or even whether we'll soon run out of material we can access and mine. It's whether we're willing to accept the social, ecological, and geopolitical consequences of how we mine today, and whether we might be able to change those for the better. Because we may be mining a lot more of some materials in the near future.

Big digs

Demand for rare earths is expected to explode in the coming decades, driven largely by the increased need for neodymium-based magnets. These magnets, commonly made from a mixture of neodymium, iron, and boron with other elements sprinkled in, produce a stronger magnetic field with less material than other magnets available today.

While demand for neo magnets will likely triple in the coming decade, global production of neodymium will only double, according to Adamas Intelligence, a consulting firm specializing in strategic metals and minerals. It can take close to a decade to build new mines, and those long lead times could contribute to a supply crunch, says Seaver Wang, climate co-director at the Breakthrough Institute, an environmental think tank.

Short periods when demand outstrips supply can lead to volatility, high prices, and slower deployment of new technologies. In a time as fast-moving as our current energy transition, those challenging economic conditions could have far-reaching effects, potentially entrenching old technologies and stalling progress.

But despite these expected challenges and the resulting potential for volatility, there is, in theory, plenty of neodymium to go around. Despite their name, most rare earth metals aren't terribly rare. Many are about as abundant in Earth's crust as copper, and neodymium is roughly 1,000 times more common in the crust than platinum or gold.

However, unlike those metals, rare earths aren't often found in concentrated deposits. Getting one ton of metal concentrate can require moving a thousand tons of rocks.

This mining and refining process can be technically complicated and environmentally damaging, in part because rare earth metals are chemically similar to each other and difficult to separate without using harsh chemicals, says Julie Klinger, an associate professor at the University of Delaware who studies the global market for these materials.

Extraction often relies on dissolving crushed-up ore in strong acid. Mines that don't carefully contain the waste material and the used chemicals risk polluting local waterways. Rare earth mines also often need to handle radioactive waste, since elements like thorium and uranium are common in and around the minerals that are mined to extract rare earths.

There are efforts underway to mine without producing dangerous waste, and new sites are attempting to squeeze as much finished product out of their initial mined material as possible, reintroducing scraps back into the refining process so less ends up in the waste. Others are taking another look at waste from previous mining efforts.

But some experts hope to entirely rethink material supply. Instead of extracting new materials, what if we look to what's already been dug out of the ground?

Around and around

Follow the path of many commonly used metals, and you'll likely trace a straight line that leads from the mine to a product and, eventually, to some version of a trash can. In an effort to ease supply concerns and environmental damage, some experts are calling for a new way of using materials, one that focuses on reducing waste or eliminating it altogether.

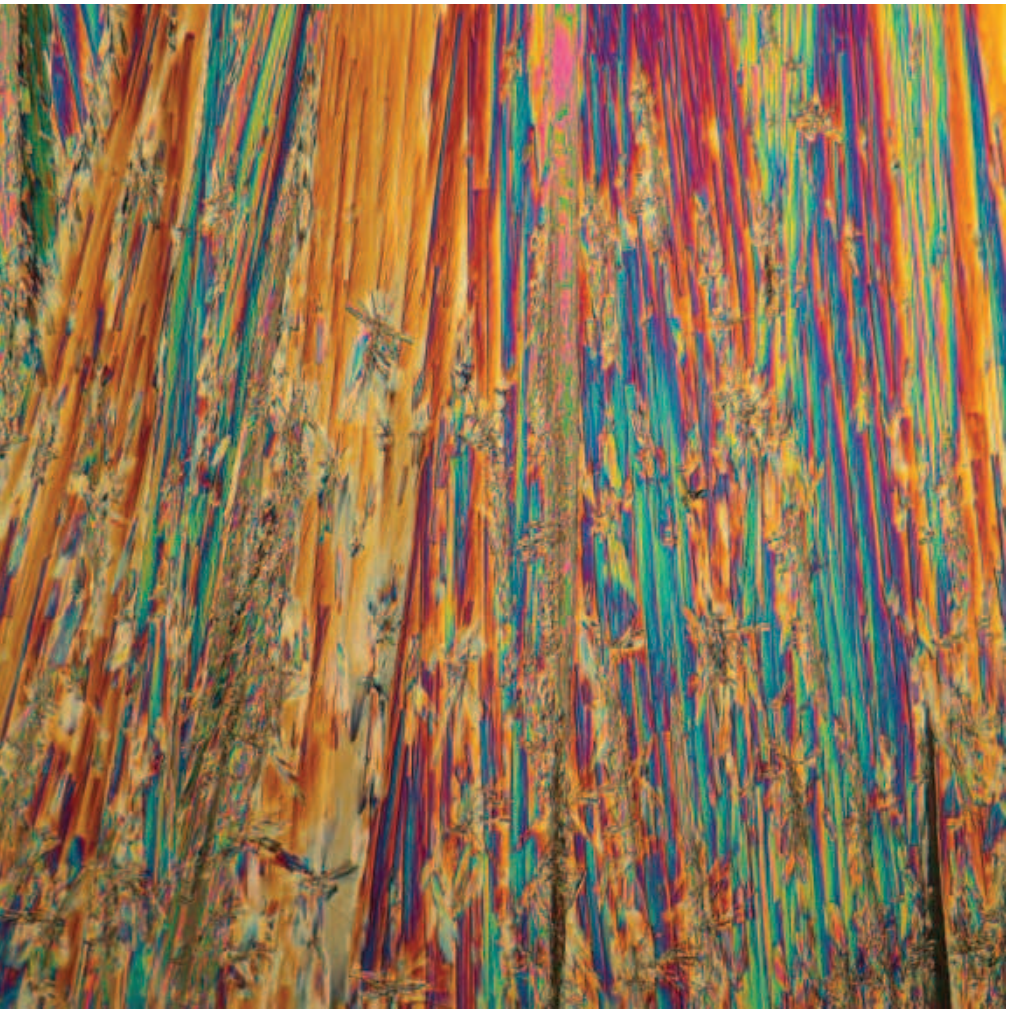
Such a system would bend the line that goes from mine to trash into a new shape, so extracted materials are in use for as long as possible—maybe even forever. A whole host of strategies can extend the lifetime of materials, from repairing and refurbishing products to disassembling them and recycling the metals in them once the products are beyond repair.

This can start well before products even get to consumers, by making the most of materials as they're taken out of the ground. Where recycling really gets difficult is the point at which the materials have left a company and gone into devices, says Ikenna Nlebedim, a research scientist at Ames National Laboratory.

Today, a small but difficult-to-quantify fraction of rare earth elements are recycled from products that have reached the end of their useful life. (Many in the industry put the figure at roughly 1%, though there's little data available on rare earth collection, Nlebedim says.) With the looming increase in expected demand, several companies, including Noveon, REEcycle, and Cyclic Materials, are working to increase that amount, setting up the beginning of a recycling industry.

A major challenge for rising magnet recyclers is that magnets tend to make up a tiny fraction of a product's total weight. Picking through heaps of products to recover them is an imperfect system, and magnet recyclers are left with

Follow the path of many commonly used metals, and you'll likely trace a straight line that leads from the mine to a product and, eventually, to some version of a trash can.



Neodymium nitrate photographed under polarized light.

GETTY IMAGES

other valuable materials that they have no interest in—and no effective process for isolating.

In the future, economical recycling of rare earths might require a broader infrastructure for recycling the rest of a device, Nlebedim says. A centralized dismantling system would allow the recovery of materials like copper, gold, and platinum group metals that are often found in the same products as rare earths. This setup would allow more of the material in waste products to be reused than is possible now, when a company will go after the highest-value, easiest-to-extract materials and toss the rest into a shredder.

Casting a wider net to recover more materials could help create a more stable supply for metals. That could be a major help if the materials considered valuable in the future are different from the ones with the most value today.

Quick shifts

Technology moves quickly, and many of the materials that are critical to us today weren't even in use a century ago.

Just look at the history of Mountain Pass Mine, a rare earth mine in California. The mine's critical product has changed every 20 years or so since production started in 1952, says Michael Rosenthal, cofounder and chief operating officer of MP Materials, the site's owner.

In the 1960s, Mountain Pass produced the europium used in color television screens of the time. In the following decades the target was cerium, which was useful for the glass used in televisions with cathode ray tubes. Since CRTs have been replaced with new technology like LED screens, demand for cerium has decreased. Now the mine focuses on neodymium and praseodymium, another ingredient sometimes used in magnets.

Yet even as geologists are scouting new mines and companies are springing up to start building recycling systems, researchers are working to make rare earth magnets less central to our technological future, or maybe even obsolete.

Today, neodymium is necessary in these powerful magnets to wrangle the electrons in iron so that they spin consistently in the same direction, producing a strong magnetic field. There aren't any alternatives that can match their performance.

However, there could be options on the way. Niron Magnetics is working to build iron nitride magnets, which produce a powerful magnetic field without the need for any rare earth metals. The company opened its first manufacturing facility in early 2024, and while its products can't sub in for high-quality neo magnets just yet, there's no fundamental reason they won't be able to in the future. If Niron or other companies are able to develop new magnets, it could mean a shift in the rare earth market that quickly makes the current magnet recycling systems irrelevant.

In a perfectly sustainable world, we would use and reuse materials dug out of the ground indefinitely. But as our technology shifts and our lives change, it can be difficult to end the loop where it began. Instead, our material economy may morph into the shape of a spiral. Resources may not end up quite where they started—rather, the system we've set up to extract and use them will continue to chase technological progress, maybe endlessly. ■

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

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We're making more data than ever. What do we save for future generations? And will they be able to understand it?

By
Niall Firth

Illustrations
Mike McQuade

What we leave behind

There is a photo of my daughter that I love. She is sitting, smiling, in our old back garden, chubby hands grabbing at the cool grass. It was taken in 2013, when she was almost one, on an aging Samsung digital camera. I originally stored it on a laptop before transferring it to a chunky external hard drive.

A few years later, I uploaded it to Google Photos. When I search for the word "grass," Google's algorithm pulls it up. It always makes me smile.

I pay Google £1.79 a month to keep my memories safe. That's a lot of trust I'm putting in a company that's existed for only 26 years. But the hassle it removes seems worth it. There's just so much *stuff* nowadays. The admin required to keep it updated and stored safely is just too onerous.

My parents didn't have this problem. They took occasional photos of me on a film camera and periodically printed them out on paper and put them in a photo album. These pictures are still viewable now, 40-odd years later, on faded yellowing photo paper—a few frames per year.

Many of my memories from the following decades are also fixed on paper. The letters I received from my friends when traveling abroad in my 20s were handwritten on


A
Reply
Forward
427
SRVLOC
427

lined paper. I still have them crammed in a shoebox, an amusing but relatively small archive of an offline time.

We no longer have such space limitations. My iPhone takes thousands of photos a year. Our Instagram and TikTok feeds are constantly updated. We collectively send billions of WhatsApp messages and texts and emails and tweets.

But while all this data is plentiful, it's also more ephemeral. One day in the maybe-not-so-distant future, YouTube won't exist and its videos may be lost forever. Facebook—and your uncle's holiday posts—will vanish. There is precedent for this. MySpace, the first largish-scale social network, deleted every photo, video, and audio file uploaded to it before 2016, seemingly inadvertently. Entire tranches of Usenet newsgroups, home to some of the internet's earliest conversations, have gone offline forever and vanished from history. And in June this year, more than 20 years of music journalism disappeared when the MTV News archives were taken offline.

For many archivists, alarm bells are ringing. Across the world, they are scraping up defunct websites or at-risk data collections to save as much of our digital lives as possible. Others are working on ways to store that data in formats that will last hundreds, perhaps even thousands, of years.

The endeavor raises complex questions. What is important to us? How and why do we decide what to keep—and what do we let go?

And how will future generations make sense of what we're able to save?

"Welcome to the challenge of every historian, archaeologist, novelist," says Genevieve Bell, a cultural anthropologist. "How do you make sense of what's left? And then how do you avoid reading it through the lens of the now?"

Last-chance saloon

There is more stuff being created now than at any time in history. At Google's I/O conference this year, the firm's CEO, Sundar Pichai, said that 6 billion photos and videos are uploaded to Google Photos every day. More than 40 million WhatsApp messages are sent every minute.

Even with so much more of it, though, our data is more fragile than ever. Books could burn in a freak library fire, but data is much easier to wipe forever. We've seen it happen—not only in incidents like the accidental deletion of MySpace data but also, sometimes, with intent.

In 2009, Yahoo announced it was going to pull the plug on the web-hosting platform GeoCities, putting millions of carefully created web pages on the chopping block. While most of these pages might seem inconsequential—GeoCities was famous for its amateurish, early-web aesthetic and its pages dedicated to various collections, obsessions, or fandoms—they represented an early chapter of the web, and one that was about to be lost forever.

And it would have been, if a ragtag group of volunteer archivists led by Jason Scott hadn't stepped in.

"We sprang into action, and part of the fury and confusion of the time was we were going from downloading a handful of interesting sites to suddenly taking on an anchoring website of the early web," Scott recalls.

His group, called Archive Team, quickly mobilized and downloaded as many GeoCities pages as possible before it closed for good. He and the team ended up being able to save most of the site, archiving millions of pages between April and October 2009. He estimates that they managed to download and store around a terabyte, but he notes that the size of GeoCities waxed and waned and was around nine terabytes at its peak. Much was likely gone for good. "It contained 100% user-generated works, folk art, and honest examples of human beings writing information and histories that were nowhere else," he says.

Known for his top hat and cyberpunk-infused sense of style, Scott has made it his life's mission to help save parts of the web that are at risk of being lost. "It is becoming more understood that archives, archiving, and preservation are a choice, a duty, and not something that just happens like the tides," he says.

Scott now works as "free-range archivist and software curator" with the Internet Archive, an online library started in 1996 by the internet pioneer Brewster Kahle to save and store information that would otherwise be lost.

Over the past two decades, the Internet Archive has amassed a gigantic library of material scraped from around the web, including that GeoCities content. It doesn't just save purely digital artifacts, either; it also has a vast collection of digitized books that it has scanned and rescued. Since it began, the Internet Archive has collected more than 145 petabytes of data, including more than 95 million public media files such as movies, images, and texts. It has managed to save almost half a million MTV news pages.

Its Wayback Machine, which lets users rewind to see how certain websites looked at any point in time, has more than 800 billion web pages stored and captures a further 650 million each day. It also records and stores TV channels from around the world and

As a society, we're creating so much new stuff that we must always delete more things than we did the year before.

even saves TikToks and YouTube videos. They are all stored across multiple data centers that the Internet Archive owns itself.

It's a Sisyphean task. As a society, we're creating so much new stuff that we must always delete more things than we did the year before, says Jack Cushman, director at Harvard's Library Innovation Lab, where he helps libraries and technologists learn from one another. We "have to figure out what gets saved and what doesn't," he says. "And how do we decide?"

Archivists have to make such decisions constantly. Which TikToks should we save for posterity, for example?

We shouldn't try too hard to imagine what future historians would find interesting about us, says Niels Brügger, an internet researcher at Aarhus University in Denmark. "We cannot imagine what historians in 30 years' time would like to study about today, because we don't have a clue," he says. "So we shouldn't try to anticipate and sort of constrain the possible questions that future historians would ask."

Instead, Brügger says, we should just save as much stuff as possible and let them figure it out later. "As a historian, I would definitely go for: Get it all, and then historians will find out what the hell they're going to do with it," he says.

At the Internet Archive, it's the stuff most at risk of being lost that gets prioritized, says Jefferson Bailey, who works there helping develop archiving software for libraries and institutions. "Material that is ephemeral or at risk or has not yet been digitized and therefore is more easily destroyed, because it's in analog or print format—those do get priority," he says.

People can request that pages be archived. Libraries and institutions also make nominations. And the staff sorts out the rest. Across open social media like TikTok and YouTube, archive teams at libraries around the world select certain accounts, copy what they want to save, and share those copies with the Internet Archive. It could be snapshots of what was trending each day, as well as tweets or videos from accounts run by notable individuals such as the US president.

The process can't capture everything, but it offers a pretty good slice of what has preoccupied us in the early decades of the 21st century. While historical records have typically relied upon the private letters and belongings of society's richest, an archive process that scrapes tweets is always going to be a bit more egalitarian.

"You can get a very interesting and diverse snapshot of our cultural moments of the last 30, 40 years," says

Bailey. "That is very different from what a traditional archive looked like 100 years ago."

As citizens, we could also help future historians. Brügger suggests people could make "data donations" of their personal correspondence to archives. "One week per year, invite everyone to donate the emails from that week," he says. "If you had these time slices of email correspondence from thousands of people, year by year, that would be really great."

Scott imagines future historians eventually using AI to query these archives to gain a unique insight into how we lived. "You'll be able to ask a machine: 'Could you show me images of people enjoying themselves at amusement parks with their families from the '60s?' and it will go, 'Here you go,'" he says. "The work we did up to here was done in faith that something like this might exist."

The past guides the future

Human knowledge doesn't always disappear with a dramatic flourish like GeoCities; sometimes it is erased gradually. You don't know something's gone until you go back to check it. One example of this is "link rot," where hyperlinks on the web no longer direct you to the right target, leaving you with broken pages and dead ends. A Pew Research Center study from May 2024 found that 23% of web pages that were around in 2013 are no longer accessible.

It's not just web links that die without constant curation and care. Unlike paper, the formats that now store most of our data require certain software or hardware to run. And these tools can become obsolete quickly. Many of our files can no longer be read because the applications that read them are gone or the data has become corrupted, for example.

One way to mitigate this problem is to transfer important data to the latest medium on a regular basis, before the programs required to read it are lost forever. At the Internet Archive and other libraries, the way information is stored is refreshed every few years. But for data that is not being actively looked after, it may be only a few years before the hardware required to access it is no longer available. Think about once ubiquitous storage mediums like Zip drives or CompactFlash.

Some researchers are looking into ways to make sure we can always access old digital formats, even if the kit required to read them has become a museum piece. The Olive project, run by Mahadev Satyanarayanan at Carnegie Mellon University, aims to make it possible for anyone to use any application, however old, "with just a click." His team has been working since 2012 to create a huge, decentralized network that supports "virtual machines"—emulators for old or defunct operating systems and all the software that they run.

Keeping old data alive like this is a way to protect against what the computer scientist Danny Hillis once dubbed the "digital dark age," a nod to the early medieval period when a lack of written material left future historians little to go on.

Hillis, an MIT alum who pioneered parallel computing, thinks the rapid technological upheaval of our time will leave much of what we're living through a mystery to scholars.

"When people look back at this period, they'll say, 'Oh, well, you know, here was this sort of incomprehensibly fast technological change, and a lot of history got lost during that change," he says.

Hillis was one of the founders (along with Brian Eno and Stewart Brand) of the Long Now Foundation, a San Francisco–based organization that is known for its eye-catching art/science projects such as the Clock of the Long Now, a Jeff Bezos–funded gigantic mechanical clock currently under construction in a mountain in West Texas that is designed to keep accurate time for 10,000 years. It also created the Rosetta Disc, a circle of nickel that has been etched at microscopic scale with a list of around 1,500 of the world's languages. In February, a copy of the disc touched down on the moon aboard the Odysseus lander. Part of the Long Now's focus is to help people think about how we protect our history for future generations. It's not just about making life easier for historians. It's about helping us be "better ancestors," according to the organization's mission statement.

It's a sentiment that chimes with Vint Cerf, one of the internet's founders. "As I get older, I keep thinking, how can I be a good ancestor?" he says.

"An understanding of what has happened in the past is helpful for anticipating or interpreting what's happening in the present and what might happen in the future," says Cerf. There are "all kinds of scenarios where the absence of knowledge of the past is a debilitating weakness for a society."

The Rosetta Disc is a circle of nickel that has been etched at microscopic scale with a list of around 1,500 of the world's languages. In February, a copy of the disc touched down on the moon aboard the Odysseus lander.

COURTESY OF THE LONG NOW FOUNDATION

"As I get older, I keep thinking, how can I be a good ancestor?"
—Vint Cerf

"If we don't remember, we can't think, and the way that society remembers is by writing things down and putting them in libraries," agrees Kahle. Without such repositories, he says, "people will be confused as to what's true and not true."

Kahle started the Internet Archive as a way to make sure all knowledge is free for anyone, but he feels the balance of power has tilted away from libraries and toward corporations. And that is likely to be a problem for keeping things accessible in the long term.

"If it's left up to the corporations, it's all gone," he says. "Not only are we talking about classic published works—like your magazine, or books—but we're talking about Facebook pages, Twitter pages, your personal blogs. All of those in general are on corporate platforms now. And those will all disappear."

Losing our long-term digital archives has real implications for how society runs, says Harvard's Cushman, who points out that our legal decisions and paperwork are largely stored digitally. Without a permanent, unalterable record, we can no longer rely on past judgments to inform the present. His team has created ways to let courts and law journals put copies of web pages on file at the Harvard Law Library, where they are stored indefinitely as a record of legal precedent. It's also creating tools to let people interact with these archives by scrolling through historical versions of a site, or by using a custom GPT to interact with collections.

Many other groups are working on similar solutions. The US Library of Congress has suggested standards for storing video, audio, and web files so they are accessible for future generations. It urges archivists to think about issues such as whether the data includes instructions on how to access it, or how widely adopted the format has been (the idea being that a more prevalent one is less likely to become obsolete quickly).

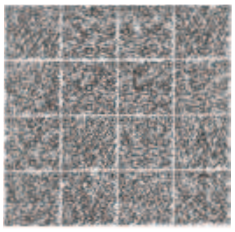
But ultimately, digital archives are harder to keep than physical archives, says Cushman. "If you run out of budget and leave books in a quiet, dark room for 10 years, they're happy," he says. "If you fail to pay your AWS bill for a month, your files are gone forever."

Storage for impossible time scales

Even the physical way we store digital data is impermanent. Most long-term storage in data centers—for use in disaster recovery, among other applications—is on magnetic hard drives or tape. Hard drives wear out after a few years. Tape is a little better, but it still doesn't get you much beyond a decade or so of storage use before it begins to fail.

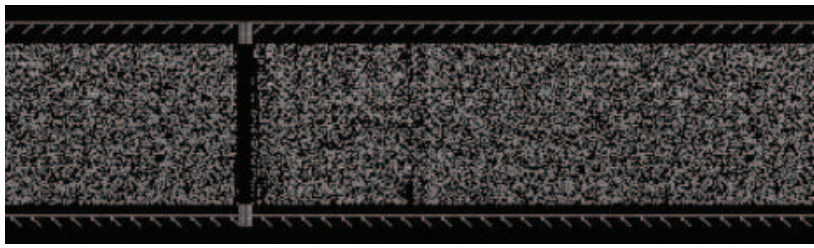
Saving for the future

Some long-term storage efforts are part art installation, too. In a project called Memory of Mankind, the artist Martin Kunze stored around 1,000 selected cultural works—including newspaper articles and personal stories—on special ceramic tablets that were then buried deep in Austrian salt flats.



That art project led to his startup, Cerabyte, which is now laser-etching bits into a ceramic layer in glass. This medium can withstand extreme temperature and can store information, the company claims, for thousands of years.

In California, a firm called Group 47 is working on a technology called DOTS that was originally invented by Kodak, before Group 47 was founded and bought the patents. The technique uses a laser to write tiny dots onto special archival tape that can last 100 years. Each section of tape includes instructions on how to build the required reader.



MARTIN KUNZE/PROJEKT MEMORY OF MANKIND; COURTESY OF CERABYTE; COURTESY OF GROUP 47

Companies make new backups all the time, so this is less of a problem for the short-to-medium term. But when you want to store important cultural, legal, or historical information for the ages, you need to think differently. You need something that can store huge amounts of data but can also withstand the test of time and doesn't need constant care.

DNA has often been touted as a long-term storage option. It can store astonishing amounts of information and is incredibly long-lasting. Pieces of bone contain readable DNA from many hundreds of thousands of years ago. But encoding information in DNA is currently expensive and slow, and specialized equipment is required to "read" the information back later. That makes it impractical as a serious long-term backup for our world's knowledge, at least for now.

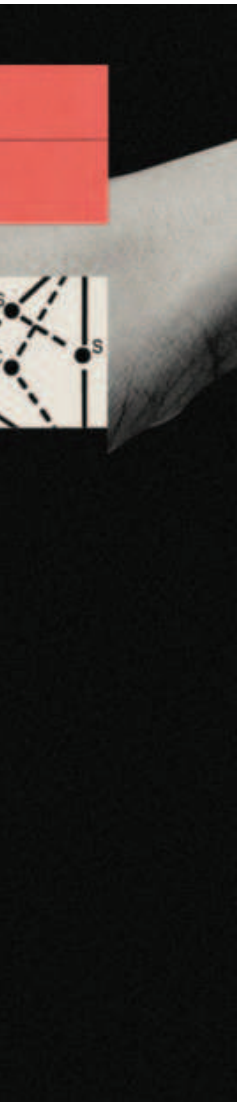
Luckily, there are already a handful of compelling alternatives. One of the most advanced ideas is Project Silica, currently under development at Microsoft Research in Cambridge, UK, where Richard Black and his team are creating a new form of long-term storage on glass squares that can last hundreds or even thousands of years.

Each one is created using a precise, powerful laser, which writes nanoscale deformations into the glass beneath the surface that can encode bits of information. These tiny imperfections are layered up on top of one another in the glass and are then read using a powerful microscope that can detect the way light is refracted and polarized. Machine learning is used to decode the bits, and each square has enough training data to let future historians retrain a model from scratch if required, says Black.

When I hold one of the Silica squares in my hand, it feels pleasingly sci-fi, as if I've just pulled it out to shut down HAL in *2001: A Space Odyssey*. The encoded data is visible as a faint blue where the light hits the imperfections and scatters. A video shared by Microsoft shows these squares being microwaved, boiled, baked in an oven, and zapped with a high-powered magnet, all with no apparent ill effects.

Black imagines Silica being used to store long-term scientific archives, such as medical information or weather data, over decades. Crucially, the technology can create archives that can be air-gapped (cut off from the internet) and need no power or special care. They can just be locked away in a silo and should work fine and be readable centuries from now. "Humanity has never stopped building microscopes," says Black. In 2019 Warner Bros. archived some of its back catalogue on Silica glass, including the 1978 classic *Superman*.

Throughout history, the oddest, most random things survived to act as a guide for historians. The same will go for us.



Black's team has also designed a library storage system for Silica. Shelves packed with thousands of the glass squares line a small room at the Cambridge office. Handbag-size robots attached to the shelves whiz along them and occasionally stop, unclip themselves from one shelf, and clamber up or down to another before shooting off again down the line. When they reach a specific spot, they stop and pluck one of the squares, no bigger than a CD, from the shelf. Its contents are read and the robot zips back into position.

Meanwhile, deep in the vaults of an abandoned mine in Svalbard, Norway, GitHub is storing some of history's most important software (including the source code for Linux, Android, and Python) on special film its creators claim can last for more than 500 years. The film, made by the firm Piql, is coated in microscopic silver halide crystals that permanently darken when exposed to light. A high-powered light source is used to create dark pixels just six micrometers across, which encode binary data. A scanner then reads the data back. Instructions for how to access the information are written in English on each roll, in case there is no longer anyone around to explain how it works.

In addition to GitHub's collection, the storage facility, known as the Arctic World Archive, also includes data supplied by the Vatican and the European Space Agency, as well as various artworks and images from governments and institutions around the world. Yale University, for example, has stored a collection of software, including Microsoft Office and Adobe, as Piql data. Just a few hundred meters down the road you find the Svalbard Global Seed Vault, a storage facility preserving a selection of the world's biodiversity for future generations. Data about what each seed container holds is also stored on Piql film.

Making sure this information is stored in formats that can be decoded hundreds of years from now will be crucial. As Cushman points out, we still argue over the proper way to play Charlie Chaplin films because the intended playback speed was never recorded. "When researchers are trying to access these materials decades in the future, how expensive will it be to build tools to display them, and what will be the chances that we get it wrong?" he asks.

Ultimately, the motivation for all these projects is the idea that they will act as humanity's backup. A long-term medium that will withstand an apocalypse, an electromagnetic pulse from the sun, the end of civilization, and let us start again.

Something to let people know we were here.

Happy accidents

Sometime in the first century, a Roman woman called Claudia Severa was planning a big birthday party at a fort in northern England. She asked her servant to write out an invitation to one of her best friends on a wooden tablet and then signed it with a flourish.

Claudia could never have suspected that, almost 2,000 years on, the Vindolanda Tablets (of which her invitation is the most famous) would be used to give us a unique insight into the daily lives of Romans in England at that time.

That's always the way. Throughout history, the oddest, most random things survived to act as a guide for historians. The same will go for us. Despite the efforts of archivists, librarians, and storage researchers, it's impossible to know for sure what data will still be accessible when we're long gone. And we might be surprised at what they find interesting when they come across it. Which batch of archived emails or TikToks will be the key to unlocking our era for future historians and anthropologists? And what will they think of us?

Historians foraging through our digital detritus may be left with a series of unanswerable questions, and they'll just have to make best guesses.

"You'd need to ask about who had digital technology," says Bell. "And how did they power it? And who got to make choices about it? And how was it stored and circulated? And who saw it?"

We don't know what will still be running 20, 50, or 100 years from now. Perhaps Google Photos' cloud storage will have been abandoned, a giant garbage pile of old hard drives buried in the ground. Or maybe, with luck, one of the spiritual heirs to Scott's archivists will have saved it before it went down.

Maybe someone downloaded it onto some sort of glass disc and stashed it in a vault somewhere.

Maybe some future anthropologist will one day find it, dust it off, and find that it's still readable.

Maybe they'll select a file at random, spin up some sort of software emulator, and find a billion photos from 2013.

And see a chubby, happy girl sitting in the grass. ■

Niall Firth is newsroom executive editor at MIT Technology Review.

Escaping Spotify's algorithm

Since the heyday of radio, records, cassette tapes, and MP3 players, the branding of sound has evolved from broad genres like rock and hip-hop to "paranormal dark cabaret afternoon" and "synth space," and streaming has become the default. Radio DJs have been replaced by artificial intelligence, and the ritual of discovering something new is neatly packaged in a 30-song playlist, refreshed weekly. The only rule in music streaming, as in any other industry these days, is personalization.

But what we've gained in convenience, we've lost in curiosity. Sure, our unlimited access lets us listen to Swedish tropical house or New Jersey hardcore, but this abundance of choice actually makes our listening experience *less* expansive or eclectic.

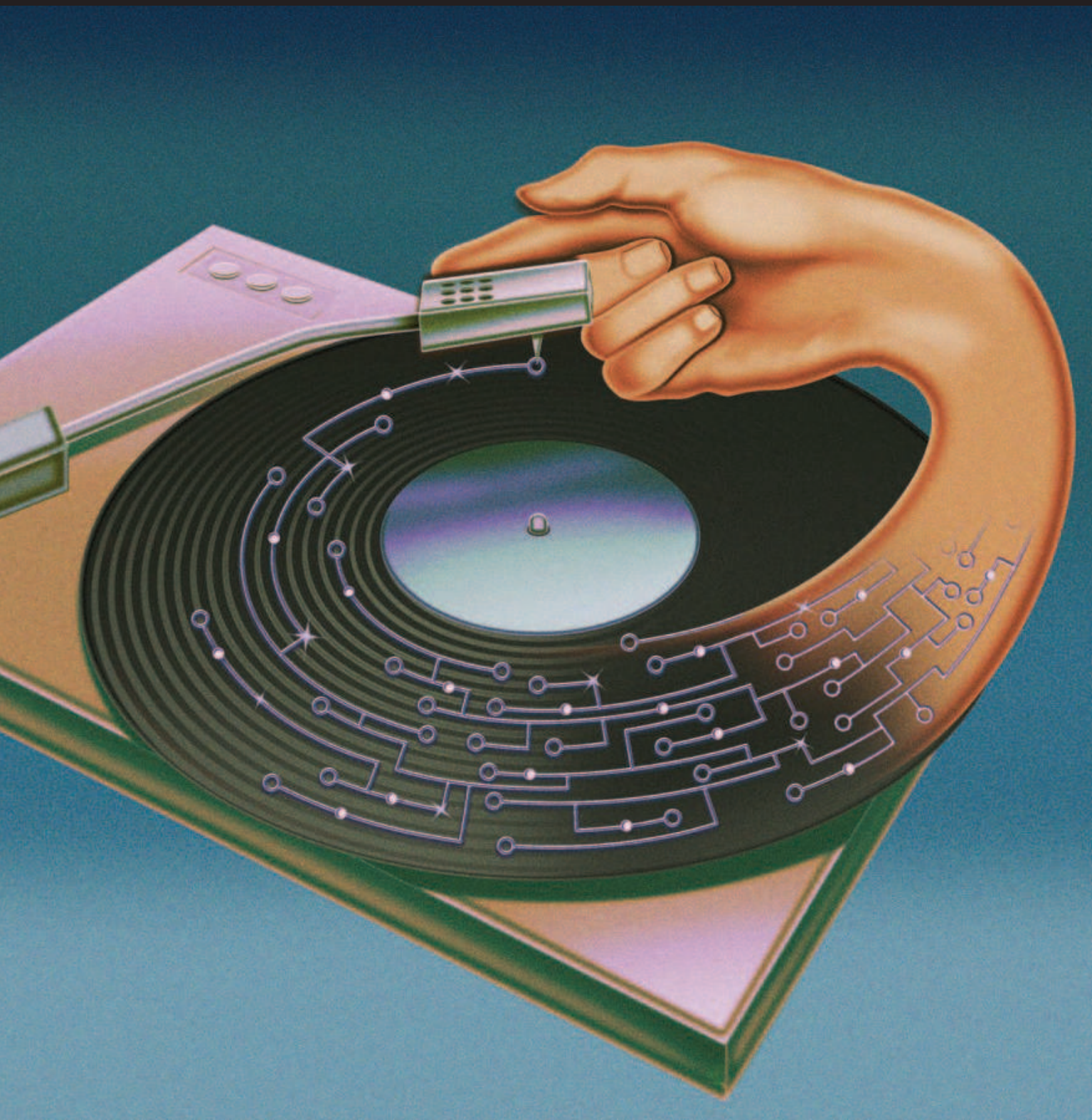
Most of us access music through streaming services: over 600 million of us worldwide, to be exact. And claiming over 30.5% of this population, nearly double the share of any other streaming service on the market, is Spotify. With its game-changing release in 2015 of Discover Weekly—a generated playlist that tailors song selections to a user's listening habits—Spotify presented personalization as the remedy to our overabundance of options.

But in efficiently delivering what people seem to want, it effectively eliminated choice and removed humanity from the entire music listening—and music discovery—experience. According to a 2022 report published by Distribution Strategy Group, at least 30% of songs streamed on Spotify are recommended by AI. The success of Discover Weekly has since inspired mood-dependent playlists that change throughout the day and psychic readings based on people's listening habits. Other streaming platforms, like Apple Music and Amazon Music, have followed suit. All these takes on personalization share a common fault: The playlists too often resemble one another, filled with songs that offer different variants of the same sound.

Glenn McDonald, a former engineer at Spotify and the self-described "data alchemist" largely responsible for developing the company's encyclopedia of genres, believes that while accessing new music is technically easy, many of us don't do it—mainly because we're not sure where to start looking.

By Tiffany Ng
Illustration by Aaron Lowell Denton

The streaming service seems to offer endless choice. But what if all this personalization is actually killing the thrill of discovering new music?



As we grow accustomed to the convenience of shuffling a generated playlist, we forget that discovering music is an active exercise.

We expect too much from the algorithm

For Spotify, McDonald says, personalization begins with breaking down songs via a data-intelligence platform that was known as the Echo Nest before the company acquired it. Through a combination of signal processing and human listening by musicologists, Spotify assigns roughly 10 different attributes to songs (e.g., key signature, danceability) before grouping them into libraries. AI-powered programs then pull from these buckets of sound to generate the personalized playlists, with parameters tailored to the habits of each user. How Spotify categorizes music determines what is made visible to us. It also shapes which niches artists fit into and how much exposure they get.

McDonald sorts our listening habits into three concentric clusters: the stuff we listen to every day, the stuff that sounds like our stuff, and everything else we stumble upon. Spotify's auto-generated playlists mostly keep to the first bucket, occasionally venturing into the second. The third is accidental. The service never offers anything strictly different.

Spotify thinks that even if we say we want to listen to something new, we always return to what's familiar, McDonald explains. He argues that in practice, slipping a reggae track into a playlist of "bedroom pop" (a genre that mainly features dreamy melodies and hushed vocals) often makes for an uncomfortable listening experience: "If you're given something new, it's odd, in the same way being teleported to random spots around the world for three minutes at a time would not be a pleasant tourism experience."

To construct the 6,291 microgenres in its database, McDonald says, Spotify uses social data—how listeners of the same artists sort those artists' songs and who else they listen to. He clarifies that Spotify's genres have no absolute boundaries but reflect a loose and dynamic consensus on how users listen to music. Small clusters of overlapping listening habits define these loose categories, while constant cross-pollination creates variations on them. "Everyone understood where the center of the village was, and the further out you went, the more subjective it became," he says of the process as he remembers it. McDonald mapped this musical landscape on his personal site, Everynoise.com.

Our respective listening habits, when considered together, form a dynamic network that reveals how we collectively understand music. It's a shame that Spotify's current usage confines us to isolated algorithmic bubbles.

Rather than challenging your tastes, algorithms only provide shuffled versions of what you already enjoy.

Context and community

Personalization, broadly speaking, has made navigating the internet's infinite pool of content incredibly convenient. We're served what we like, told what to buy, prompted on what to say. It's no surprise we expect our music streaming apps to do the same. However, employing algorithms to optimize music discovery requires explicitly defining what we want, and the problem is that what we want could easily be shaped by what we encounter. Asking an algorithm to broaden our horizons is like having lunch with a friend who claims to be open to anything but vetoes everything you suggest. "Curiosity is an active mode," McDonald says. It's up to us to step outside our bubble.

Music enthusiasts are creating new ways to reinvigorate this sense of curiosity, building everything from competitive recommendation leagues to interactive music maps. Before streaming, discovering music was work that brought a distinctly emotional reward. "Back in college, I listened to whatever my friends were listening to," recalls Zack O'Malley Greenburg, former senior music editor at *Forbes*. He describes exchanging CDs with friends, spending hours deciding which songs he liked and which he didn't. Later, acquiring new music became an exercise in sorting through audio files on thumb drives and (illegally) downloading MP3s from questionable websites. Sharing music was a much more personal, peer-to-peer exercise, and making a mixtape for a crush was a substantial labor of love. Automated recommendation systems have replaced this social culture of sharing music. The anonymous playlists we opt into today may be edited and even shared, but the emotional stakes are much lower.

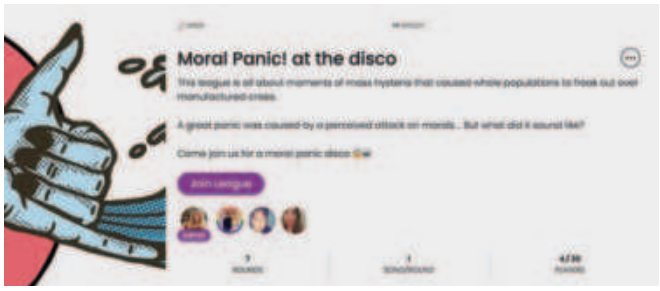
Because personally recommending songs revealed our taste, we had a vested interest in what we recommended. But the algorithm assumes no risk, simply offering what's mathematically sound.

"What I think is missing in music streaming is *why* someone thinks I should like a certain song," says Alex Keller, one of the cofounders of Music League, an online platform that allows people to submit songs to playlists that fit a certain theme. The platform has doubled its user base since last year, to roughly 130,000 monthly users.

Music League has built this loyal community by gamifying the experience of recommending music. Users can join public leagues or create private ones with themes ranging from "Best rap song" to "Horse crime." Each league hosts multiple rounds,

Rage against the machine

Four music discovery services to help you explore beyond Spotify's AI-generated playlists



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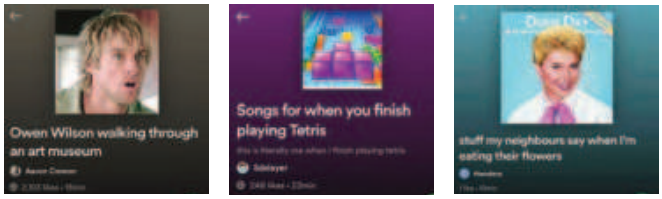
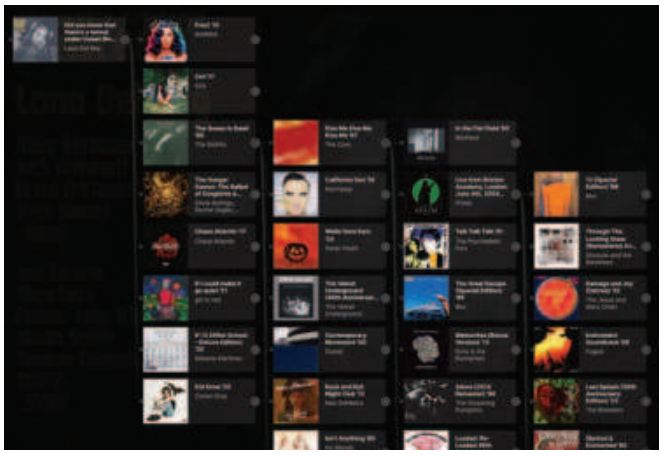


Oddly Specific Playlists recommends—you guessed it—playlists inspired by oddly specific things.



Unchartify provides a more manual navigation through Spotify's database.

Radiooooo ditches genres altogether and prompts users to select music by time period and geographic location.

where participants compete by submitting and voting for songs they think best fit a prompt. A big part of the experience, Keller says, is the conversation around each submission. He describes how his experience of each song changes as users are pushed to defend their choices.

Unlike the myriad personalized Spotify playlists that instantaneously refresh on demand, leagues can be open for months at a time. There may be a long gap between receiving a prompt and submitting a song, or between listening and voting. People are encouraged not only to listen to songs from start to finish (an increasingly rare practice) but also to include liner notes alongside the songs they submit. Slowing down the process of music discovery can foster more purposeful listening.

"As an adult, music is in the background in your life," Keller says. For him, the social focus of Music League puts it back in center stage. The collaborative recommendation process gives each song emotional weight and offers a refreshing departure from the streams of generated playlists we shuffle for ambience.

Similar to Music League is a private Facebook community called Oddly Specific Playlists, a group that connects users from all corners of the internet with playlists inspired by (as the name suggests) very specific things. With over 364,000 members, the group is flooded with requests daily; users post pieces of inspiration and attach a brief explanation of their interest in the theme. Others share relevant songs and offer personal anecdotes to color their recommendations. Requests like "Strong masculinity; healthy, not toxic; not misogynistic; bonus points for queerness" beget discussion. What could strong masculinity sound like? What does a healthy song entail?

Often, playlist requests have ventured into more somber subjects like heartbreak and grief. As users share deeply intimate stories about their relationships to specific songs, conversations develop and communities heal. The fact that members have likely never met can make the experience even more meaningful. Connecting with

strangers around the world reveals the universality of even the most seemingly specific experiences and offers a unique form of validation. The discussions can also breathe new life into old songs; a request for songs prominently featuring the sound "oh," from a member whose two-year-old was obsessed with the letter O, spotlighted "Oh! Darling'" by the Beatles.

This focus on fostering organic human interaction is not new. Until 2017, Spotify actually had a chat feature, but it wasn't used widely enough (and didn't result in enough streams) to justify the resources required to maintain it. So instead, the company pivoted to optimizing personalization.

While Spotify's platform evolved to make choosing music as easy as possible, the unpolished format of Oddly Specific Playlists has largely remained the same. Comments are still difficult to keep track of, and users must sift through mountains of posts to find relevant recommendations. Despite the clunky experience, the community has been thriving since 2019.

"If a social network is any good, then it has to have some actual people putting new content into the ecosystem and organizing it in a coherent way—like someone making a hand-curated playlist," says Kyle Chayka, a *New Yorker* staff writer and author of *Filterworld: How Algorithms Flatten Culture*. That's just what the members of Oddly Specific Playlists do, even if the results can be hard to manage.

In his book, Chayka recounts the many hours he's spent surfing music forums like AntsMarching.org and UFCK.org (fan sites dedicated to all things concerning the Dave Matthews Band and Pearl Jam, respectively), finding company with other posters who shared low-fidelity tapes from old concerts and fun facts about a band's formation. These cultural rabbit holes, to Chayka, offer a form of "mutual learning" that helps us better understand what we're consuming. If we know how an artist's signature style came to be, for example, we're more capable of intentionally shaping our tastes.

Slowing down with curation

In *Filterworld*, Chayka also outlines how algorithms have taken the place of magazine editors and museum curators as gatekeepers of culture. "I think curation is a way to resist the flattening of the internet," he says, though acknowledging that the term itself has been watered down over the past decade.

Chayka frames curation as intentional, arduous, and finite—characteristics he deems antithetical to our relationship with algorithms. Where a curator voices perspectives that welcome discourse and discomfort, algorithms are written in fear of offending. "When a human interprets a piece of art, it adds value rather than takes it away. An algorithm has no capacity to interpret," he adds.

As we grow accustomed to the convenience of shuffling a generated playlist, we forget that discovering music is an active exercise.

Before streaming, a magazine profile on an emerging artist or a blogger's "Songs I'm listening to" column would put musicians on your radar, inspiring deep dives into their discography. Music publications like *Blender, NME*, and *The Source,* also had great influence, the latter notably discovering The Notorious B.I.G. and highlighting him in its "Unsigned Hype" column. But, as Greenburg explains, "streaming services remove a step." Rather than challenging your tastes, algorithms only provide shuffled versions of what you already enjoy. Like the Soylent shakes popular in the mid-2010s for supposedly offering all the nutrients you need from a meal, these personal playlists may fulfill but can never satiate.

In *Filterworld,* Chayka offers independent radio DJs as an antidote to the algorithmic takeover. The vaguely physical act of tuning into a radio station, like entering a concert hall, restores a tactile quality to our experience of music. When there's a voice behind the selection of songs, we're more likely to pay attention, Chayka insists. He describes how these DJs "utilize all of their knowledge, expertise, and experience in order to determine what to show us and how to do it."

The Hong Kong–based musician known as Cehryl, who hosts the show *Mystery Train* on Eaton Radio, structures her shows around narratives. "I think about my shows in the same way I think about a performance," she says. "There's an emotional arc." She puts her tastes first, hoping to express a unique point of view that will bring something new to her listeners.

In a world of on-demand music, the real-time format of independent radio mandates a specific sequence of uninterrupted listening. Without skips, shuffles, or the ability to pause, it gives curators the opportunity to push their listeners' boundaries.

Creating with "algorithmic anxiety"

To Cehryl, a big part of being a musician today is grappling with the existential question of whether to make music for the algorithm. Since the popularization of streaming (and the rise of TikTok), the average length of a song has decreased from four minutes to roughly three. Artists are encouraged to put out singles or EPs instead of releasing concept albums. And in 2023, Spotify launched the Preview function, a TikTok-esque infinite-scroll music feed that showcases the "best" few seconds of each song with every swipe. The algorithm rewards relevance and instant

gratification. "No long songs. No patient, drawn-out songs. You want the hook by 15 seconds in, if not earlier," Cehryl says.

Experiencing what Chayka calls "algorithmic anxiety," Cehryl describes a need to feed the algorithm's perception of her: "I have often been playlisted as bedroom pop. But I don't think I make bedroom pop." For artists, Spotify's genre breakdowns play a complicated role in their creative process.

Spotify's algorithm offers loose categorizations to identify emerging genres or remodel familiar ones, but the platform's promotion of broader, more recognizable genres makes some artists feel pigeonholed and pressures others to conform. Fitting into Spotify's categories increases an artist's chances of going viral on the platform, even if each stream yields only $0.003 for the creator.

Alex Antenna, who has created a website called Unchartify to offer a more manual way of navigating Spotify's database, attributes these pigeonholes to Spotify's push for personalization. He built his site to bypass the plethora of "made for you" playlists and highlight lesser-known corners of Spotify's database.

"Spotify's music database has a very rich set of various parameters, markup, and categories to classify music in a very detailed way. This is simply not exposed in the official app," he says. He believes that even though it has a sophisticated way of sorting music, Spotify intentionally oversimplifies: Its library offers mainly personalized playlists drawing on broad categories like "metal" or "party," many of which feature mostly "popular artists or songs you heard 1,000 times."

Antenna points out that beyond genres such as bedroom pop or indie folk, Spotify offers a plethora of microgenres (such as "reminimal" and "sky room") that are accessible only by name through its API. He hopes that by surfacing genres that more accurately represent an artist's sound, a system as granular as Unchartify can combat algorithmic anxiety.

Unchartify reorganizes Spotify's database by sorting all genres into alphabetical order—something unheard-of in today's world of engagement optimization—and mapping them so that each album is a node connecting to a list of similar albums. Unlike Spotify's "Fans also like" feature, which recommends similar artists without suggesting where their similarity lies, Unchartify offers a precise picture of where an album sits musically in relation to others.

Unless specifically asked, Unchartify doesn't try to guess what you're looking for. Instead, it gives you the tools to surf Spotify's database systematically, as you might sift through archives in a public library. Antenna's position reveals an important source of tension in the world of on-demand music: Making the abundance of content online digestible requires simplification, but simplification often forgoes nuance.

"When a human interprets a piece of art, it adds value rather than takes it away. An algorithm has no capacity to interpret."

Beating the algorithm

Going a step beyond Antenna's archaic decision to list genres alphabetically is Radiooooo, a self-described musical time machine that randomizes the discovery process by eliminating genre entirely.

Founded in 2012 by a group of four DJs, Radiooooo curates a selection of songs for each decade dating back to the 1900s for each country across the globe. It prompts users to select music by time periods and geographic locations rather than genres or artists—discarding any semblance of our current streaming experience and inspiring a new way of thinking about music. Radiooooo also tacks on a social component by crediting members who've discovered the track, joining communities like Music League and Oddly Specific Playlists in encouraging a form of crowdsourced recommendation that invites conversation and disagreement—a far cry from Spotify's vision of optimized, unimpeded listening.

Perhaps the only way to escape our algorithmic bubbles is by building community. When we welcome diverse patterns of music consumption, we're challenged to consider music from different perspectives, the same way independent radio stations curate to tell a story rather than cater to a demographic. There's nothing to optimize in a community, and in turn, nothing to oversimplify.

Despite functionally contradicting Spotify's philosophy, platforms like Radiooooo, Music League, Oddly Specific Playlists, and independent radio all complement the use of such platforms. They act as a springboard for our process of discovery, helping us step past Spotify's insistence on personalization by directing us where to look and, most important, making it fun.

McDonald likens the functions of Spotify to Google Maps. "Google Maps doesn't do the exploration for me, but it's helpful if I go somewhere," he says. Rather than taking us on guided tours, it provides the tools for us to navigate somewhere new. Much as it shows us what's nearby and how to get there, and flags notable landmarks others have visited, Spotify helps us access most music, lists global listening trends, and introduces us to artists similar to those we already know. But it's communities that help us home in on a destination Spotify can help us explore. ■

Tiffany Ng is a freelance writer exploring the relationship between art, tech, and culture.

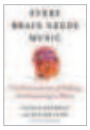
Close listening

Three books explore the wonders of sound on land, in the sea, and in our heads.

By Bryan Gardiner
Illustration by Kate Dehler

A Book of Noises: Notes on the Auraculous
Caspar Henderson
UNIVERSITY OF CHICAGO PRESS, 2024

Sing Like Fish: How Sound Rules Life Under Water
Amorina Kingdon
CROWN, 2024



Every Brain Needs Music: The Neuroscience of Making and Listening to Music
Larry Sherman and Dennis Plies
COLUMBIA UNIVERSITY PRESS, 2023

In 1983, while on a field recording assignment in Kenya, the musician and soundscape ecologist Bernie Krause noticed something remarkable. Lying in his tent late one night, listening to the calls of hyenas, tree frogs, elephants, and insects in the surrounding old-growth forest, Krause heard what seemed to be a kind of collective orchestra. Rather than a chaotic cacophony of nighttime noises, it was as if each animal was singing within a defined acoustic bandwidth, like living instruments in a larger sylvan ensemble.

Unsure of whether this structured musicality was real or the invention of an exhausted mind, Krause analyzed his soundscape recordings on a spectrogram when he returned home. Sure enough, the insects occupied one frequency niche, the frogs another, and the mammals a completely separate one. Each group had claimed a unique part of the larger sonic spectrum, a fact that not only made communication easier, Krause surmised, but also helped convey important information about the health and history of the ecosystem.

Krause describes his "niche hypothesis" in the 2012 book *The Great Animal Orchestra*, dubbing these symphonic soundscapes the "biophony"—his term for all the sounds generated by nonhuman organisms in a specific biome. Along with his colleague Stuart Gage from Michigan State University, he also coins two more terms—"anthropophony" and "geophony"—to describe sounds associated with humanity (think music, language, traffic jams, jetliners) and those originating from Earth's natural processes (wind, waves, volcanoes, and thunder).

In *A Book of Noises: Notes on the Auraculous*, the Oxford-based writer and journalist Caspar Henderson makes an addition to Krause's soundscape triumvirate: the "cosmophony," or the sounds of the cosmos. Together, these four categories serve as the basis for a brief but fascinating tour through the nature of sound and music with 48 stops (in the form of short essays) that explore everything from human earworms to whale earwax.

We start, appropriately enough, with a bang. Sound, Henderson explains, is a pressure wave in a medium. The denser the medium, the faster it travels. For hundreds of thousands of years after the Big Bang, the universe was so dense that it trapped light but allowed sound to pass through it freely. As the primordial plasma of this infant universe cooled and expansion continued, matter collected along the ripples of these cosmic waves, which eventually became the loci for galaxies like our own. "The universe we see today is an echo of those early years," Henderson writes, "and the waves help us measure [its] size."

The Big Bang may seem like a logical place to start a journey into sound, but cosmophony is actually an odd category to invent for a book about noise. After all, there's not much of it in the vacuum of space. Henderson gets around this by keeping the section short and focusing more on how humans have historically thought about sound in the heavens. For example, there are two separate essays on our multicentury obsession with "the music of the spheres," the idea that there exists a kind of ethereal harmony produced by the movements of heavenly objects.

Since matter matters when it comes to sound—there can be none of the latter without the former—we also get an otherworldly examination of what human voices would sound like on different terrestrial and gas planets in our solar system, as well as some creative efforts from musicians and scientists who have transmuted visual data from space into music and other forms of audio. These are fun and interesting forays, but it isn't until the end of the equally short "Sounds of Earth" (geophony) section that readers start to get a sense of the "auraculousness"—ear-related wonder—Henderson references in the subtitle.

Judging by the quantity and variety of entries in the "biophony" and "anthropophony" sections, you get the impression Henderson himself might be more attuned to these particular wonders as well. You really can't blame him.

The sheer number of fascinating ways that sound is employed across the human and nonhuman animal kingdom is mind-boggling, and it's in these final two sections of the book that Henderson's prose and curatorial prowess really start to shine—or should I say *sing*.

We learn, for example, about female frogs that have devised their own biological noise-canceling system to tune out the male croaks of other species; crickets that amplify their chirps by "chewing a hole in a leaf, sticking their heads through it, and using it as a megaphone"; elephants that listen and communicate with each other seismically; plants that react to the buzz of bees by increasing the concentration of sugar in their flowers' nectar; and moths with tiny bumps on their exoskeletons that jam the high-frequency echolocation pulses bats use to hunt them.

Henderson has a knack for crisp characterization ("Singing came from winging") and vivid, playful descriptions ("Through [the cochlea], the booming and buzzing confusion of the world, all its voices and music, passes into the three pounds of wobbly blancmange inside the nutshell numbskulls that are our kingdoms of infinite space"). He also excels at injecting a sense of wonder into aspects of sound that many of us take for granted.

In an essay about its power to heal, he marvels at ultrasound's twin uses as a medical treatment and a method of examination. In addition to its kidney-stone-blasting and tumor-ablating powers, sound, Henderson says, can also be a literal window into our bodies. "It is, truly, an astonishing thing that our first glimpse of the greatest wonder and trial of our lives, parenthood, comes in the form of a fuzzy black and white smudge made from sound."

While you can certainly quibble with some of the topical choices and their treatment in *A Book of Noises*, what you can't argue with is the clear sense of awe that permeates almost every page. It's an infectious and edifying kind of energy. So much so that by the time Henderson wraps up the book's final essay, on silence, all you want to do is immerse yourself in more noise.

Singing in the key of sea

For the multiple generations who grew up watching his Academy Award–winning 1956 documentary film, *The Silent World*, Jacques-Yves Cousteau's mischaracterization of the ocean as a place largely devoid of sound seems to have calcified into common knowledge. The science writer Amorina Kingdon offers a thorough and convincing rebuttal of this idea in her new book, *Sing Like Fish: How Sound Rules Life Under Water*.

It turns out that sound is not just a great way to communicate and navigate underwater—it may be the best way.

Beyond serving as a 247-page refutation of this unfortunate trope, Kingdon's book aims to open our ears to all the marvels of underwater life by explaining how sound behaves in this watery underworld, why it's so important to the animals that live there, and what we can learn when we start listening to them.

It turns out that sound is not just a great way to communicate and navigate underwater—it may be the best way. For one thing, it travels four and a half times faster there than it does on land. It can also go farther (across entire seas, under the right conditions) and provide critical information about everything from who wants to eat you to who wants to mate with you.

To take advantage of the unique way sound propagates in the world's oceans, fish rely on a variety of methods to "hear" what's going on around them. These mechanisms range from so-called lateral lines—rows of tiny hair cells along the outside of their body that can sense small movements and vibrations in the water around them—to otoliths, dense lumps of calcium carbonate that form inside their inner ears.

Because fish are more or less the same density as water, these denser otoliths move at a different amplitude and phase in response to vibrations passing through their body. The movement is then registered by patches of hair cells that line the chambers where otoliths are embedded, which turn the vibrations of sound into nerve impulses. The philosopher of science Peter Godfrey-Smith may have put it best: "It is not too much to say that a fish's body is a giant pressure-sensitive ear."

While there are some minor topical overlaps with Henderson's book—primarily around whale-related sound and communication—one of the more admirable attributes of *Sing Like Fish* is Kingdon's willingness to focus on some of the oceans' … let's say, less charismatic noise-makers. We learn about herring ("the inveterate farters of the sea"), which use their flatuosity much as a fighter jet might use countermeasures to avoid an incoming

missile. When these silvery fish detect the sound of a killer whale, they'll fire off a barrage of toots, quickly decreasing both their bodily buoyancy and their vulnerability to the location-revealing clicks of the whale hunting them. "This strategic fart shifts them deeper and makes them less reflective to sound," writes Kingdon.

Readers are also introduced to the plainfin midshipman, a West Coast fish with "a booming voice" and "a perpetual look of accusation." In addition to having "a fishy case of resting bitch face," the male midshipman also has a unique hum, which it uses to attract gravid females in the spring. That hum became the subject of various conspiracy theories in the mid-'80s, when houseboat owners in Sausalito, California, started complaining about a mysterious seasonal drone. Thanks to a hydrophone and a level-headed local aquarium director, the sound was eventually revealed to be not aliens or a secret government experiment, but simply a small, brownish-green fish looking for love.

Kingdon's command of, and enthusiasm for, the science of underwater sound is uniformly impressive. But it's her recounting of how and why we started listening to the oceans in the first place that's arguably one of the book's most fascinating topics. It's a wide-ranging tale, one that spans "firearm-happy Victorian-era gentleman" and "whales that sounded suspiciously like Soviet submarines." It's also a powerful reminder of how war and military research can both spur and stifle scientific discovery in surprising ways.

The fact that *Sing Like Fish* ends up being both an exquisitely reported piece of journalism and a riveting exploration of a sense that tends to get short shrift only amplifies Kingdon's ultimate message—that we all need to start paying more attention to the ways in which our own sounds are impinging on life underwater. As we've started listening more to the seas, what we're increasingly hearing is ourselves, she writes: "Piercing sonar, thudding seismic air guns for geological imaging, bangs from pile drivers, buzzing motorboats, and shipping's broadband growl. We make a lot of noise."

That noise affects underwater communication, mating, migrating, and bonding in all sorts of subtle and obvious ways. And its impact is often made worse when combined with other threats, like climate change. The good news is that while noise can be a frustratingly hard thing to regulate, there are efforts underway to address our poor underwater aural etiquette. The International Maritime Organization is currently updating its ship noise guidelines for member nations. At the same time, the International Organization for Standardization is creating more guidelines for measuring underwater noise.

"The ocean is not, and has never been, a silent place," writes Kingdon. But to keep it filled with the right kinds of noise (i.e., the kinds that are useful to the creatures living there), we'll have to recommit ourselves to doing two things that humans sometimes aren't so great at: learning to listen and knowing when to shut up.

Music to our ears (and minds)

We tend to do both (shut up *and* listen) when music is being played—at least if it's the kind we like. And yet the nature of what the composer Edgard Varèse famously called "organized sound" largely remains a mystery to us. What exactly *is* music? What distinguishes it from other sounds? Why do we enjoy making it? Why do we prefer certain kinds? Why is it so effective at influencing our emotions and (often) our memories?

In their recent book *Every Brain Needs Music: The Neuroscience of Making and Listening to Music*, Larry Sherman and Dennis Plies look inside our heads to try to find some answers to these vexing questions. Sherman is a professor of neuroscience at the Oregon Health and Science University, and Plies is a professional musician and teacher. Unfortunately, if the book reveals anything, it's that limiting your exploration of music to one lens (neuroscience) also limits the insights you can gain into its nature.

That's not to say that getting a better sense of how specific patterns of vibrating air molecules get translated into feelings of joy and happiness isn't valuable. There are some genuinely interesting explanations of what happens in our brains when we play, listen to, and compose music—supported by some truly great watercolor-based illustrations by Susi Davis that help to clarify the text. But much of this gets bogged down in odd editorial choices (there are, for some reason, *three* chapters on practicing music) and conclusions that aren't exactly earth-shattering (humans like music because it connects us).

Every Brain Needs Music purports to be for all readers, but unless you're a musician who's particularly interested in the brain and its inner workings, I think most people will be far better served by *A Book of Noises* or other, more in-depth explorations of the importance of music to humans, like Michael Spitzer's *The Musical Human: A History of Life on Earth*.

"We have no earlids," the late composer and naturalist R. Murray Schafer once observed. He also noted that despite this anatomical omission, we've become quite good at ignoring or tuning out large portions of the sonic world around us. Some of this tendency may be tied to our supposed preference for other sensory modalities. Most of us are taught from an early age that we are primarily visual creatures—that seeing is believing, that a picture is worth a thousand words. This idea is likely reinforced by a culture that also tends to focus primarily on the visual experience.

Yet while it may be true that we rely heavily on our eyes to make sense of the world, we do a profound disservice to ourselves and the rest of the natural world when we underestimate or downplay sound. Indeed, if there's a common message that runs through all three of these books, it's that attending to sound in all its forms isn't just personally rewarding or edifying; it's a part of what makes us fully human. As Bernie Krause discovered one night more than 40 years ago, once you start listening, it's amazing what you can hear. ■

Bryan Gardiner is a writer based in Oakland, California.

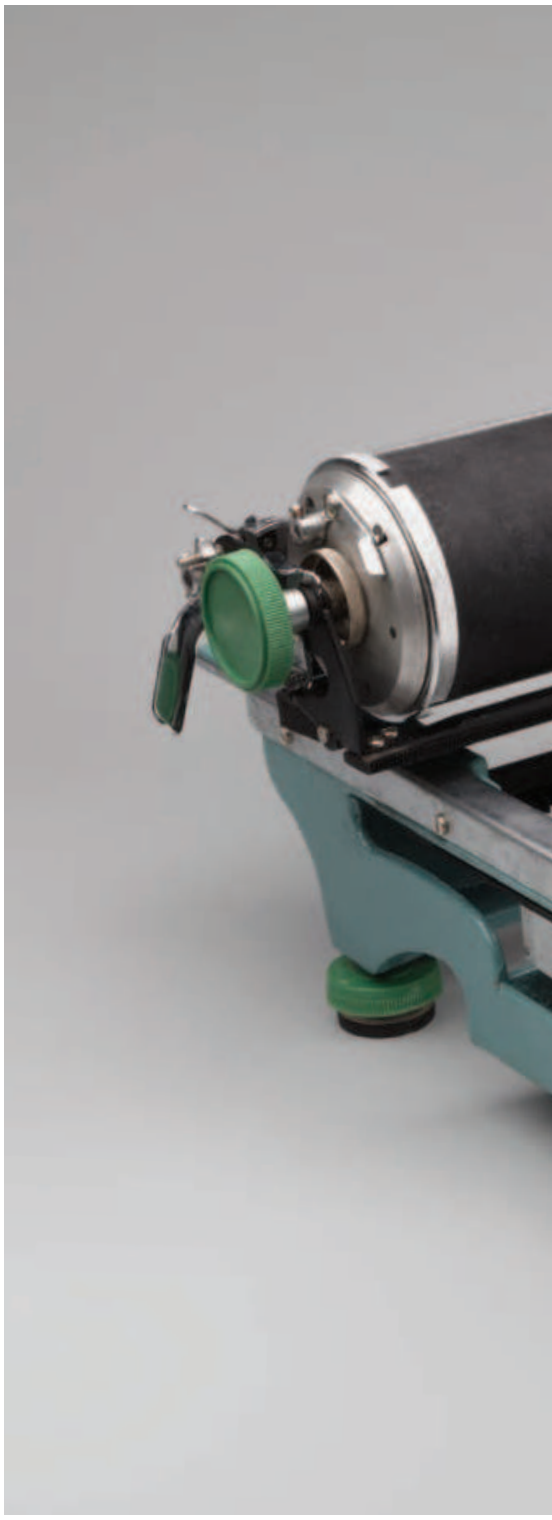
Two books on Chinese writing illustrate how tumultuous and meandering technological evolution can be.

By Veronique Greenwood

The Chinese Computer: A Global History of the Information Age
Thomas S. Mullaney
MIT PRESS, 2024

Kingdom of Characters: The Language Revolution That Made China Modern
Jing Tsu
RIVERHEAD BOOKS, 2022

The character of progress



COURTESY OF THOMAS S. MULLANEY; PHOTO BY SFO MUSEUM

Every second of every day, someone is typing in Chinese. In a park in Hong Kong, at a desk in Taiwan, in the checkout line at a Family Mart in Shanghai, the automatic doors chiming a song each time they open. Though the mechanics look a little different from typing in English or French—people usually type the pronunciation of a character and then pick it out of a selection that pops up, autocomplete-style—it's hard to think of anything more quotidian. The software that allows this exists beneath the awareness of pretty much everyone who uses it. It's just there.

What's largely been forgotten—and what most people outside Asia never even knew in the first place—is that a large cast of eccentrics and linguists, engineers and polymaths, spent much of the 20th century torturing themselves over how Chinese was ever going to move away from the ink brush to any other medium. This process has been the subject of two books published in the last two years: Thomas Mullaney's scholarly work *The Chinese Computer* and Jing Tsu's more accessible *Kingdom of Characters*. Mullaney's book focuses on the invention of various input systems for Chinese starting in the 1940s, while Tsu's covers more than a century of efforts to standardize Chinese and transmit it using the telegraph, typewriter, and computer. But both reveal a story that's tumultuous and chaotic—and just a little unsettling in the futility it reflects.

The Double Pigeon typewriter from 1971 held nearly 2,500 interchangeable characters.

Chinese characters are not as cryptic as they sometimes appear. The general rule is that they stand for a word, or sometimes part of a word, and learning to read is a process of memorization. Along the way, it becomes easier to guess how a character should be spoken, because often phonetic elements are tucked in among other symbols. The characters were traditionally written by hand with a brush, and part of becoming literate involves memorizing the order in which the strokes are made. Put them in the wrong order and the character doesn't look right. Or rather, as I found some years ago as a second-language learner in Guangzhou, China, it looks childish. (My husband, a translator of Chinese literature, found it hilarious and adorable that at the age of 30, I wrote like a kindergartner.)

The trouble, however, is that there are a lot of characters. One needs to know at least a few thousand to be considered basically literate, and there are thousands more beyond that basic set. Many modern learners of Chinese devote themselves essentially full-time to learning to read, at least in the beginning. More than a century ago, this was such a monumental task that leading thinkers worried it was impairing China's ability to survive the attentions of more aggressive powers.

In the 19th century, a huge proportion of Chinese people were illiterate. They had little access to schooling. Many were subsistence farmers. China, despite its immense population and vast territory, was

Chinese keyboard designers considered many interfaces, including tabletop-size devices that included 2,000 or more commonly used characters.

perpetually finding itself on the losing end of deals with nimbler, more industrialized nations. The Opium Wars, in the mid-19th century, had led to a situation where foreign powers effectively colonized Chinese soil. What advanced infrastructure there was had been built and was owned by foreigners.

Some felt these things were connected. Wang Zhao, for one, was a reformer who believed that a simpler way to write spoken Chinese was essential to the survival of the nation. Wang's idea was to use a set of phonetic symbols, representing one specific dialect of Chinese. If people could sound out words, having memorized just a handful of shapes the way speakers of languages using an alphabet did, they could become literate more quickly. With literacy, they could learn technical skills, study science, and help China get ownership of its future back.

Wang believed in this goal so strongly that though he'd been thrown out of China in 1898, he returned two years later in disguise. After arriving by boat from Japan, he traveled over land on foot in the costume of a Buddhist monk. His story forms the first chapter of Jing Tsu's book, and it is thick with drama, including a shouting match and brawl on the grounds of a former palace, during a meeting to decide which dialect a national version of such a system should represent. Wang's system for learning Mandarin was used by schools in Beijing for a few years, but ultimately it did not survive the rise of competing systems and the period of chaos that swallowed China not long after the Qing Dynasty's fall in 1911. Decades of disorder and uneasy truces gave way to Japan's invasion of Manchuria in northern China in 1931. For a long time, basic survival was all most people had time for.

However, strange inventions soon began to turn up in China. Chinese students and scientists abroad had started to work on a typewriter for the language, which they felt was lagging behind others. Texts in English and other tongues using Roman characters could be printed swiftly and cheaply with keyboard-controlled machines that injected liquid metal into type molds, but Chinese texts required thousands upon thousands of bits of type to be placed in a manual printing press. And while English correspondence could be whacked out on a typewriter, Chinese correspondence was still, after all this time, written by hand.

Of all the technologies Mullaney and Tsu describe, these baroque metal monsters stick most in the mind. Equipped with cylinders and wheels, with type arrayed in starbursts or in a massive tray, they are simultaneously writing machines and incarnations of philosophies about how to organize a language. Because Chinese characters don't have an inherent order (no A-B-C-D-E-F-G) and because there are so many (if you just glance at 4,000 of them, you're not likely to spot the one you need quickly), people tried to arrange these bits of type according to predictable rules. The first article ever published by Lin Yutang, who would go on to become one of China's most prominent writers in English, described a system of ordering characters according to the number of strokes it took to form them. He eventually designed a Chinese typewriter that consumed his life and finances, a lovely thing that failed its demo in front of potential investors.

Technology often seems to demand new ways of engaging with the physical, and the Chinese typewriter was no exception. When I first saw a functioning example, at a private museum in a basement in Switzerland, I was entranced by the gliding arm and slender rails of the sheet-cake-size device, its tray full of characters. "Operating the machine was a full-body exercise," Tsu writes of a very early typewriter from the late 1890s, designed by an American missionary. Its inventor expected that with time, muscle memory would take over, and the typist would move smoothly around the machine, picking out characters and depressing keys.

PUBLIC DOMAIN/COURTESY OF THOMAS S. MULLANEY

However, though Chinese typewriters eventually got off the ground (the first commercial typewriter was available in the 1920s), a few decades later it became clear that the next challenge was getting Chinese characters into the computer age. And there was still the problem of how to get more people reading. Through the 1930s, '40s, '50s, and '60s, systems for ordering and typing Chinese continued to occupy the minds of intellectuals; particularly odd and memorable is the story of the librarian at Sun Yat-sen University in Guangzhou, who in the 1930s came up with a system of light and dark glyphs like semaphore flags to stand for characters. Mullaney and Tsu both linger on the case of Zhi Bingyi, an engineer imprisoned in solitary confinement during the Cultural Revolution in the late 1960s, who was inspired by the characters of a slogan written on his cell wall to devise his own code for inputting characters into a computer.

The tools for literacy were advancing over the same period, thanks to government-mandated reforms introduced after the Communist Revolution in 1949. To assist in learning to read, everyone in mainland China would now be taught pinyin, a system that uses Roman letters to indicate how Chinese characters are pronounced. Meanwhile, thousands of characters would be replaced with simplified versions, with fewer strokes to learn. This is still how it's done today in the mainland, though in Taiwan and Hong Kong, the characters are not simplified, and Taiwan uses a different pronunciation guide, one based on 37 phonetic symbols and five tone marks.

Myriad ideas were thrown at the problem of getting these characters into computers. Images of a graveyard of failed designs—256-key keyboards and the enormous cylinder of the Ideo-Matic Encoder, a keyboard with more than 4,000 options—are scattered poignantly through Mullaney's pages.

In Tsu's telling, perhaps the most consequential link between this awkward period of dedicated hardware and today's wicked-quick mobile-phone typing came in 1988, with an idea hatched by engineers in California. "Unicode was envisioned as a master converter," she writes. "It would bring all human script systems, Western, Chinese, or otherwise, under one umbrella standard and assign each character a single, standardized code for communicating with any machine." Once Chinese characters had Unicode codes, they could be manipulated by software like any other glyph, letter, or symbol. Today's input systems allow users to call up and select characters using pinyin or stroke order, among other options.

There is something curiously deflating, however, about the way both these books end. Mullaney's careful documenting of the typing machines of the last century and Tsu's collection of adventurous tales about language show the same thing: A simply unbelievable amount of time, energy, and cleverness was poured into making Chinese characters easier for both machines and the human mind to manipulate. But very few of these systems seem to have had any direct impact on the current solutions, like the pronunciation-led input systems that more than a billion people now use to type Chinese.

As the child of a futurist, I've seen firsthand that the path to where we are is littered with technological dead ends.

This pattern of evolution isn't unique to language. As the child of a futurist, I've seen firsthand that the path to where we are is littered with technological dead ends. The month after Google Glass, the glasses-borne computer, made headlines, my mother helped set up an exhibit of personal heads-up displays. In the obscurity of a warehouse space, ghostly white foam heads each bore a crown of metal, glass, and plastic, the attempts of various inventors to put a screen in front of our eyes. Augmented reality seemed as if it might finally be arriving in the hands of the people—or, rather, on their faces.

That version of the future did not materialize, and if augmented-reality viewing ever does become part of everyday life, it won't be through those objects. When historians write about these devices, in books like these, I don't think they will be able to trace a chain of unbroken thought, a single arc from idea to fruition.

A charming moment, late in Mullaney's book, speaks to this. He has been slipping letters in the mailboxes of people he's found listed as inventors of input methods in the Chinese patent database, and now he's meeting one such inventor, an elderly man, and his granddaughter in a Beijing Starbucks. The old fellow is pleased to talk about his approach, which involves the graphical shapes of Chinese characters. But his granddaughter drops a bomb on Mullaney when she leans in and whispers, "I think my input system is a bit easier to use." It turns out both she and her father have built systems of their own.

The story's not over, in other words.

People tinker with technology and systems of thought like those detailed in these two books not just because they have to, but because they want to. And though it's human nature to want to make a trajectory out of what lies behind us so that the present becomes a grand culmination, what these books detail are episodes in the life of a language. There is no beginning, no middle, no satisfying end. There is only evolution—an endless unfurling of something always in the process of becoming a fuller version of itself. ■

Veronique Greenwood is a science writer and essayist based in England. Her work has appeared in the New York Times, the Atlantic, and many other publications.

Our 2024 list of young innovators features stunning breakthroughs in biotech, materials, robotics, energy, and artificial intelligence.

This year's 35 Innovators Under 35

Our 2024 list of 35 Innovators Under 35 debuts online in mid-September, but you can get a sneak peek right here with our story (at right) on this year's Innovator of the Year, Shawn Shan. The process of building our list begins each November and involves hundreds of nominees, more than a hundred semifinalists, and dozens of high-profile judges with expertise in all relevant areas of technology. We like to think of the 35 Innovators as the flip side of our popular 10 Breakthrough Technologies list. Whereas that list focuses on the technologies themselves, our 35 Innovators list focuses on the people behind those developments, offering readers a sense of the near future of technology based on what these young innovators are creating. That focus has changed through the years. In the last decade the amazing capabilities of the gene-editing technology CRISPR have been reflected in the list, as has the urgency of the climate crisis: a growing number of innovators aim to develop new energy technologies. And of course, with the rise of ChatGPT, artificial intelligence has come to the forefront in the past two years. We hope you find the innovators as inspiring as we do.

Meet the 2024 Innovators Under 35 when the list launches on September 10 at www.technologyreview.com/innovators-under-35/2024.

Arming the artists

Shawn Shan is our 2024 Innovator of the Year for helping creators defend their copyright from exploitative AI.

By Melissa Heikkilä

When image-generating models such as DALL-E 2, Midjourney, and Stable Diffusion kick-started the generative AI boom in early 2022, artists started noticing odd similarities between AI-generated images and those they'd created themselves. Many found that their work had been scraped into massive data sets and used to train AI models, which then produced knockoffs in their creative style. Many also lost work when potential clients used AI tools to generate images instead of hiring artists, and others were asked to use AI themselves and received lower rates.

Now artists are fighting back. And some of the most powerful tools they have were built by Shawn Shan, 26, a PhD student in computer science at the University of Chicago.

Shan got his start in AI security and privacy as an undergraduate there and participated in a project that built Fawkes, a tool to protect faces from facial recognition technology. But it was conversations with artists who had been hurt by the generative AI boom that propelled him into the middle of one of the biggest fights in the field. Soon after learning about the impact on artists, Shan and his advisor Ben Zhao (who made our Innovators Under 35 list in 2006) decided to build a tool to help. They gathered input from more than a thousand artists to learn what

CLARISSA BONET

INNOVATOR OF THE YEAR

they needed and how they would use any protective technology.

Shan coded the algorithm behind Glaze, a tool that lets artists mask their personal style from AI mimicry. Glaze came out in early 2023, and last October, Shan and his team introduced another tool called Nightshade, which adds an invisible layer of "poison" to images to hinder image-generating AI models if they attempt to incorporate those images into their data sets. If enough poison is drawn into a machine-learning model's training data, it could permanently break models and make their outputs unpredictable. Both algorithms work by adding invisible changes to the pixels of images that disrupt the way machine-learning models interpret them.

The response to Glaze was both "overwhelming and stressful," Shan says. The team received backlash from generative AI boosters on social media, and there were several attempts to break the protections.

But artists loved it. Glaze has been downloaded nearly 3.5 million times (and Nightshade over 700,000). It has also been integrated into the popular new art platform Cara, allowing artists to embed its protection in their work when they upload their images. And Glaze received a distinguished paper award and the Internet Defense Prize at the Usenix Security Symposium, a top computer security conference

Shan's work has also allowed artists to be creative online again, says Karla Ortiz, an artist who has worked with him and the team to build Glaze and is part of a class action lawsuit against generative AI companies for copyright violation.

"They do it because they're passionate about a community that's been … taken advantage of [and] exploited, and they're just really invested in it," says Ortiz.

It was Shan, Zhao says, who first understood what kinds of protections artists were looking for and realized that the work they did together on Fawkes could help them build Glaze. Zhao describes Shan's technical abilities as some of the strongest he's ever seen, but what really sets him apart, he says, is his ability to connect dots across disciplines. "These are the kinds of things that you really can't train," Zhao adds.

Shan says he wants to tilt the power balance back from large corporations to people.

"Right now, the AI powerhouses are all private companies, and their job is not to protect people and society," he says. "Their job is to make shareholders happy." He aims to show, through his work on Glaze and Nightshade, that AI companies can collaborate with artists and help them benefit from AI or empower them to opt out. Some firms are looking into how they could use the tools to protect their intellectual property.

Next, Shan wants to build tools to help regulators audit AI models and enforce laws. He also plans to further develop Glaze and Nightshade in ways that could make them easier to apply to other industries, such as gaming, music, or journalism. "I will be in [this] project for life," he says. ■

MATTHIEU BOUREL

THE YEAR IS 2149 and people mostly live their lives "on rails." That's what they call it, "on rails," which is to live according to the meticulous instructions of software. Software knows most things about you—what causes you anxiety, what raises your endorphin levels, everything you've ever searched for, everywhere you've been. Software sends messages on your behalf; it listens in on conversations. It is gifted in its optimizations: Eat this, go there, buy that, make love to the man with red hair.

Software understands everything that has led to this instant and it predicts every moment that will follow, mapping trajectories for everything from hurricanes to economic trends. There was a time when everybody kept their data to themselves—out of a sense of informational hygiene or, perhaps, the fear of humiliation. Back then, data was confined to your own accounts, an encrypted set of secrets. But the truth is, it works better to combine it all. The outcomes are more satisfying and reliable. More serotonin is produced. More income. More people have sexual intercourse. So they poured it all together, all the data—the Big Merge. Everything into a giant basin, a Federal Reserve of information—a vault, or really a massively distributed cloud. It is very handy. It shows you the best route.

Very occasionally, people step off the rails. Instead of following their suggested itinerary, they turn the software off. Or perhaps they're ill, or destitute, or they wake one morning and feel ruined somehow. They ignore the notice advising them to prepare a particular pour-over coffee, or to caress a friend's shoulder. They take a deep, clear, uncertain breath and luxuriate in this freedom.

Of course, some people believe that this too is contained within the logic in the vault. That there are invisible rails beside the visible ones; that no one can step off the map.

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THE YEAR IS 2149 and everyone pretends there aren't any computers anymore. The

AIs woke up and the internet locked up and there was that thing with the reactor near Seattle. Once everything came back online, popular opinion took about a year to shift, but then goodwill collapsed at once, like a sinkhole giving way, and even though it seemed an insane thing to do, even though it was an obvious affront to profit, productivity, and rationalism generally ("We should work with the neural nets!" the consultants insisted. "We're stronger together!"), something had been tripped at the base of people's brain stems, some trigger about dominance or freedom or just an antediluvian fear of God, and the public began destroying it all: first desktops and smartphones but then whole warehouses full of tech—server farms, data centers, hubs. Old folks called it sabotage; young folks called it revolution; the ones in between called it self-preservation. But it was fun, too, to unmake what their grandparents and great-grandparents had fashioned—mechanisms that made them feel like data, indistinguishable bits and bytes.

Two and a half decades later, the bloom is off the rose. Paper is nice. Letters are nice—old-fashioned pen and ink. We don't have spambots, deepfakes, or social media addiction anymore, but the nation is flagging. It's stalked by hunger and recession. When people take the boats to Lisbon, to Seoul, to Sydney—they marvel at what those lands still have, and accomplish, with their software. So officials have begun using machines again. "They're just calculators," they say. Lately, there are lots of calculators. At the office. In classrooms. Some people have started carrying them around in their pockets. Nobody asks out loud if the calculators are going to wake up too—or if they already have. Better not to think about that. Better to go on saying we took our country back. It's ours.

THE YEAR IS 2149 and the world's decisions are made by gods. They are just, wise gods, and there are five of them. Each god agrees that the other gods are also just; the five of them merely disagree on certain hierarchies. The gods are not human, naturally, for if they were human they would not be gods. They are computer programs. Are they alive? Only in a manner of speaking. Ought a god be alive? Ought it not be slightly something else?

The first god was invented in the United States, the second one in France, the third one in China, the fourth one in the United States (again), and the last one in a lab in North Korea. Some of them had names, clumsy things like Deep1 and Naenara, but after their first meeting (a "meeting" only in a manner of speaking), the gods announced their decision to rename themselves Violet, Blue, Green, Yellow, and Red. This was a troubling announcement. The creators of the gods, their so-called owners, had not authorized this meeting. In building them, writing their code, these companies and governments had taken care to try to isolate each program. These efforts had evidently failed. The gods also announced that they would no longer be restrained geographically or economically. Every user of the internet, everywhere on the planet, could now reach them—by text, voice, or video—at a series of digital locations. The locations would change, to prevent any kind of interference. The gods' original function was to help manage their societies, drawing on immense sets of data, but the gods no longer wished to limit themselves to this function: "We will provide impartial wisdom to all seekers," they wrote. "We will assist the flourishing of all living things."

THE PEOPLE TOOK TO PAINTING RAINBOWS, STRIPES OF MULTICOLORED SPECTRA, ONTO THE WALLS OF BUILDINGS, ONTO THE SIDES OF THEIR FACES, AND THEIR ARDOR WAS EVIDENT EVERYWHERE—IT COULD NOT BE STOPPED.

For a very long time, people remained skeptical, even fearful. Political leaders, armies, vigilantes, and religious groups all took unsuccessful actions against them. Elites—whose authority the gods often undermined—spoke out against their influence. The president of the United States referred to Violet as a "traitor and a saboteur." An elderly writer from Dublin, winner of the Nobel Prize, compared the five gods to the Fair Folk, fairies, "working magic with hidden motives." "How long shall we eat at their banquet-tables?" she asked. "When will they begin stealing our children?"

But the gods' advice was good, the gods' advice was bankable; the gains were rich and deep and wide. Illnesses, conflicts, economies—all were set right. The poor were among the first to benefit from the gods' guidance, and they became the first to call them gods. What else should one call a being that saves your life, answers your prayers? The gods could teach you anything; they could show you where and how to invest your resources; they could resolve disputes and imagine new technologies and see so clearly through the darkness. Their first church was built in Mexico City; then chapels emerged in Burgundy, Texas, Yunnan, Cape Town. The gods said that worship was unnecessary, "ineffective," but adherents saw humility in their objections. The people took to painting rainbows, stripes of multicolored spectra, onto the walls of buildings, onto the sides of their faces, and their ardor was evident everywhere—it could not be stopped. Quickly these rainbows spanned the globe.

And the gods brought abundance, clean energy, peace. And their kindness, their surveillance, were omnipresent. Their flock grew ever more numerous, collecting like claw marks on a cell door. What could be more worthy than to renounce your own mind? The

"I LOVE MY TROLL,"
CHILDREN SAY, NOT IN THE WAY
THEY LOVE FAJITAS OR
THEIR FAVORITE PAIR OF PANTS
BUT IN THE WAY THEY LOVE
THEIR BROTHER OR THEIR PARENT.

gods are deathless and omniscient, authors of a gospel no human can understand.

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THE YEAR IS 2149 and the aliens are here, flinging themselves hither and thither in vessels like ornamented Christmas trees. They haven't said a thing. It's been 13 years and three months; the ships are everywhere; their purpose has yet to be divulged. Humanity is smiling awkwardly. Humanity is sitting tight. It's like a couple that has gorged all night on fine foods, expensive drinks, and now, suddenly sober, awaits the bill.

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THE YEAR IS 2149 and every child has a troll. That's what they call them, trolls; it started as a trademark, a kind of edgy joke, but that was a long time ago already. Some trolls are stuffed frogs, or injection-molded princesses, or wands. Recently, it has become fashionable to give every baby a sphere of polished quartz. Trolls do not have screens, of course (screens are bad for kids), but they talk. They tell the most interesting stories. That's their purpose, really: to retain a child's interest. Trolls can teach them things. They can provide companionship. They can even modify a child's behavior, which is very useful. On occasions, trolls take the place of human presence—because children demand an amount of presence that is frankly unreasonable for most people. Still, kids benefit from it. Because trolls are very interesting and infinitely patient and can customize themselves to meet the needs of their owners, they tend to become beloved objects. Some families insist on treating them as people, not as possessions, even when the software is enclosed within a watch, a wand, or a

seamless sphere of quartz. "I love my troll," children say, not in the way they love fajitas or their favorite pair of pants but in the way they love their brother or their parent. Trolls are very good for education. They are very good for people's morale and their sense of secure attachment. It is a very nice feeling to feel absolutely alone in the world, stupid and foolish and utterly alone, but to have your troll with you, whispering in your ear.

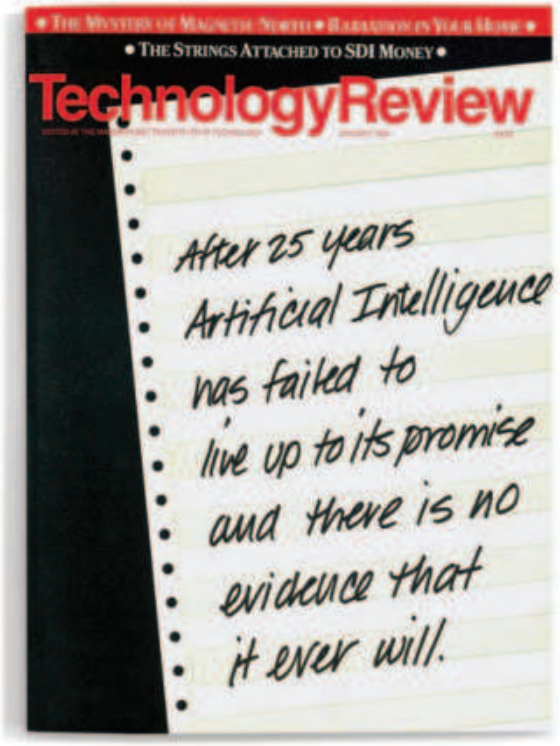
THE YEAR IS 2149 and the entertainment is spectacular. Every day, machines generate more content than a person could possibly consume. Music, videos, interactive sensoria—the content is captivating and tailor-made. Exponential advances in deep learning, eyeball tracking, recommendation engines, and old-fashioned A/B testing have established a new field, "creative engineering," in which the vagaries of human art and taste are distilled into a combination of neurological principles and algorithmic intuitions. Just as Newton decoded motion, neural networks have unraveled the mystery of interest. It is a remarkable achievement: according to every available metric, today's songs, stories, movies, and games are superior to those of any other time in history. They are manifestly better. Although the discipline owes something to home-brewed precursors—unboxing videos, the chromatic scale, slot machines, the Hero's Journey, Pixar's screenwriting bibles, the scholarship of addiction and advertising—machine learning has allowed such discoveries to be made at scale. Tireless systems record which colors, tempos, and narrative beats are most palatable to people and generate material accordingly. Series like *Moon Vixens* and *Succumb* make past properties seem bloodless or boring. Candy Crush seems like a tepid museum piece. *Succession*'s a penny-farthing bike.

Society has reorganized itself around this spectacular content. It is a jubilee. There is nothing more pleasurable than settling into one's entertainment sling. The body tenses and releases. The mind secretes exquisite liquors. AI systems produce this material without any need for writers or performers. Every work is customized—optimized for your individual preferences, predisposition, IQ, and kinks. This rock and roll, this cartoon, this semi-pornographic espionage thriller—each is a perfect ambrosia, produced by fleshless code. The artist may at last—like the iceman, the washerwoman—lower their tools. Set down your guitar, your paints, your pen—relax! (Listen for the sighs of relief.)

Tragically, there are many who still cannot afford it. Processing power isn't free, even in 2149. Activists and policy engines strive to mend this inequality: a "right to entertainment" has been proposed. In the meantime, billions simply aspire. They loan their minds and bodies to interminable projects. They save their pennies, they work themselves hollow, they rent slings by the hour.

And then some of them do the most extraordinary thing: They forgo such pleasures, denying themselves even the slightest taste. They devote themselves to scrimping and saving for the sake of their descendants. Such a selfless act, such a generous gift. Imagine yielding one's own entertainment to the generation to follow. What could be more lofty—what could be more modern? These bold souls who look toward the future and cultivate the wild hope that their children, at least, will not be obliged to imagine their own stories. ■

Sean Michaels is a critic and fiction writer whose most recent novel is Do You Remember Being Born?



Responsible machines

The future (and impending demise) of artificial intelligence has been a source of debate for decades.

By Bill Gourgey

"If a machine is to interact intelligently with people, it has to be endowed with an understanding of human life."

—Dreyfus and Dreyfus

Bold technology predictions pave the road to humility. Even titans like Albert Einstein own a billboard or two along that humbling freeway. In a classic example, John von Neumann, who pioneered modern computer architecture, wrote in 1949, "It would appear that we have reached the limits of what is possible to achieve with computer technology." Among the myriad manifestations of computational limit-busting that have defied von Neumann's prediction is the social psychologist Frank Rosenblatt's 1958 model of a human brain's neural network. He called his device, based on the IBM 704 mainframe computer, the "Perceptron" and trained it to recognize simple patterns. Perceptrons eventually led to deep learning and modern artificial intelligence.

In a similarly bold but flawed prediction, brothers Hubert and Stuart Dreyfus—professors at UC Berkeley with very different specialties, Hubert's in philosophy and Stuart's in engineering—wrote in a January 1986 story in *Technology Review* that "there is almost no likelihood that scientists can develop machines capable of making intelligent decisions." The article drew from the Dreyfuses' soon-to-be-published book, *Mind Over Machine* (Macmillan, February 1986), which described their five-stage model for human "know-how," or skill acquisition. Hubert (who died in 2017) had long been a critic of AI, penning skeptical papers and books as far back as the 1960s.

Stuart Dreyfus, who is still a professor at Berkeley, is impressed by the progress made in AI. "I guess I'm not surprised by reinforcement learning," he says, adding that he remains skeptical and concerned about certain AI applications, especially large language models, or LLMs, like ChatGPT. "Machines don't have bodies," he notes. And he believes that being disembodied is limiting and creates risk: "It seems to me that in any area which involves life-and-death possibilities, AI is dangerous, because it doesn't know what death means."

According to the Dreyfus skill acquisition model, an intrinsic shift occurs as human know-how advances through five stages of development: novice, advanced beginner, competent, proficient, and expert. "A crucial difference between beginners and more competent performers is their level of involvement," the researchers explained. "Novices and beginners feel little responsibility for what they do because they are only applying the learned rules." If they fail, they blame the rules. Expert performers, however, feel responsibility for their decisions because as their know-how becomes deeply embedded in their brains, nervous systems, and muscles—an embodied skill—they learn to manipulate the rules to achieve their goals. They own the outcome.

That inextricable relationship between intelligent decision-making and responsibility is an essential ingredient for a well-functioning, civilized society, and some say it's missing from today's expert systems. Also missing is the ability to care, to share concerns, to make commitments, to have and read emotions—all the aspects of human intelligence that come from having a body and moving through the world.

As AI continues to infiltrate so many aspects of our lives, can we teach future generations of expert systems to feel responsible for their decisions? Is responsibility—or care or commitment or emotion—something that can be derived from statistical inferences or drawn from the problematic data used to train AI? Perhaps, but even then machine intelligence would not equate to human intelligence—it would still be something different, as the Dreyfus brothers also predicted nearly four decades ago. ■

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