MIT Technology Review

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AstroTurf wars

Killer microbes from the mirror world

PLUS!

New fiction from Jeff VanderMeer

Clone Wolf

Colossal Biosciences said it cloned endangered red wolves. But what has it actually made?

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There is no nature

By Mat Honan

Mat Honan is editor in chief of MIT Technology Review.

When people talk about "nature," they're generally talking about things that aren't made by human beings. Rocks. Reefs. Red wolves. But while there is plenty of God's creation to go around, it is hard to think of anything on Earth that human hands haven't affected.

In the Brazilian rainforest, scientists have found microplastics in the bellies of animals ranging from red howler monkeys to manatees. In remotest Yakutia, where much of the earth remains untrodden by human feet, the carbon in the sky above melts the permafrost below. In the Arctic Ocean, artificial light from ship traffic—on the rise as the polar ice cap melts away—now disrupts the nightly journey of zooplankton to the ocean surface, one of the largest animal migrations on the planet. The remote mountain lakes of the Alps are contaminated with all kinds of synthetic chemicals. Polar bears are full of flame retardants. Cesium-137, fallout from nuclear bomb explosions, lightly rimes the entire planet.

These examples are mostly pollution—nuclear, carbon, chemical, light—but I raise them not to highlight the ways human industry and technology degrade the environment but to note how the things humans build *change* it. Nobody really knows what the exact effects of all that will be, but my point is that no part of the globe is free of human fingerprints. We have literally changed the world.

We've changed ourselves as well. Humans are especially adept at bending human nature. Everything about us is up for grabs—appearance, health, our very thoughts. Pharmaceuticals, surgeries, vaccines, and hormones give us longer lives, take away our pain, ease our anxiety and depression, make us faster, stronger, more resilient. We're getting glimpses of technologies that will let us change who our children will become before they're even born. Electrodes implanted in people's brains let them control computers and translate thoughts into speech. Prosthetics and exoskeletons straight out of comic books restore and enhance physical abilities, while gene-editing technologies like CRISPR are rewriting our very DNA. And meanwhile, people have taken the sum total of all the information we have ever written down and poured it into vast calculating machines in an effort—at least by some—to build an intelligence greater than our own.

So what even is nature, or natural, in this context? Is it "environmentalist," in the conventional sense, to try to preserve what one could argue no longer exists? Should we employ technology to try to make the world more "natural"?

Those questions led us to approach this Nature issue with humility. We try to grapple with them all the time—*MIT Technology Review* is, after all, a review of how people have altered and built upon nature.

And it's a place to think about how we might repair it. Take solar geoengineering, for example—a subject we have covered with increasing frequency over the past few years. The basic idea of geoengineering is to find a technological fix for a problem technology caused: Burning petrochemicals to fuel the Industrial Revolution turned Earth's atmosphere into a heat sink, fundamentally breaking the climate. Some geoengineers think that releasing particulate matter into the stratosphere would reflect sunlight back into space, thus reducing global temperatures. After years of theoretical discussions, some companies have begun to actively experiment with such technologies. This might seem like a great way to restore the world to a more natural state. It's also fraught with controversy and peril. It could, for example, benefit some nations while harming others. It may give us license to continue burning fossil fuels and releasing greenhouse gases. The list goes on.

Nature isn't easy.

In our May/June issue, we have attempted to take a hard look at nature in our unnatural world. We have stories about birds that can't sing, wolves that aren't wolves, and grass that isn't grass. We look for the meaning of life under Arctic ice and within ourselves—and in the far future, on a distant world, courtesy of new fiction by the renowned author Jeff VanderMeer. I don't know if any of that will answer the questions I've been asking here—but we can't help but try. It's in our nature. ■

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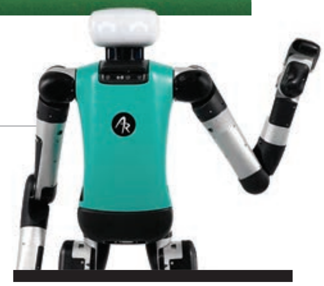

Front

Nature

Back

A lot of the time the real trick is not to withdraw from "nature" but to get better at being part of it. –p. 8

COVER PHOTOGRAPH BY TRISTAN SPINSKI

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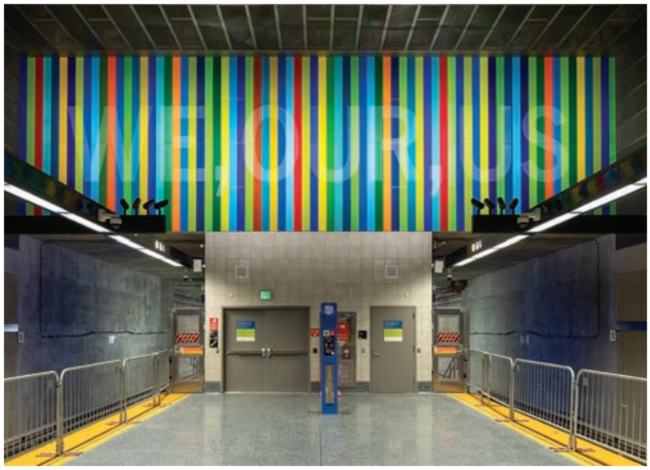
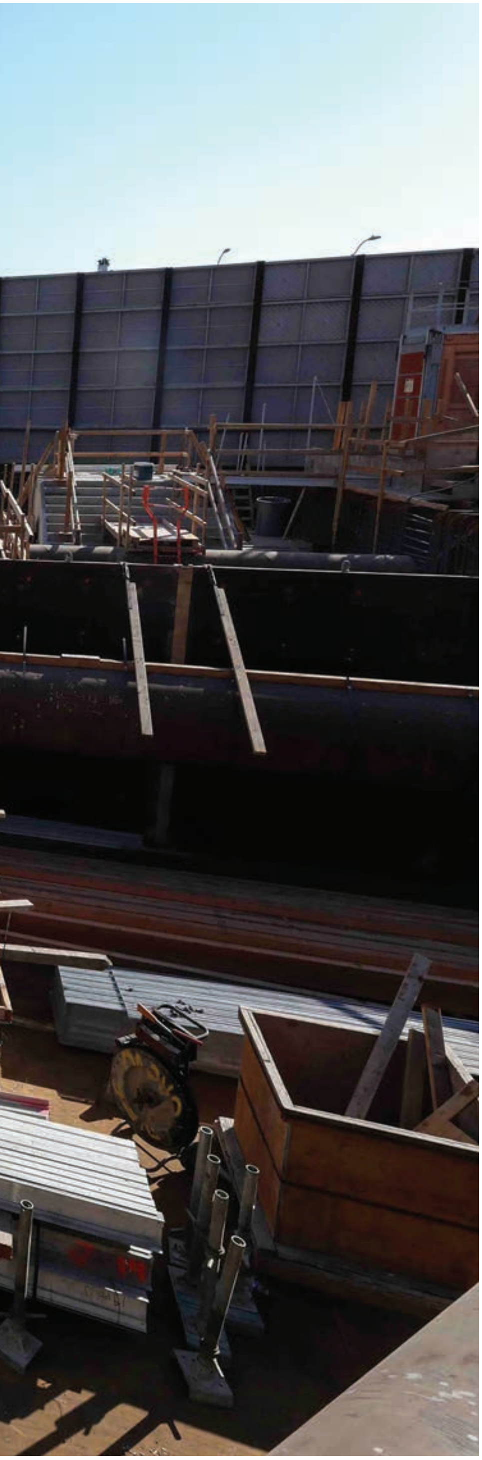




COURTESY OF LOS ANGELES COUNTY METROPOLITAN TRANSPORTATION AUTHORITY

TOP ROW:
(From left) A Metro train pulls into La Cienega, Susan Silton's art at Fairfax, and art by Eamon Ore-Giron at La Brea.

BELOW:
A dig in 2023 exposes the guts of LA under one of the city's busiest intersections.

TUNNEL VISION

Going underground

The long-under-construction Los Angeles subway arrives in a famous part of town. By Adam Rogers

Los Angeles deserves its reputation as the quintessential car city—the rhythms of its 2,200 square miles are dictated by wide boulevards and concrete arcs of freeways. But it once had a world-class rail transit system, and for the last three decades, the city has been rebuilding a network of trolleys and subways. In May, a new four-mile segment with three new subway stations will open along Wilshire Boulevard, a key east-west corridor that connects downtown LA to the Pacific Ocean. What today can be an hours-long drive through a busy, museum-packed stretch of the city will be, if all goes well, a 25-minute train ride.

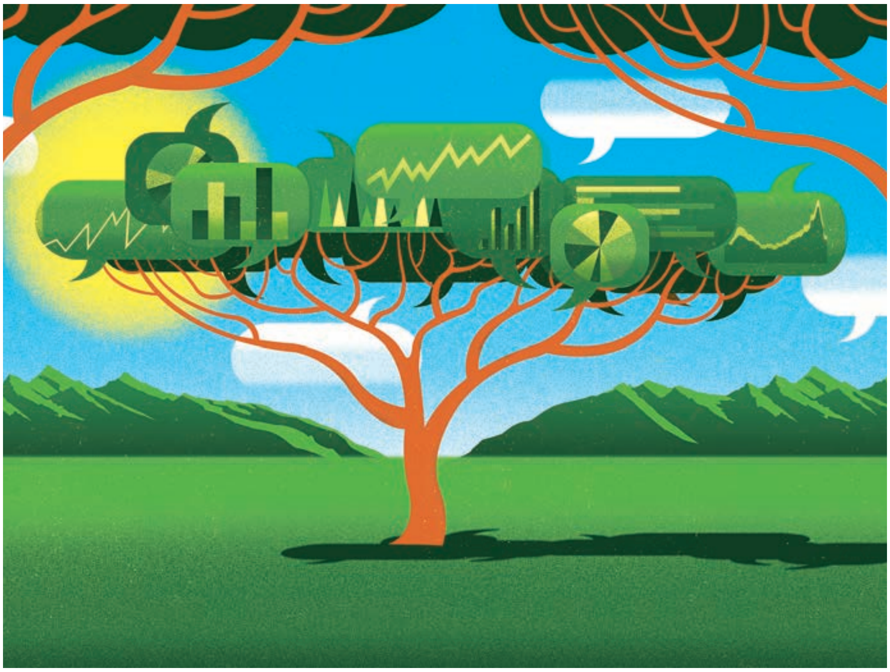
The existence of subway stops in this part of town—known as Miracle Mile—is a technological triumph over geography and geology. The ground underneath it is literally a disaster waiting to happen—it's tarry and full of methane. One of those methane deposits actually exploded in 1985, destroying a department store in the neighborhood. In response, the city pushed its new train routes to other parts of town.

These days, dirt full of flammable goo is no longer a problem. "The technology finally caught up with the concerns," says LA Metro's James Cohen, a longtime manager of the engineering for this stretch of subway. The key was an earth-pressure-balance tunnel-boring machine, an automated digger that is designed to chew through ground packed with explosive gas. It sends removed dirt topside via conveyor belts and slides precast concrete liner segments into the tunnel, which are joined together with gaskets to create a gas- and waterproof tube. All that let the machine dig about 50 feet every day.

Meanwhile, engineers excavated the stations from the street level down. They worked mostly on weekends, digging out a space and then decking it with concrete so that work could go on underneath while LA drivers continued to exercise their God-given right to get around by car above.

Did the project finish on time? No. Did it come in under budget? Also no; this segment alone cost nearly $4 billion. Is the city now racing to build housing and walkable areas to take full advantage of the extension? Oh, please. Yet the new stations still manage to feel, in the end, transformative—as if Los Angeles's train has finally come in. ■

Adam Rogers is interim director for print at MIT Technology Review.



METRICS

Humans and nature, quantified

The United Nations wants to know who has the best relationship with the natural world. That's tough to measure. By Emma Marris

As a movement, environmentalism has been pretty misanthropic. Understandably so—we humans have done some destructive things to the ecosystems around us. In the 21st century, though, mainstream conservation is learning that humans can be a force for good. Foresters are turning to Indigenous burning practices to prevent wildfires. Biologists are realizing that flower-dotted meadows were ancient food-production landscapes that need harvesting or they'll disappear. And the once endangered peregrine falcon now thrives in part thanks to nesting sites on skyscrapers and abundant urban prey: rats.

For decades (two, but that counts), I've been writing about how humans aren't metaphysically different from any other species on Earth. Conservation can't only be about fencing people out of protected areas. A lot of the time the real trick is not to withdraw from "nature" but to get better at being part of it.

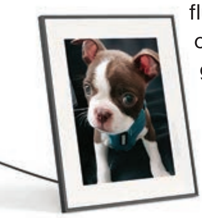
Still, I recognize that living in harmony with nature sounds like a mushy idea. I was therefore stoked to participate in a meeting in Oxford, UK, that sought to build more precise tools to assess human-nonhuman relationships. Scientists have invented lots of measurements of environmental destruction, from parts per million of carbon dioxide to extinction rates to "planetary boundaries." These have their uses, but they engage people mostly through dread. Why not invent metrics, we thought, that would engage people's hopes and dreams?

It was harder than I expected. How do you quantify how good people in any given nation are at living with other Earthlings? Some of the metrics the group proposed seemed to me to be too similar to the older, more adversarial approach. Why tally the agricultural land use per person, for example? Environmentalists have typically seen farms as the opposite of nature, but they're also potential sites for both edible and inedible biodiversity. Some of us were keen on

Recommendation engine

BUY

Aura digital picture frame
Digital frames are old tech, but judging by podcast ad prevalence, a whole new generation may be discovering them. The days of hand-loading pics via memory stick are over; the current generation (Aura and competitors like Skylight and Nixplay) are seamless (plug in, connect to Wi-Fi, upload photos to the app)—essential tech for far-flung families. At last, everyone can get wedding, vacation, and grandkid photos out of their phones and onto Grandma's sideboard. Prices range from $150 to $500, depending on size.



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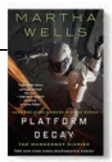


***Platform Decay* by Martha Wells**
The new Murderbot is here! The new Murderbot is here! Ahem. Sorry. In a season with a bunch of new entries in popular sci-fi series—Adrian Tchaikovsky's *Children of Strife*, a new Imperial Radch book from Ann Leckie, *The Faith of Beasts* from *The Expanse* creators James S.A. Corey—the return of Martha Wells's neurodivergent liberated killer robot with a conscience is a standout. Murderbot tales have turned into a fun TV show, and on the page, Wells combines genre pulp with thoughtful characters and world-building. Her books about an avenging android are always remarkably human.

ALSO READ

***The Wall Dancers: Searching for Freedom and Connection on the Chinese Internet* by Yi-Ling Liu**

The "wall" in the title is the Great Firewall, the system of surveillance and censorship that pervades Chinese online culture. But *Wall Dancers* doesn't judge. Through the stories of four very-online people in China, Yi-Ling Liu shows us a messy, inventive, constrained, and lively digital world. Liu acknowledges the pressures that shape life online while focusing on the agency of the people she features. The result is a portrait of limited freedom and maximum improvisation.

NEIL WEBB (ILLUSTRATION); COURTESY PHOTOS satellite imagery to calculate things like how close people live to green space. But without local information, you can't prove that people can actually *access* that space.

Eventually the 20 or so scientists, authors, and philosophers who met in Oxford settled on three basic questions. First, is nature thriving and accessible to people? We wanted to know if humans could engage with the world around them. Second, is nature being used with care? (Of course, "care" could mean lots of things. Is it just keeping harvests under maximum sustainable yield? Or does it require a completely circular economy?) And third, is nature safeguarded? Again, not easy to assess. But if we could roughly measure each of these three things, the numbers could combine into an overall score for the quality of a human-nature relationship.

We published our ideas in *Nature* last year. Though they weren't perfect, green-space remote sensing and agricultural footprint calculations made the cut. Since then, a team in the United Nations Human Development Office has continued that work, planning to debut a Nature Relationship Index (NRI) later this year alongside the 2026 Human Development Report. Everyone loves a ranked list; we hope countries will want to score well and will compete to rise to the top.

Pedro Conceição, lead author of the Human Development Report, tells me that he wants the new index to shift how countries see their environmental programs. (He wouldn't give me spoilers as to the final metrics, but he did tell me that nothing from our *Nature* paper made it in.) The NRI, Conceição says, will be critical for "challenging this idea that humans are inherent destroyers of nature and that nature is pristine." Narratives around constraints, limits, and boundaries are polarizing instead of energizing, he says. So the NRI isn't about how badly we are failing. It speaks to aspirations for a green, abundant world. As we do better, the number goes up—and there is no limit. ■

Emma Marris is the author of Wild Souls: Freedom and Flourishing in the Non-Human World.

PUBLIC DOMAIN (ISEGYE IDOL); MAD MAN FILMS VIA YOUTUBE (MR. NOBODY); COURTESY OF NETFLIX (ACASTER)

3 THINGS

MIT Technology Review AI reporter Michelle Kim shares what's on her radar.

Isegye Idol

If you thought K-pop was weird, virtual idols—humans who perform as anime-style digital characters via motion capture—will blow your mind. My favorite is a girl group called Isegye Idol, created by Woowakgood, a Korean VTuber (a streamer who likewise performs as a digital persona). Isegye Idol's six members are anonymous, which seems to let them deploy a rare breed of honesty and humor. They play games (League of Legends, Go, Minecraft), chitchat, and perform kitschy music that's somewhere between anime soundtrack and video-game score. It's very DIY—and very intimate. And the group's wild popularity speaks to the mood of Gen Z South Koreans, famously lonely and culturally adrift—struggling to find work, giving up on dating, trying to find friendships online. Isegye Idol shows what a magical online universe people can build when reality stops working for them.

Mr. Nobody Against Putin

Pavel Talankin didn't have the easiest life as a schoolteacher in the copper-smelting town of Karabash, Russia; UNESCO once called it the most toxic place on Earth. But video he shot, partially in secret, makes it clear he loved it—the smokestacks, the cold, the ice mustache he'd get walking around outside, and, most of all, his bright-eyed students. That makes it all the more painful when a distant, grinding war and state propaganda change the town. An antiwar progressive with a democracy flag in his classroom, Talankin had to deal with a new patriotic curriculum, mandatory parades, visits from mercenaries—and the loss of the creative space he'd built with his students. Talankin's footage tells his story in this Oscar-winning documentary from director David Borenstein, and what struck me most is how strange it is being an adult around kids. We shape them in profound ways we might not even recognize.

Repertoire by James Acaster

I am the kind of person who will pay $150 to watch a comedian in a smelly theater in San Francisco that charges $20 for a can of water—because I am crazy enough to hope that standup will not die. In February, I saw the British comedian James Acaster perform live ... and it was a mediocre show. But *Repertoire*, his 2018 miniseries on Netflix, is gold. Shot shortly after Acaster went through a breakup, the four-part show features him portraying, among other characters, a cop who goes undercover as a standup comedian, forgets who he is, and gets divorced. And then things get weird. "What if every relationship you've ever been in," Acaster asks, "is somebody slowly figuring out they didn't like you as much as they hoped they would?" If the best comedy comes from paying attention to the hellhole that you're in, I wish Acaster many more pitfalls.

JOB TITLES OF THE FUTURE

Wildlife first responder

By Emily Senkosky

Grizzly bears have made such a comeback across eastern Montana that in 2017, the state hired its first-ever prairie-based grizzly manager: wildlife biologist Wesley Sarmento.

For some seven years, Sarmento worked to keep both the bears, which are still listed as threatened under the Endangered Species Act, and the humans, who are sprawling into once-wild spaces, out of trouble. Based in the small city of Conrad, he acted sort of like a first responder, trying to defuse potential danger. He even got caught in some himself—which is why, before he left the role to pursue a PhD, he turned to drones to get the job done.

The bear necessities

Sarmento was studying mountain goats in Glacier National Park when he first started working with bears. To better understand how goats responded to the apex predator, he dressed up in a bear costume once a week for over three years.

When he later started as grizzly manager, he often drove long distances to push bears away from farms, where they might be feasting on spilled grains from leaky silos. Sarmento would typically arrive armed with a shotgun, cracker shells, and bear spray, but after he narrowly escaped getting mauled one day, he knew he had to pivot: "I was like, *I am gonna get myself killed*."

A bird's-eye view

He first took a drone into the field in 2022, when a grizzly mom and two cubs were found rummaging around in a silo outside of town. The drone's infrared sensors helped him quickly find their location, and he used the aircraft's sound to drive them away from the property. (Researchers suspect bears instinctively dislike the whir of blades because it sounds like a swarm of bees.) "The whole thing was so clean and controlled," he says. "And I did it all from the safety of my truck."

The flying machine that Sarmento bought for $4,000—a fairly simple model with 30 minutes of battery life—has since proved its worth, detecting grizzlies in perilous terrain he'd otherwise have to approach on foot.

A new technological foundation

Now studying wildlife ecology at the University of Montana, Sarmento is hoping to design a drone campus police can use to deter black bears from school grounds. In the future, he hopes, AI image recognition might be broadly integrated into his wildlife management work—maybe even helping drones identify bears and autonomously divert them from high-traffic areas.

"The hope is to keep exploring applications," he says. "Drones are the next frontier." ■

Emily Senkosky is a writer with a master's degree in environmental science journalism from the University of Montana.

ALAMY

DISPATCH

The $400,000 wild goose chase

One California town hates its gaggle so much it's deploying the Goosinator. By Annika Hom

"Pull over!" I order my brother one sunny February afternoon. Our target is in sight: a gaggle of Canada geese, pecking at grass near the dog park. As I approach, tiptoeing over their grayish-white poop, I notice that one bird wears a white cuff around its slender black neck. It's a GPS tracker—part of a new tech-centered campaign to drive the geese out of my hometown of Foster City, California.

About 300 geese live in this sleepy Bay Area suburb, equal to nearly 1% of our human population—and some say this town isn't big enough for the both of us. Goose poop notoriously blanketed our middle school's lawn, and the birds have hassled residents for generations. My own grandmother remembers when geese took over her garage for five whole minutes before waddling out. She says, "I wanted to kill them, but I thought I'd get in trouble."

Indeed, that idea doesn't fly here. City officials backed out of a previous plan to kill 100 geese following uproar from local environmentalists. Still, the poop creates a public health hazard; the birds need to go.

So the city paid nearly $400,000—roughly $1,300 per goose—to Wildlife Innovations, a company that resolves conflicts between humans and wildlife, to haze the geese with gadgets. The company's approach is "basically, making the geese less comfortable," Dan Biteman, head of the goose management plan and senior wildlife biologist at Wildlife Innovations, tells me.

THE PLACE:
Foster City, CA
USA

The need for such conflict resolution is on the rise as land development collides with changes in animal behavior. Though overpopulation of Canada geese is a national nuisance in the US, such tensions also surface with other species in this country and elsewhere, including grizzlies on the Montana prairies, coyotes on San Francisco streets, and savanna elephants in Tanzania parks.

So the people whose job it is to deal with recalcitrant critters are bringing on the gadgets.

Back in Foster City, I spot a black camera mounted to a tree trunk at Gull Park by the lagoon. They're in seven parks around town, programmed to snap photos every 15 minutes and transmit them back to Wildlife Innovations HQ. If they detect geese, a biologist immediately drives over to disperse the birds. One team member uses devices like lasers or drones; another brings along a goose-hating border collie named Rocky.

As a special measure, staff deploy the "Goosinator," a small, remote-controlled neon-orange pontoon boat with a fearsome dog-like mouth painted on its bow, meant to evoke geese's fear of coyotes and bright colors. It comes with attachable wheels and can zoom around on land or water to chase birds away. Biteman tells me the company is thinking about mounting speakers on trees and flying drones that will screech the calls of goose predators like red-tailed hawks or golden eagles.

The company received federal permits required by the Migratory Bird Treaty Act to stick GPS trackers on 10 geese, too. This way, staff can surveil the geese and research their behavior and movements.

At local goose hangouts, signs that look like "Wanted" posters alert the public to the new plan. As I watch some culprits graze (and defecate) on a church lawn, I think to myself: *Enjoy it while it lasts.* ■

Annika Hom is an award-winning independent journalist. She's written for National Geographic, Wired, and more.

Above: A gaggle gallivants along Foster City Boulevard. Some geese, like the one on the left, wear GPS trackers as part of the Foster City goose management plan, while belligerent birds must grapple with the Goosinator (right).

ANNIKA HOM; ADOBE STOCK (MAP)

Group chat

We want to hear from you! Tell us what's on your mind, share your perspective, or ask us a question by writing to newsroom@technologyreview.com.

Analog AMA

Q: Is hydrogen the answer to AI's power demands?

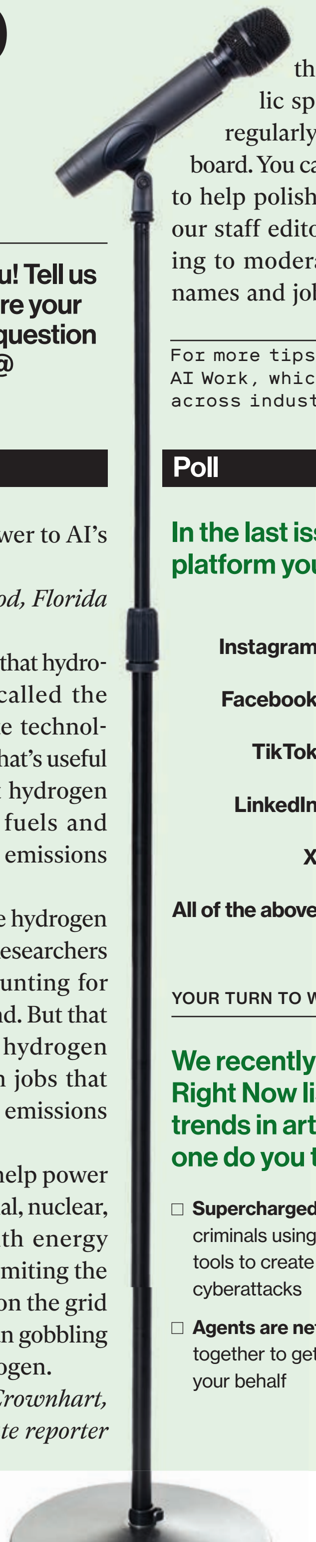
—Jeff S. from Hollywood, Florida

A: Probably not. It's true that hydrogen is sometimes called the Swiss Army knife of climate technology—it's a zero-carbon fuel that's useful across industries. But most hydrogen today is made with fossil fuels and comes with greenhouse-gas emissions attached.

Now, it's possible to make hydrogen with renewable electricity. Researchers and companies are even hunting for natural deposits underground. But that limited supply of cleaner hydrogen probably has better uses in jobs that don't have many ways to cut emissions today, like making steel.

Other technologies can help power the grid, including geothermal, nuclear, and renewables paired with energy storage. Scaling those and limiting the strain that data centers put on the grid are likely better solutions than gobbling up a limited supply of hydrogen.

—Casey Crownhart, senior climate reporter



Tech tip

CURIOUS ABOUT HOW OUR TEAM USES THE TECHNOLOGIES AROUND US? LEARN ABOUT A TOOL THAT ONE OF OUR STAFFERS HAS TRIED AT HOME OR WORK, OR GET THEIR ADVICE ON HOW TO MANAGE THE TECH IN YOUR LIFE.

Perhaps you're in a role that involves a lot of public speaking, or where you're regularly presenting to a team or board. You can use generative AI tools to help polish your talk, as several of our staff editors do. If you're preparing to moderate an event, input the names and job titles of your speakers and ask for a list of questions tailored to that group—it might help you refine your own ideas. Or if you're trying to memorize a talk and need a fresh way to review it, upload your slide deck to a tool like ChatGPT or Copilot and ask it to quiz you on the material.

—Abby Ivory-Ganja, senior engagement editor

For more tips like this, check out our new limited-run newsletter, Making AI Work, which explores how large language models are being applied across industries. Sign up at technologyreview.com/MakingAIWork.

Poll

In the last issue's Group Chat, we asked which social media platform you're ready to take a break from. Here's what you said:

Instagram	12.5%
Facebook	16.67%
TikTok	0%
LinkedIn	0%
X	0%
All of the above	70.83%

YOUR TURN TO WEIGH IN!

We recently published our inaugural 10 Things That Matter in AI Right Now list, which describes key technologies and emerging trends in artificial intelligence. Here are a few of our picks. Which one do you think could affect society most this year?

- ☐ **Supercharged hacking** has criminals using widely available tools to create spammy cyberattacks
- ☐ **Agents are networking** together to get things done on your behalf
- ☐ **World models** aim to use spatial data and physics to better reflect reality
- ☐ **Automatic science** has scientists experimenting with LLMs for research
- ☐ **Weaponized fakes** make spreading propaganda easier

SCAN NOW TO ANSWER

GETTY IMAGES

Choice signals

Does free will exist? Neuroscientist Uri Maoz devises experiments to reveal how—or whether—the brain makes decisions.

By Sarah Scoles
Portrait by Chris Lake

Uri Maoz loved doing his human research, back when he was getting his PhD. He was studying a very specific topic in computational neuroscience: how the brain instructs our arms to move and how our gray matter in turn perceives that motion.

Then his professor asked him to deliver an undergrad lecture. Maoz assumed his boss was going to tell him exactly what to do, or at least throw some PowerPoint slides his way. But no. Maoz had free rein to teach anything, as long as it was relevant to the students. "I could have gone to human brain augmentation," he says. "Cyborgs or whatever."

Yet that admittedly fun and borderline sci-fi topic wasn't what popped, unbidden, into his mind. His idea, he recalls with excitement: "What neuroscience has to say about the question of free will!"

How—or whether—humans make decisions (like, say, about what to discuss in an undergrad lecture) had been on his mind since he'd read an article in his early twenties suggesting that … maybe they didn't. This question might naturally beget others: Had he even had a choice about whether to read that article in the first place? How would he ever know if he was responsible for making decisions in his life or if he just had the illusion of control?

"After that, there was no turning back," says Maoz, now a professor at Chapman University, in California. He finished his PhD work in human movement, but afterward he scooted further up the neural chain to find out how desires and beliefs turn into actions—from raising an arm to choosing someone to ask out to dinner on a Friday night.

Today, Maoz is a central figure in the attempt to (sort of, maybe) answer how that neural chain functions. His research has since overturned and reinterpreted canonical neuroscience studies and united the straight-scientific and philosophical sides of the free-will question. More than anything, though, he's succeeded in uncovering new wrinkles in the debate.

Machines and magic tricks

The concept of free will seems straightforward, but it doesn't have a universally accepted definition. One intuitive notion is that it's the ability to make our own decisions and take our own actions on purpose—that we control our lives. But physicists might ask if the universe is deterministic, following a preordained path, and if human choices can still happen in such a universe.

That's a question for them, Maoz says. What neuroscientists can do is figure out what's going on in the brain when people make decisions. "And that's what we're trying to do: to understand how our wishes, desires, beliefs, turn into actions," he says.

By the time Maoz had finished his PhD, in 2008, neuroscientific research into the question had been going on for decades. One foundational study from the 1960s showed that a hand movement—something a person seemingly decides to do—was preceded by the appearance in the brain of an electrical signal called the "readiness potential."

Building on that result, in the 1980s a neuroscientist named Benjamin Libet did the experiment that had first piqued Maoz's interest in the topic—one that many, until recently, interpreted as a death knell for the concept of free will.

"He just had people sit there, and whenever they feel like it, they would go *like this*," says Maoz, wiggling his wrist. Libet would then ask where a rotating dot was on a screen when they first had the urge to flick. He found that the readiness potential appeared not only before they moved their hand but before they reported having the urge to move—or, in Libet's interpretation, before they knew they were going to move.

Studies since have confirmed the observation and shown that the readiness potential appears a second or two—and maybe, fMRI implies, up to 10 seconds—before participants report making a conscious decision. "It suggests we are essentially passengers in a self-driving car," says Maoz. "The unconscious biological machine does all the steering, but our conscious mind sits in the driver's seat and takes the credit."

An electrical impulse in our brains can shed only so much light on whether we truly are the architects of our own fates.

Maoz initially approached his own research with variations on Libet's experiments. He worked with epilepsy patients who already had electrodes in their brains, for clinical purposes, and was able to predict which hand they would raise before they raised it.

Still, some of the Libet-inspired studies people were doing nagged at him. "All these results were about completely arbitrary decisions. Raise your hand whenever you feel like it," he says. "Why? No reason." A decision like that is quite different from, say, choosing to break up with your partner. Try telling someone they weren't in the driver's seat for *that*.

The field wasn't looking at meaningful decisions, he says—the ones that actually set the course of lives.

Maoz began pulling in philosophers to help guide his approach. They would challenge him to confront the semantic differences between things like intention, desire, and urge. Neuroscientists have tended to lump those concepts together, but philosophers tease them apart: Desire is a want that doesn't necessarily progress toward an action; urge carries implications of immediacy and compulsion; and intention involves committing to a plan. (Maoz has come to focus specifically on intention—including, recently, the potential intentions of AI.)

In 2017, he organized his first in a series of free-will conferences, drawing many autonomy-interested philosophers. "Thank you so much for coming," he recalls saying at the opening of the meeting. "As if you had a choice." One day, the crew took an excursion out on a lake. As the group munched on shrimp, someone joked that they hoped the boat didn't sink, because everybody in the field would die.

The comment didn't make Maoz feel existential dread. Instead, he figured that if the whole field was already there, why not lasso them all into writing a research grant? "He just thinks what should be the next step and just has a very good ability to just make it happen," says Liad Mudrik, a neuroscientist at Tel Aviv University and a frequent collaborator.

That ability is special among scientists, says Chapman colleague Aaron Schurger, with whom Maoz co-directs the Laboratory for Understanding Consciousness, Intentions, and Decision-Making (LUCID, appropriately). "I really think that Uri is kind of at the nexus of this field right now because he's really, really good at bringing people together around these big ideas," he says.

Donations and interruptions

Maoz has recently been making progress on one of the big ideas that have consistently occupied his working hours: how trivial and significant decisions play out differently in the brain. In collaborations with Mudrik, he's parsed the neural difference between picking and choosing—their terms for arbitrary decisions and those that change your life and tug on your emotions.

Readiness potential? Their measurements didn't clock it ahead of choices. In 2019, Maoz and a crew published a paper measuring the electrical activity in people's brains as they pressed a key to choose one of two nonprofits to donate $1,000 to—for real, with actual dollars. Then the researchers compared that activity with what they saw when the same group pressed a key at random to donate $500 each to two nonprofits. The team saw the readiness potential in the arbitrary decision, but not for the $1,000 question.

Libet's result, they concluded, doesn't apply to the important stuff, which means readiness potential might not actually be a sign that your brain is making a choice before you're aware of it. "If Libet would have chosen to focus on deliberate decisions, then maybe the entire debate about neuroscience proving free will to be an illusion would have been spared from us," Mudrik says.

Maoz's research has spurred others to reinterpret Libet's work. It's "enriched my thought process a great deal," says Bianca Ivanof, a psychologist whose dissertation scrutinized Libet's methods. They turn out to identify readiness potential at different times depending on how the rotating-dot setup is designed, complicating the ability to compare and interpret results.

Maoz has also continued to gather data on the subject. Last year, for example, he used an EEG to measure electrical signals in people's brains as they got ready to press a keyboard space bar. At random moments, he interrupted their preparations with an audible tone and asked them about their intentions. He saw no connection between the readiness potential and whether or not they were planning to tap the key—evidence that the potential doesn't represent the buildup of either conscious or unconscious plans. The team did see a signal, though, in a different part of the brain when people said they were preparing to move.

So … that's free will? Sadly, Maoz would be compelled to say *Well, not exactly*. An electrical impulse in our brains can shed only so much light on whether we truly are the architects of our own fates. And maybe the confusing data from neurons is actually the point. "I don't think it is a yes-or-no question," Maoz says. Maybe our less meaningful choices *aren't* mindfully made but big ones are; maybe we have the conscious power to change an intended action, but only if our brains are in a particular state.

Neuroscientists likely can't figure out, on their own, if free will exists. But they can, Maoz says, parse how semantically distinct decision-making forces—desires, urges, intentions, wishes, beliefs—manifest in our brains and become actions. "That is something that we are making progress on," he says, "and I think that that's going to help us understand what we do control." And perhaps also help us make peace with what we do not. ■

Sarah Scoles is a freelance science journalist and author based in southern Colorado.

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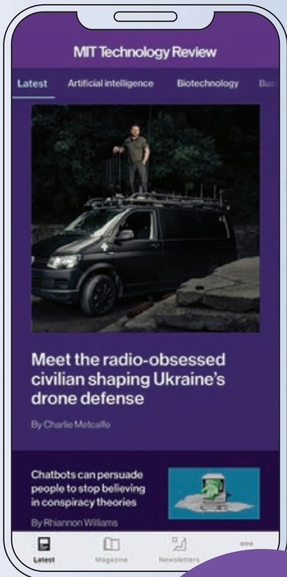

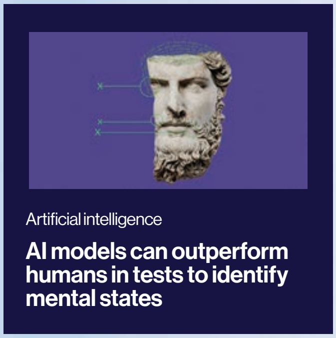

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The missing step between hype and profit

By Will Douglas Heaven

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

In February, I picked up a flyer at an anti-AI march in London. I can't say for sure whether or not its writers meant to riff on *South Park*'s underpants gnomes. But if they did, they nailed it: "Step 1: Grow a digital super mind," it read. "Step 2: ? Step 3: ?"

Produced by Pause AI, an international activist group that co-organized the protest, it ended with this plea to the reader: "Pause AI until we know what the hell Step 2 is."

In the *South Park* episode "Gnomes," which first aired in 1998, Kenny, Kyle, Cartman, and Stan discover a community of gnomes that sneak out at night to steal underpants from dressers. Why? The gnomes present their pitch deck. "Phase 1: Collect underpants. Phase 2: ? Phase 3: Profit."

The gnomes' business plan has since become one of the greats among internet memes, used to satirize everything from startup strategies to policy proposals. Memelord in chief Elon Musk once invoked it in a talk about how he planned to fund a mission to Mars. Right now, it captures the state of AI. Companies have built the tech (Step 1) and promised transformation (Step 3). How they get there is still a big question mark.

As far as Pause AI is concerned, Step 2 must involve some kind of regulation. But exactly what it will call for and who will enforce it are up for debate.

AI boosters, on the other hand, are convinced that Step 3 is salvation and tend to glaze over the middle bit. They see us racing toward sunny uplands on the back of an "economically transformative technology," as OpenAI's chief scientist, Jakub Pachocki, put it to me a few weeks ago. They know where they *want* to go—more or less: It's hazy up there and still some way off. But everyone's taking a different route. Will they all make it? Will anyone?

For every big claim about the future, there is a more sober assessment of how the rubber meets the road—one that quells the hype. Consider two recent studies. One, from Anthropic, predicted what types of jobs are going to be most affected by LLMs. (A takeaway: Managers, architects, and people in the media should prepare for change; groundskeepers, construction workers, and those in hospitality, not so much.) But their predictions are really just guesses, based on what kinds of tasks LLMs *seem* to be good at rather than how they really perform in the workplace.

Another study, put out in February by researchers at Mercor, an AI hiring startup, tested several AI agents powered by top-tier models from OpenAI, Anthropic, and Google DeepMind on 480 workplace tasks frequently carried out by human bankers, consultants, and lawyers. Every agent they tested failed to complete most of its duties.

Why is there such wide disagreement? There are a number of factors. For a start, it's crucial to consider who is making the claims (and why). Anthropic has skin in the game. What's more, most of the people telling us that something big is about to happen have reached that conclusion largely on the basis of how fast AI coding tools are getting. But not all tasks can be hacked with coding. Other studies have found that LLMs are bad at making strategic judgment calls, for example.

What's more, when they're deployed, the tools aren't just dropped into a cleanroom. They need to work in places contaminated with people and existing workflows. And sometimes adding AI will make things worse. Sure, maybe those workflows need to be torn up and refashioned around the new technology for it to achieve transformative status, but that will take time (and guts).

That big hole? It's right where Step 2 should be. The lack of agreement on exactly what's about to happen—and how—creates an information vacuum that gets filled by the latest wild claim of the week, evidence be damned. We're so unmoored from any real understanding of what's coming and how it will be deployed that a single social media post can (and does) shake markets.

We need fewer guesses and more evidence. But that's going to require transparency from the model makers, coordination between researchers and businesses, and new ways to evaluate this technology that tell us what really happens when it's rolled out in the real world.

The tech industry (and with it the world's economy) rests on the held-out promise that AI really will be transformative. But that is not yet a sure bet. Next time you hear bold claims about the future, remember that most businesses are still figuring out what to do with their underpants. ■

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PATRICK LÉGER

It's time to make a plan for nuclear waste

By Casey Crownhart

Casey Crownhart is senior climate reporter at MIT Technology Review.

Today, nuclear energy enjoys a rare moment of support across the political spectrum in the US. Interest from tech companies that are scrambling to meet demand for massive data centers has sparked a resurgence of money and attention in the industry. That newfound interest is exactly why it's time to talk about an old problem: nuclear waste.

In the US alone, nuclear reactors produce about 2,000 metric tons of high-level waste each year. And there's nowhere to put it.

Though newly popular, the nuclear program in the US is nothing new. The US hosts more reactors and production capacity than any other country in the world. And yet nearly seven decades after the first permanent nuclear facility in the US went online, there's still not a long-term solution for nuclear waste. Used fuel is largely stored onsite at operating and shut-down reactors, in pools and casks made of steel and concrete. Experts generally agree that these methods are safe, but they're not designed to be permanent.

The leading strategy around the world for long-term storage of this high-level radioactive waste is to house it in a deep geological repository—dig a hole, put radioactive material down there, and fill it up with concrete. These holes, hundreds of meters underground, are designed to be a permanent home.

There aren't any operating geological repositories for spent fuel yet, but some countries are well on their way. Finland is the furthest along; as of 2026, the country is testing its facility. Final approvals are expected soon, and operations could start later this year. Some other countries aren't far behind.

France is home to over 50 nuclear reactors, and its grid gets more of its power from nuclear than any other. The country also has the world's most established program for reprocessing spent fuel. The process separates out the plutonium and uranium to create a type of fuel known as mixed oxide (MOX) fuel. But reprocessing isn't a perfect recycling loop, so the leftovers from this process still need somewhere to go. The country currently stores waste onsite at the La Hague reprocessing plant, but it plans to build a repository. Initial approvals could come later this decade, and pilot operations could start up by 2035.

Technically, the US also has a destination for its spent fuel: Yucca Mountain in Nevada. The site, which is on federal land, was designated by Congress in 1987. However, progress has entirely stalled out because of political opposition. In 2011, the federal government stopped providing funding for the site, and for roughly a decade, there's been no activity to speak of.

In the meantime, waste continues to pile up.

The nuclear industry is kicking into a new gear around the world. China is home to the world's fastest-growing nuclear energy program, and countries including Bangladesh and Turkey are building their first reactors.

Even the long-established US program is seeing growth: Interest in and approval for nuclear energy have spiked, and Big Tech is throwing money around to meet rising electricity demand. Companies are proposing (and beginning to receive regulatory approval for) next-generation reactors, which employ different coolants, fuels, and designs.

The nuclear industry is kicking into a new gear around the world.

Given all this new interest, and the impending arrival of new types of nuclear waste, it's time for nuclear companies, as well as their powerful customers, to push for progress on building geological storage facilities. As the richest country on the planet and home to a large chunk of the activity in next-generation reactors, the US should aim to join the leaders rather than continue to lag behind.

Directing even a small fraction of the recent surge in funding and attention to progress on waste could make a difference. Some experts are calling for a new organization in the US to manage nuclear waste rather than leaving it to the Department of Energy. This organization would mirror programs in Finland, Canada, and France.

The process of planning, building, and commissioning a permanent solution for nuclear waste is a long one. Finland started planning in the 1980s and selected its site in the early 2000s, and it's nearly ready to start accepting waste. For countries that don't have a permanent storage solution sorted, the best time to start was decades ago. But the second-best time is now. ■

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PATRICK LÉGER

What's in a name? Moderna's "vaccine" vs. "therapy" dilemma

By Antonio Regalado

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

Is it the Department of Defense or the Department of War? The Gulf of Mexico or the Gulf of America? A vaccine—or an "individualized neoantigen treatment"?

That's the Trump-era vocabulary paradox facing Moderna, the covid-19 shot maker whose plans for next-generation mRNA vaccines against flus and emerging pathogens have been dashed by vaccine skeptics in the federal government. Canceled contracts and unfriendly regulators have pushed the Massachusetts-based biotech firm to a breaking point. Last year, Robert F. Kennedy Jr., head of the Department of Health and Human Services, zeroed in on mRNA, unwinding support for dozens of projects—including a $776 million award to Moderna for a bird flu vaccine. By January, the company was warning it might have to stop late-stage programs to develop vaccines against infections altogether.

That raises the stakes for a second area of Moderna's research. In a partnership with Merck, it's been using its mRNA technology to destroy tumors through a very, very promising technique known as a cancer vacc—

"It's not a vaccine," a spokesperson for Merck jumped in before the V-word could leave my mouth. "It's an individualized neoantigen therapy."

Oh, but it is a vaccine. And here's how it works. Moderna sequences a patient's cancer cells to find the ugliest, most peculiar molecules on their surface. Then it packages the genetic code for those same molecules, called neoantigens, into a shot. The patient's immune system has its orders: Kill any cells with those yucky surface markers.

Mechanistically, it's similar to the covid-19 vaccines. What's different, of course, is that the patient is being immunized against a cancer, not a virus.

And it looks like a possible breakthrough. This year, Moderna and Merck showed that such shots halved the chance that patients with the deadliest form of skin cancer would die from a recurrence after surgery.

In its formal communications, like regulatory filings, Moderna hasn't called the shot a cancer vaccine since 2023. That's when it partnered up with Merck and rebranded the tech as individualized neoantigen therapy, or INT. Moderna's CEO said at the time that the renaming was to "better describe the goal of the program." (BioNTech, the European vaccine maker that's also working in cancer, has shifted its language too, moving from "neoantigen vaccine" in 2021 to "mRNA cancer immunotherapies" in its latest report.)

The logic of casting it as a therapy is that patients already have cancer—so it's a treatment as opposed to a preventive measure. But it's no secret what the other goal is: to distance important innovation from vaccine fearmongering, which has been inflamed by high-ranking US officials. "Vaccines are maybe a dirty word nowadays, but we still believe in the science and harnessing our immune system to not only fight infections, but hopefully to also fight … cancers," Kyle Holen, head of Moderna's cancer program, said last summer during BIO 2025, a big biotech event in Boston.

Not everyone is happy with the word games. Take Ryan Sullivan, a physician at Massachusetts General Hospital who has enrolled patients in Moderna's trials. He says the change raises questions over whether trial volunteers are being properly informed. "There is some concern that there will be patients who decline to treat their cancer because it is a vaccine," Sullivan told me. "But I also felt it was important, as many of my colleagues did, that you have to call it what it is."

But is it worth going to the mat for a word? Lillian Siu, a medical oncologist at the Princess Margaret Cancer Centre, in Toronto, who has played a role in safety testing for the new shots, watches US politics from a distance. She believes name change is acceptable "if it allows the research to continue."

Holen told me the doctors complaining to Moderna were basically motivated by a desire to defend vaccines—which are, of course, among the greatest public health interventions of all time. They wanted the company to stand strong.

But that's not what's happening. When Moderna's latest results were published in February, the paper's main text didn't use the word "vaccine" at all. It was only in the footnotes that you could see the term—in the titles of old papers and patents.

All this could be a sign that Kennedy's strategy is working. His agencies often appear to make mRNA vaccines a focus of people's worries, impede their reach, devalue them for companies, and sideline their defenders.

Still, Moderna's strategy may be working too. So far, at least, the government hasn't had much to say about the company's cancer vacc— I mean, its individualized neoantigen therapy. ■

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PATRICK LÉGER

CHASING

Last year, Colossal Biosciences announced that it had cloned several specimens of “the most critically endangered wolf in the world.”

But had it? The answer is complex—and raises pressing questions about the future of conservation.

Canids emerge at dusk in Galveston Island, Texas. Researchers have discovered that the animals carry DNA from red wolves, which were declared extinct in the wild in 1980.

GHOSTS

By
Boyce Upholt

Photographs
Tristan Spinski

If you want to capture something wolflike, it's best to embark before dawn.

So on a morning this January, with the eastern horizon still pink-hued, I drove with two young scientists into a blanket of fog. Forty miles to the west, the industrial sprawl of Houston spawned a golden glow. Tanner Broussard's old Toyota Tacoma bumped over the levee-top roads as killdeer, flushed from their rest, flew across the beams of his headlights.

Broussard peered into the darkness, looking for traps. "I have one over here," he said, slowing slightly. A master's student at McNeese State University, he was quiet and contemplative, his bearded face half-hidden under a black ball cap. "Nothing on it," he said, blandly. The truck rolled on.

Wolves and their relations—dogs, jackals, coyotes, and so on—are classed in the family *Canidae*, and the canid that dominated this landscape in eastern Texas was once the red wolf. But as soon as white settlers arrived on the continent, *Canis rufus* found itself under siege. The war on wolves "lasted 200 years," federal researchers once put it, in a surprisingly evocative report. "The wolf lost." By 1980, the red wolf was declared extinct in the wild, its population reduced to a small captive breeding population.

Still, for decades afterward, people noted that strange wolflike creatures persisted along the Gulf Coast. Finally, in 2018, scientists confirmed that some local coyotes were more than coyotes: They were taller, long-legged, their coats shaded with hints of cinnamon. These animals contained relict red wolf genes. They became known as the ghost wolves.

Broussard grew up in southwest Louisiana, watching coyotes trot across his parents' ranch. The thrilling fact that these might have been not just coyotes but something more? That reset a rambling academic career. In 2023, Broussard had recently returned to college after a seven-year pause, and his budding obsession with wolves narrowed his focus. Before he finished his bachelor's degree, he began to supply field data to a prominent conservation nonprofit.

Then, last year, just before he began his master's studies, he woke to disconcerting news. A startup called Colossal Biosciences claimed to have resuscitated the dire wolf, a large canid that went extinct more than 10,000 years ago. Pundits debated the utility of the project and whether the clones—technically, gray wolves with some genetic tweaks—could really be called dire wolves. But what mattered to Broussard was Colossal's simultaneous announcement that it had cloned four red wolves.

"That surprised pretty much everybody in the wolf community," Broussard said as we toured the wildlife refuge where he'd set his traps. The Association of Zoos and Aquariums runs a program that sustains red wolves through captive breeding; its leadership had no idea a cloning project was underway. Nor did ecologist Joey Hinton, one of Broussard's advisors, who had trapped the canids Colossal used to source the DNA for its clones. Some of Hinton's former partners were collaborating with the company, but he didn't know that clones were on the table.

There was already disagreement among scientists about the entire idea of de-extinction. Now Colossal had made these mystery clones, whose location was kept secret. Even the *purpose* of the clones was murky to some scientists; just how they might restore red wolf populations was unclear.

Red wolves had always been a contentious species, hard for scientists to pin down. The red wolf research community was already marked by the inevitable interpersonal tensions of a small and passionate group. Now Colossal's clones became one more lightning rod. Perhaps the most curious question, though, was whether the company had cloned red wolves at all.

You can think of the red wolf as the wolf of the East—an apex predator that once roamed the forests and grasslands and marshes everywhere from Texas to Illinois to New York. Smaller than a gray wolf (though a good bit larger than a coyote), this was a sleek beast, with, according to one old field guide, a "cunning fox-like appearance": long body, long legs; clearly built to run across long distances. Its coat was smooth and flat and came in many colors: a reddish tone that comes out in the right light, yes, but also, despite the name, white and gray and, in certain regions and populations, an ominous all black.

We know these details thanks to a few notes from early naturalists. As writer Andrew Moore writes in his new book, *The Beasts of the East*, by the time a mammalogist decided to class these eastern wolves as a standalone species in the 1930s, the red wolf had been extirpated from the East Coast and was rapidly dwindling across its range. Working with remnant skulls and other specimens, the mammalogist chose the name red wolf—which was later enshrined with the Latinate *Canis rufus*—because that's what these wolves were called in the last place they survived.

The looming extinction of the red wolf turned out to be a good thing for coyotes. *Canis latrans* is a distant relative of wolves that split away from a common ancestor thousands of years ago and might be considered, as one canid biologist put it to me, the "wolf of the Anthropocene." Their smaller size means they need less food and can survive in smaller and more fragmented territory, the kind that modern humans tend to build.

Red wolves had kept coyotes out of eastern America, outcompeting them for prey. Now, as the wolves declined, the coyotes began to slip in. The last red wolves, which lived in Louisiana and Texas, decided a strange and smaller mate was preferable to no mate at all. Soon the territory became a genetic jumble, home to both wolves and coyotes and hybrids that, after several generations of intermixing, came in every shade between. Scientists call such a population a "hybrid swarm," and it poses a genetic threat to the declining species: As more coyotes poured east, and as all the canids kept interbreeding, there would be nothing that was "purely" wolf.

For years, no one seemed to notice. Perhaps trappers in the region mistook the new hybrids for wolves—or were happy to take the higher bounty that a wolf pelt earned. Finally, though, by the 1960s, as the concept of endangered species first emerged, biologists began to worry for the disappearing wolf.

The best solution they could come up with was a program of mass extermination. Over several years, trappers rounded up hundreds of canids in Texas and Louisiana. Those deemed true red wolves (on the basis of their howls and skull shape) were whisked away to breed in captivity. Most of the rest were euthanized. In 1980, the red wolf was declared extinct in the wild. To put it plainly: The red wolf was wiped out intentionally, in a roundabout effort to keep it alive.

Just 14 individuals survived this gauntlet; today's wolves descend from 12 of those. They became the ark, the source material for the few hundred red wolves that live today. There are about 280 in the "Species Survival Plan" population, living in captivity, and another 30 or so that roam a federal refuge in coastal North Carolina, and that the government deems "nonessential" and "experimental." According to the US Fish and Wildlife Service, to be classified as a representative of the protected entity known as *Canis rufus*, an animal must trace at least 87.5% of its lineage to the 12 founders.

The scientist who led this trapping-and-breeding program understood that the federal government would be narrowing the red wolf's gene pool precipitously—so much so that the result could be an entirely new species. None of those notably black wolves persisted in the new population, for example. But what other choice existed? A new kind of wolf, free of the taint of the invading coyote, seemed better than no wolf at all.

After I learned about Colossal's clones, I decided to travel to eastern Texas. The clones were hidden away on an unnamed refuge, but on this coastline, I might be able to at least see the animals that provided their genetic material. I arrived in the small town of Winnie on a balmy afternoon in January and met up with Broussard and another graduate student, Patrick Cunningham, at a Tex-Mex joint to discuss the challenges of studying red wolves.

The last red wolves, which lived in Louisiana and Texas, decided a strange and smaller mate was preferable to no mate at all.

"We don't have a good reference genome," Cunningham said. We can collect DNA from the descendants of the 12 founders, but not from the countless wolves that had been killed. It's difficult to extract usable DNA from old samples. So our picture of what the species used to look like is limited.

Studies of the genes we do have, meanwhile, have proved controversial. When a Princeton geneticist named Bridgett vonHoldt

The American red wolf, <u>Canis rufus</u>, is the most endangered wolf species in the world. This pup is one of four animals said to be clones of this native North American species.

COURTESY OF COLOSSAL BIOSCIENCES

dug into the genome of the Species Survival Plan population, she found little about their DNA that could set them apart from other wolflike American canids. In 2016, in a paper in *Science Advances*, vonHoldt and her coauthors wondered if there ever really *was* a separate southern wolf species. Perhaps the 12 founders were just coyotes injected with some smaller portion of wolf.

Her paper called for complex new interpretations of the Endangered Species Act. We should, she wrote, focus less on *species* and more on the function a group of animals performs. The red wolves deserved protection, then, as creatures that filled the same role as truly endangered wolves and carried some of their genetics. Nonetheless, for *Canis rufus*, the timing of the paper was bad news.

The red wolves roaming that federal reserve in North Carolina are supposed to be a first step toward the species' return to the wild. But some locals never liked the idea of living alongside wolves. By 2016, state officials had turned against the recovery program and were requesting its termination. The wild population, which had included as many as 120 a few years earlier, was falling. But the US Fish and Wildlife Service had paused further releases of wolves. Now a group of scientists, led by vonHoldt, was saying that the red wolf showed "a lack of unique ancestry." Why spend money, some people wondered, on a species that does not exist?

Part of the problem was that the concept of a "species" is less sturdy than your high school biology teacher might have led you to believe. The most familiar definition is that a species consists of animals that can produce fertile offspring. But that's a rule various species of canids violate all the time; it's long been clear that North America's soup of *Canis* genes is something less like a family tree and more like a river—one that's broken by islands and sandbars into many braided channels that split and merge and re-split.

VonHoldt suggested that the modern red wolf is a channel in that river, part wolf and part coyote, that appeared surprisingly recently. But a year after her study came out, other researchers claimed that her data, if interpreted differently, could suggest that the red wolf braid had emerged tens of thousands of years ago, meaning this was a species that had long been on its own evolutionary journey.

These nuances were confusing for the policymakers who oversaw actual, living animals. "Congress was just like, 'What is going on?'" Cunningham said. "'Why is there not just a simple explanation for what this thing is?'"

Given the policy implications, the National Academies of Science, Engineering, and Medicine tasked a panel of scientists with finding that simple answer. Their report, published in 2019, declared that the red wolf *is*, by virtue of its appearance and seemingly long-standing isolated population, a species. As their study got underway, though, a new question was arising: What to make of the strange canids on the Gulf Coast, those today called the ghost wolves?

The path to that name began in 2008, when a photographer from Galveston Island, Texas, grew obsessed with the oversized local coyotes. He began to take photos of the packs, which he distributed to scientists, seeking answers: What were they? By 2016, the photos had reached Joey Hinton, then a postdoctoral researcher at the University of Georgia.

Hinton had spent more than a decade trapping wolves and coyotes in North Carolina, and his work has always focused on live animals, especially visual ways to distinguish red wolves and coyotes. So he was a good choice for helping the photographer, Ron Wooten, figure out the status of the canids. In his freezer Wooten also had tissue samples he'd collected from road-killed coyotes. These could be used by a geneticist to give a fuller picture of the canids' ancestry. So vonHoldt was brought in too. The result was a 2018 paper, with Hinton as a coauthor, that identified the Galveston Island canids as at least part red wolf.

These canids were not, to be clear, *actual* red wolves; no canid on the Gulf Coast is descended from the government's 12 canonical founders, so under current policy, none can be officially classified as a wolf. Subsequent studies have found that, on average, the ancestry of the region's canids is less than half red wolf, and often far less. In scientific terms, the red wolf had *introgressed* into the Gulf Coast population—its genes had leaked across the species boundary and lodged themselves in a different population.

Hinton, vonHoldt, and their coauthors also noted the presence of what they called "ghost alleles"—DNA sequences unknown in any other named species. The Occam's razor assumption was that, in these already wolfy coyotes, these sequences likely represented *Canis rufus* genetics that had not been captured in the sweep of the marsh that yielded the Species Survival Plan population. Since so much of the red wolf gene pool had been lost, these genes seemed to be a potential resource for the species—a way to expand its diversity. When the *New York Times* covered this discovery a few years later, the headline popularized the "ghost wolf" moniker that has proved so indelible.

As it happened, a separate team, focused on canids in and around federally protected marsh in Louisiana, published a similar paper in 2018, at nearly the same time. The twin discoveries raised new questions—What should we make of these creatures, the latest branch in the canid river? What do they mean for the wolves in North Carolina?—and helped researchers secure new funding.

In 2020, vonHoldt and Kristin Brzeski, a former postdoc under vonHoldt and now a professor at Michigan Technological University, launched what they called the Gulf Coast Canine Project. Brzeski, who led the field work, hired Hinton to do much of the canid trapping and sample collection. In 2022, vonHoldt, Hinton, and Brzeski were all coauthors of another paper that identified even more red-wolf-descended canids in Louisiana and noted a positive correlation between red wolf ancestry and body mass—the more red wolf genes, the bigger the animal. The paper also suggested that given this newly discovered reservoir of red wolf DNA, "genomic technologies" could prove useful in the long-term survival of the species.

It's long been clear that North America's soup of *Canis* genes is something less like a family tree and more like a river—one that's broken by islands and sandbars into many braided channels that split and merge and re-split.

VonHoldt and Brzeski eventually conceived of an ambitious project. They hoped that by carefully matching the most wolf-descended canids and breeding them together, over three generations they'd increase the proportion of red wolf genes—*de*-introgression. "I'm expecting, based on these pairings of animals, that I can stitch together the puzzle pieces," vonHoldt told me recently. "We are very likely to get puppies each generation that are higher and higher red wolf content"—enough wolf content, she hopes, to eventually win her permission to breed the resulting animals with the Species Survival Plan population of red wolves. They'd essentially be adding a new founder to the limited lineage.

Hinton told me he felt he'd been kept in the dark about the de-introgression idea. He was also worried, he says, to learn that Colossal Biosciences hovered in the background. (In a draft proposal for the project, vonHoldt indicated that Colossal would be in charge of "live capture.") Hinton says he was not comfortable collecting materials for a for-profit company that has to keep its shareholders happy.

Hinton says he reached out to state and federal officials and found they knew little about the project. (The US Fish and Wildlife Service declined to make anyone available for an interview for this story, and the Louisiana Department of Wildlife and Fisheries did not reply to requests for comment.) He knew the group's next phone call would be difficult, and indeed it was. He wound up speaking one-on-one with vonHoldt for at least half an hour.

Ron Wooten surveys a location on the edge of Galveston Island State Park in Texas. In 2016, Wooten's photographs of oversized local coyotes got the attention of Joey Hinton, then a postdoctoral researcher at the University of Georgia.

"We didn't reach an agreement," he says. After the call, he sent her a text: He was exiting the project. He believes that had Colossal not been involved, they'd all still be working as a team. Both vonHoldt and Brzeski declined to comment on what felt to them like a matter of interpersonal relationships rather than a scientific dispute. "There were challenges over time, and the tone and manner of the interactions became increasingly difficult to navigate productively," Brzeski said in an email.

Colossal was cofounded in 2021 by George Church, an eminent Harvard geneticist who, thanks to investors, could finally embark on a long-discussed dream. He wanted to make de-extinction a reality—using CRISPR gene-editing technology to, say, turn a modern elephant into something like the extinct woolly mammoth. The concept has drawn skepticism from the beginning—at best it would only be possible to make *something like* a woolly mammoth. Was there any point to that? Some scientists note that genes alone do not teach an animal how to exist in the world; indeed, since social structures affect how genes are expressed, an animal without parents may not effectively fill its ecological niche.

Less reproachable, though, was Colossal's interest in partnering with scientists who, like vonHoldt and Brzeski, focus on extant species that are endangered. This gave more heft to Colossal's gee-whiz de-extinction projects: They would, along the way, supply technology that could save our natural world.

For red wolves, such technologies could offer a quick way to expand the limited gene pool. Through genetic engineering, Colossal could take clones of the Gulf Coast canids and tune up the wolf, tune down the coyote. It would be a high-tech shortcut past vonHoldt and Brzeski's careful breeding program. "You can do the same thing much more precisely, much more quickly, much more efficiently, in vitro," says Matt James, Colossal's chief animal officer and the executive director of the Colossal Foundation, the company's nonprofit arm. VonHoldt notes that the old-fashioned approach, with breeding, means she has to take

Above:
Ecologist Joey Hinton trapped the canids that Colossal Biosciences used to source the DNA for its clones. He dismisses the clones as a way for the company to earn headlines and attract funding.

Opposite top:
Bridgett vonHoldt (left) and Kristin Brzeski (center) visit a location where canids have been spotted with an animal control worker.

Opposite bottom:
Blood and tissue samples collected by the Galveston Island Humane Society from canid roadkill will be shipped to Princeton University for DNA analysis.

a few individual canids out of the wild, into captivity—never ideal but, in her view, a worthwhile price for progress. The advantage of cloning, which Colossal has managed to do with blood samples alone, is that the wild canid populations can be kept intact.

VonHoldt has always been an advocate for wolves. Indeed, when she hypothesized that the red wolf had hybrid origins, in 2016, she'd framed it as an argument for protecting the gray wolf, which the federal government was considering removing from the Endangered Species List. (In short: If all wolves were one wolf, then it was undeniable that the species' range had contracted precipitously.) But she'd grown frustrated with the federal government's efforts to restore the red wolf, which after half a century had seen few meaningful successes, she says.

VonHoldt joined Colossal's scientific advisory board in 2023. "I love the bold, the shock and awe," she told me, explaining her decision. She saw the fact that Colossal sparked controversy as an asset, given the problems she sees in conservation: "Get something out there. Start pushing buttons and start forcing these conversations," she says. The red wolf was akin to a terminal patient who was ready to accept any and all therapies, however experimental. Why *not* embrace biotech?

She also notes that the federal budget for endangered species conservation is incredibly limited. Rely only on that money and "we can kiss our world goodbye," she said in an e-mail. The $100 million raised by the Colossal Foundation is essential, then, she says. As for the samples the team had collected on the Gulf Coast, she says, limited freezer space is often devoted to animals that are officially categorized as threatened or endangered, which the Gulf Coast canids are not. Colossal could take the samples, and the team passed them along to the company.

It was Hinton—a source for a former story—who first alerted me to Colossal's work on red wolves; he described vonHoldt and Brzeski's de-introgression project, which won federal funding in late 2024, as nefarious-sounding work to "disappear" canids off the Gulf Coast. But he did not have all the details of the project, which had changed after he left the team. He suggested they'd be "just throwing animals together," whereas vonHoldt described a careful program of observing the canids in the wild so she could determine which acted most wolflike, findings she'd cross-reference with their genetic data.

Colossal did not wind up participating in the de-introgression project. But the company *is* doing work on the red wolf that vonHoldt views as complementary: Its scientists are assembling a "pangenome" of North American canids by studying samples pulled from museums, universities, zoos, and other institutions. This data set is expected to clarify both what genetic sequences are shared across the entire canid family and what snippets differ in certain populations. The hope is that this will provide a clearer picture of the red wolf in its early days, before the coyotes arrived and the gene pool narrowed. That might shift what Colossal's James calls the government's arbitrary definition of the red wolf, to encompass more of the species' full former diversity.

RICH SAAL

The pangenome, then, might allow vonHoldt's de-introgressed canids, descended from the Gulf coast canids, to qualify as actual red wolves. Indeed, James suggested to me that more information about historic red wolves might force the government to take a new look at the Gulf Coast canids; some individuals might have high enough red wolf ancestry to be classified *as* red wolves. ("That has management implications that terrify state and federal government," he added.)

The purpose of vonHoldt's de-introgression project is to bring back certain lost red wolf genes—to create a whole new wolf lineage. But she has also pushed against the idea of "genetic purity," which she thinks limits what we protect with conservation laws; she told me emphasizing it reminds her of the human history of eugenics and "makes every part of my soul hurt." She cares less about what species are out there, in the landscape, than what ecological function the animals play, and she sees coyotes and red wolves as closely related animals that may have a role to play in one another's future survival.

Galveston locals hope that the presence of these remarkable creatures—red wolves or not—might rein in the rapid development of the island's last stands of green.

As for Colossal's clones, even vonHoldt seems to describe them as something less than a conservation breakthrough. They are a "proof of principle that we, collectively, as a scientific community, know how to do it," she told me. If an urgent need arises to clone red wolves, the groundwork has been laid.

Hinton, meanwhile, is one of several scientists I spoke with who were skeptical Colossal was doing good science, given that so much is conducted behind closed doors. He implied that the clones were nothing but an empty showpiece, a way to earn headlines and attract funders. "The work is anything but symbolic," James responded via e-mail. "It expands the genetic toolkit available for critically endangered species, demonstrates scalable approaches to biodiversity restoration, and contributes directly to preserving imperiled lineages." He noted that Colossal had intentionally decided to avoid the "snail's pace" of the peer review process and suggested that the skepticism from scientists may actually be a "panicked response to being outpaced."

Until some evidence confirms that the Gulf Coast canids—the source material for the clones—are red wolves, they can't legally be classified as such for federal conservation purposes. Nonetheless, Colossal's press release claimed that the company had "birthed two litters of cloned red wolves, the most critically endangered wolf in the world." On the same day that press release dropped, Colossal's CEO and cofounder, Ben Lamm, appeared on *The Joe Rogan Experience* and claimed that he had offered to create hundreds of red wolves for the federal government to use in recovery—for free! He was miffed when the government, under the Biden administration, replied that it wanted to spend several years and many millions of dollars to study the *potential* for cloning before it would take any action. (The company has gotten more traction with the Trump administration, Lamm said.)

When I first spoke to James at Colossal, he said that he was "cognizant" of the concerns over the names and labels and that the company's own materials described the clones as "red 'ghost' wolves." He suggested that if anyone assumed the clones were *actual* red wolves, that was because journalists had failed to grasp the nuances of the science. But this phrase appears so late in a long document that it was cut off in some versions. Later, over email, James indicated that further analysis had convinced him that what the company had created *were* red wolves, and that anyone who disagreed either could not grasp the science or is "so ideologically opposed to Colossal's conservation revolution that they are willing to compromise their scientific integrity."

VonHoldt has had her own issues with the company's communications; she told me it was "stressful" when Lamm described the clones as red wolves—which, she notes, "federally, they're not." But she values the company's work, she says, and "the thing that I value the most is shaking things up." People are paying attention to red wolves. If it's hard to decide what to call the animals on the Gulf Coast—where some heavily wolfy animals live alongside others that are more coyote—that's just proof that our concept of a "species" does not capture the complex realities on the ground.

In 2025, the same year as Colossal's wolf announcement, Hinton launched the Texas-Louisiana Canid Project. He's working in partnership with Broussard, the master's student at McNeese, in slightly different territory from vonHoldt and Brzeski—and focusing more on the animals' appearance and behavior than their genes. The Gulf Coast canids are stable and faring better than the North Carolina red wolves, and his hope is that if we learn why they've been successful for so many years, we might be able to help the official red wolf population, which is only just limping along.

I had planned to join Hinton in the field, but by the time I was able to visit, he'd had to go home to his family. So I joined Broussard on his last days trapping in Texas that season. Before I'd left for Winnie, I'd told my friends I'd be out chasing the last surviving red wolves. But there, on the Gulf Coast, I came to understand that this was just as much a story about *coyotes*.

If we throw out the concept of "endangered species," will we really protect "endangered functions" instead?

That's what Broussard and Cunningham both called the creatures. Hinton does too; he considers the animals to be a specific "ecotype" of coyote, featuring an injection of wolf DNA that has helped them adapt to the local marshes.

At vonHoldt's behest, I drove an hour down the coast to Galveston Island, where she and Brzeski began working with the island's animal control department; when locals find a coyote, the animal is captured so its blood can be collected and a GPS collar fitted on its neck. A small group of locals who support the project have come to call themselves the "ghost wolf team." They hoped that the presence of these remarkable creatures might rein in the rapid development of the island's last stands of green. Still, the people I spoke to in Galveston conceded that the animals were, if special, nonetheless a form of coyote.

VonHoldt describes Galveston Island as a potential model for what conservation could look like in the future. Top-down recovery hasn't been working, but helping more places fall in love with their local animals might. And for that to happen, we need to stop obsessing over whether or not something is a "pure" wolf. What matters, she argues, is that an animal is doing what a larger predator does in an ecosystem. She embraces the "ghost wolf" name because, more than "Gulf Coast canid," it makes clear that there's something special on the coast—something worth protecting.

Her vision is enticing: Focus on function over purity. Let evolution proceed. Stop protecting the wolf of the past and consider the wolf of the future. Such rapid genetic exchange may be necessary to help predators adapt to a hotter, increasingly shattered world, she says.

Then again, we already know what's adapted to the world we're building: coyotes. The argument against genetic purity can sound like giving up on wolves entirely, with the possible exception of whatever specimens we produce in cloning facilities. And there is the matter of politics: If we throw out the concept of "endangered species," will we really protect "endangered functions" instead? Under an administration already rolling back environmental protections, the likeliest outcome may be protecting nothing at all.

I tried in Galveston, too, to see the coyotes. Ron Wooten, the local resident who helped alert scientists to this population, dropped some pins on a map, pointing me toward several likely spots. That evening, after the sun set, I chose a quiet road that passed through marshes until it reached the island's eastern beach. It was mating season, Wooten had noted. The animals should be on the move, he said; look to the bushes. As I drove up and down the road, my headlights revealed only empty darkness. No coyote. No wolf. Fitting, perhaps—isn't absence the essence of a ghost? But whether this was a good omen was less clear. As individuals, these animals do best by avoiding us humans. As a group, their survival—like the survival of the red wolves—depends on our knowing that they are here, and were here, and deciding that is reason enough to care.

In Winnie the next morning, I went out one last time with Broussard, and we struck out again. With no coyotes in his traps and the new semester looming, he decided to take down his game cameras. Back at the hotel, I caught at least an image of what I'd been chasing: In black and white, the animals were appropriately silver, spectral, dashing across the midnight fields. In one clip, a canid paused and howled. "That's super cool," Broussard said quietly, as an echoing, interweaving chorus responded from somewhere deeper in the marsh. ■

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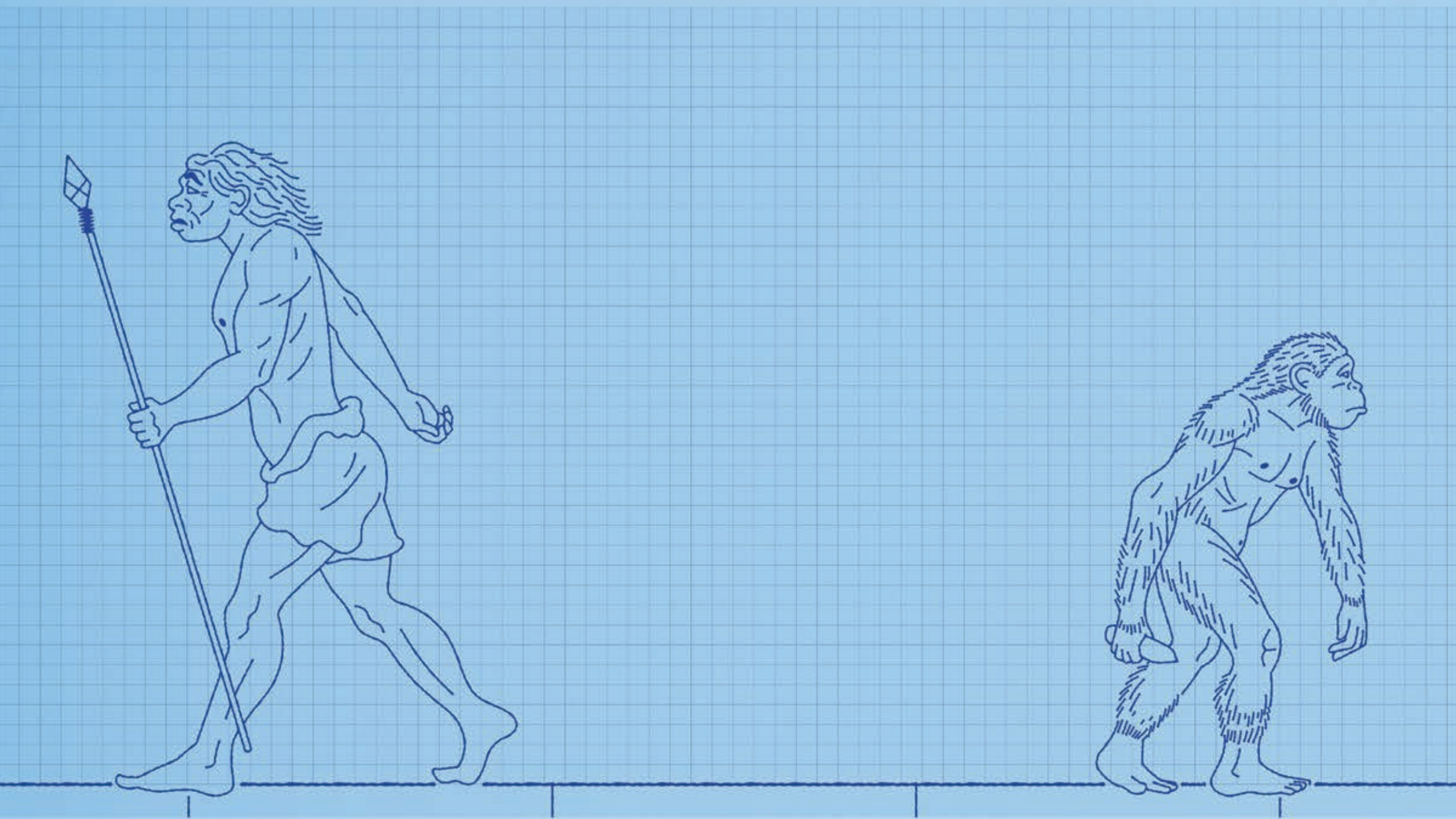


THE PROBLEM WITH THINKING YOU'RE PART

Neanderthal

The idea that modern humans inherited DNA from Neanderthal ancestors is one of the 21st century's most celebrated discoveries in evolution. It may not be that simple.

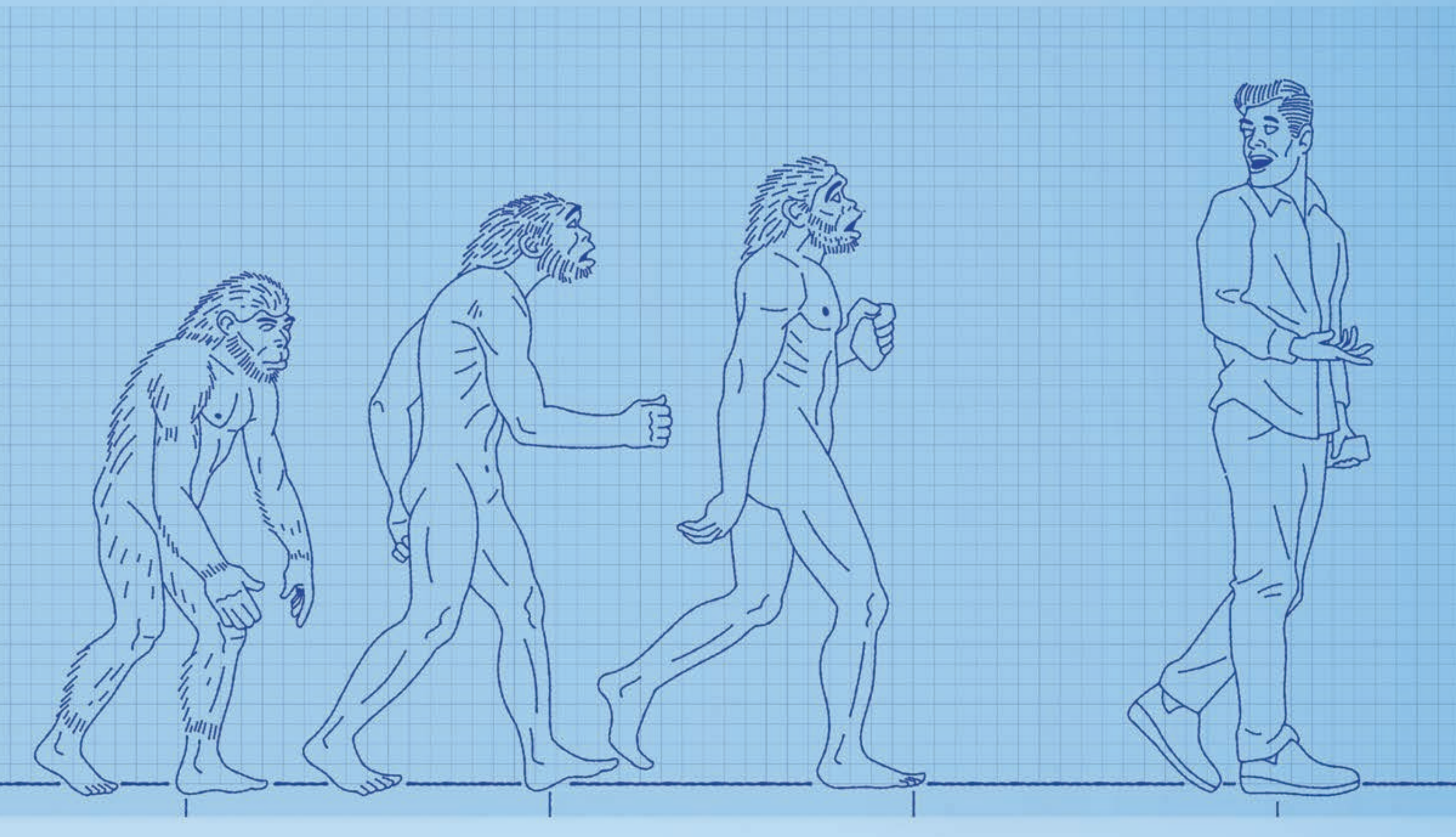
By
BEN CRAIR

Illustration
McKibillo

You've probably heard some version of this idea before: that many of us have an "inner Neanderthal." That is to say, around 45,000 years ago, when *Homo sapiens* first arrived in Europe, they met members of a cousin species—the broad-browed, heavier-set Neanderthals—and, well, one thing led to another, which is why some people now carry a small amount of Neanderthal DNA.

This DNA is arguably the 21st century's most celebrated discovery in human evolution. It has been connected to all kinds of traits and health conditions, and it helped win the Swedish geneticist Svante Pääbo a Nobel Prize.

But in 2024, a pair of French population geneticists called into question the foundation of the popular and pervasive theory.



Lounès Chikhi and Rémi Tournebize, then colleagues at the Université de Toulouse, proposed an alternative explanation for the very same genomic patterns. The problem, they said, was that the original evidence for the inner Neanderthal was based on a statistical assumption: that humans, Neanderthals, and their ancestors all mated randomly in huge, continent-size populations. That meant a person in South Africa was just as likely to reproduce with a person in West Africa or East Africa as with someone from their own community.

Archaeological, genetic, and fossil evidence all shows, though, that *Homo sapiens* evolved in Africa in smaller groups, cut off from one another by deserts, mountains, and cultural divides. People sometimes crossed those barriers, but more often they partnered up within them.

In the terminology of the field, this dynamic is called population structure. Because of structure, genes do not spread evenly through a population but can concentrate in some places and be totally absent from others. The human gene pool is not so much an Olympic-size swimming pool as a complex network of tidal pools whose connectivity ebbs and flows over time.

This dynamic greatly complicates the math at the heart of evolutionary biology, which long relied on assumptions like randomly mating populations to extract general principles from limited data. If you take structure into account, Chikhi told me recently, then there are other ways to explain the DNA that some living people share with Neanderthals—ways that don't require any interspecies sex at all.

"I believe most species are spatially organized and structured in different, complex ways," says Chikhi, who has researched population structure for more than two decades and has also studied lemurs, orangutans, and island birds. "It's a general failure of our field that we do not compare our results in a clear way with alternative scenarios." (Pääbo did not respond to multiple requests for comment.)

Chikhi and Tournebize's argument is about population structure, yes, but at heart, it is actually one about methods—how modern evolutionary science deploys computer models and statistical techniques to make sense of mountains upon mountains of genetic data.

They're not the only scientists who are worried. "People think we really understand how genomes evolve and can write sophisticated algorithms for saying what happened," says William Amos, a University of Cambridge population geneticist who has been critical of the "inner Neanderthal" theory. But, he adds, those models are "based on simple assumptions that are often wrong."

And if they're wrong, what's at stake is far more than a single evolutionary mystery.

A captivating story of interspecies passion

Back in 2010, Pääbo's lab pulled off something of a miracle. The researchers were able to extract DNA from nuclei in the cells of 40,000-year-old Neanderthal bones. DNA breaks down quickly after death, but the group got enough of it from three different individuals to produce a draft sequence of the entire Neanderthal genome, with 4 billion base pairs.

The inner Neanderthal became a story we could tell ourselves about our flaws and genetic destiny: *Don't blame me; blame the prognathic caveman hiding in my cells.*

As part of their study, they performed a statistical test comparing their Neanderthal genome with the genomes of five present-day people from different parts of the world. That's how they discovered that modern humans of non-African ancestry had a small amount of DNA in common with Neanderthals, a species that diverged from the *Homo sapiens* line more than 400,000 years ago, that they did *not* share with either modern humans of African ancestry or our closest living relative, the chimpanzee.

Pääbo's team interpreted this as evidence of sexual reproduction between ancient *Homo sapiens* and the Neanderthals they encountered after they expanded out of Africa. "Neanderthals are not totally extinct," Pääbo said to the BBC in 2010. "In some of us, they live on a little bit."

The discovery was monumental on its own—but even more so because it reversed a previous consensus. More than a decade earlier, in 1997, Pääbo had sequenced a much smaller amount of Neanderthal DNA, in that case from a cell structure called a mitochondrion. It was different enough from *Homo sapiens* mitochondrial DNA for his team to cautiously conclude there had been "little or no interbreeding" between the two species.

After 2010, though, the idea of hybridization, also called admixture, effectively became canon. Top journals like *Science* and *Nature* published study after study on the inner Neanderthal. Some scientists have argued that *Homo sapiens* would never have adapted to colder habitats in Europe and Asia without an infusion of Neanderthal DNA. Other research teams used Pääbo's techniques to find genetic traces of interbreeding with an extinct group of hominins in Asia, called the Denisovans, and a mysterious "ghost lineage" in Africa. Biologists used similar tests to find evidence of interbreeding between chimpanzees and bonobos, polar and brown bears, and all kinds of other animals.

The inner-Neanderthal hypothesis also took a turn for the personal. Various studies linked Neanderthal DNA to a head-spinning range of conditions: alcoholism, asthma, autism, ADHD, depression, diabetes, heart disease, skin cancer, and severe covid-19. Some researchers suggested that Neanderthal DNA had an impact on hair and skin color, while others assigned individuals a "NeanderScore" that was correlated with skull shape and prevalence of schizophrenia markers. Commercial genetic testing companies like 23andMe started offering customers Neanderthal ancestry reports.

The inner Neanderthal became a story we could tell ourselves about our flaws and genetic destiny: *Don't blame me; blame the prognathic caveman hiding in my cells*. Or as Latif Nasser, a host of the popular-science program *Radiolab*, put it when he was hospitalized with Crohn's disease, another Neanderthal-associated condition: "I just keep imagining these tiny Neanderthals … just, like, stabbing me and drawing these little droplets of blood out of me."

"These things become meaningful to people," Chikhi says. "What we say will be important to how people view themselves."

The pitfalls of simplistic solutions

When population geneticists built the theoretical framework for evolutionary biology in the early 20th century, genes were only abstract units of heredity inferred from experiments with peas and fruit flies. Population genetics developed theory far more quickly than it accumulated data. As a result, many data-driven scientists dismissed the study of evolution as a form

RESTORATION OF A NEANDERTHAL MAN. M0001106. SOURCE: WELLCOME COLLECTION

This model of a Neanderthal man was exhibited in the "Pre-history Gallery" at London's Wellcome Historical Medical Museum in the 1930s.

of storytelling based on unexamined assumptions and preconceived ideas.

By the '90s, though, genes were no longer abstractions but sequenced segments of DNA. Genomic sequencing grounded evolutionary studies in the kind of hard data that a chemist or physicist could respect.

Yet biologists could not simply read evolutionary history from genomes as though they were books. They were trying to determine which of a nearly infinite number of plausible histories was the most likely to have created the patterns they observed in a small sample of genomes. For that, they needed simplified, algorithmic models of evolution. The study of evolution shifted from storytelling to statistics, and from biology to computer science.

That suited Chikhi, who as a child was drawn to the predictable laws and numerical precision of math and science. He entered the field in the mid-'90s just as the first big studies of human DNA were settling old debates about human origins. DNA showed that Africa harbored far more genetic diversity than the entire rest of the planet. The new evidence supported the idea that modern humans evolved for hundreds of thousands of years in Africa and expanded to the other continents only in the last 100,000 years. For Chikhi, whose parents were Algerian immigrants, this discovery was a powerful challenge to the way some archaeologists and biologists talked about race. DNA could be used to deconstruct rather than encourage the pernicious idea that human races had deep-seated evolutionary differences based on their places of origin.

At the same time, though, he was wary of the tendency to treat DNA as the final verdict on open questions in evolution. Chikhi had been surprised when, back in 1997, Pääbo and his team used that small amount of mitochondrial DNA to rule out hybridization between *Homo sapiens* and Neanderthals. He didn't think that the absence of Neanderthal DNA there necessarily meant it wouldn't be found elsewhere in the *Homo sapiens* genome.

Chikhi's own research in the aughts opened his eyes to the gaps between historical reality and models of evolution. For one, despite the assumption of random mating, none of the animals Chikhi studied actually mated randomly. Orangutans lived in highly fragmented habitats, which restricted their pool of potential mates, and female birds were often extremely picky about their male partners.

These factors could confound an evolutionary biologist's traditional statistical tool kit. Scientists were starting to apply a mathematical technique to estimate historical population sizes for a species from the genome of just a single individual. This method showed sharp population declines in the histories of many different species. Chikhi realized, though, that the apparent declines could be an artifact of treating a structured population as one that evolved with random mating; in that case, the technique could indicate a bottleneck even if all the subgroups were actually growing in size. "This is completely counterintuitive," he says.

That's at least partly why, when Pääbo's 2010 Neanderthal genome came out, Chikhi was impressed with the sheer technical accomplishment but also leery of the findings about hybridization. "It was the type of thing we conclude too quickly based on genetic data," he says. Pääbo's work mentioned population structure as a possible alternative explanation—but didn't follow up.

Just a couple of years later, a pair of independent scientists named Anders Eriksson and Andrea Manica picked up the idea, building a model with simple population structure that explicitly excluded admixture. They simulated human evolution starting from 500,000 years ago and found that their model produced the same genomic patterns Pääbo's group had interpreted as evidence of hybridization.

"Working with structured models is really out of the comfort zone of a lot of population geneticists," says Eriksson, now a professor at the University of Tartu in Estonia.

Their research impressed Chikhi. "At the time, I thought people would focus on population structure in the evolution of humans," he says. Instead, he watched as the inner-Neanderthal hypothesis took on a life of its own. Scientists produced new methods to quantify hybridization but rarely examined whether population structure would yield the same results. To Chikhi, this wasn't science; it was storytelling, like some of the old narratives about the evolution of racial differences.

Chikhi and Tournebize decided to take a crack at the problem themselves. "I've always been very skeptical about science, and population genetics in particular," says Tournebize, now a researcher at the French National Research Institute for Sustainable Development. "We make a lot of assumptions, and the models we use are very simplistic." As detailed in a 2024 paper published in *Nature Ecology & Evolution*, they built a model of human evolution that replaced randomly mating continent-wide populations with many smaller populations linked by occasional migration. Then they let it run—a million times.

At the end of the simulation, they kept the 20 scenarios that produced genomes most similar to the ones in a sample of actual *Homo sapiens* and Neanderthals. Many of these scenarios produced long segments of DNA like the ones their peers argued could only have been inherited from Neanderthals. They showed that several statistics, which other scientists had proposed as measurements of Neanderthal DNA, couldn't actually distinguish between hybridization and population structure. What's more, they showed that many of the models that supported hybridization failed to accurately predict other known features of human evolution.

"A model will say there was admixture but then predict diversity that is totally incompatible with what we actually know of human diversity," Chikhi says. "Nobody seems to care."

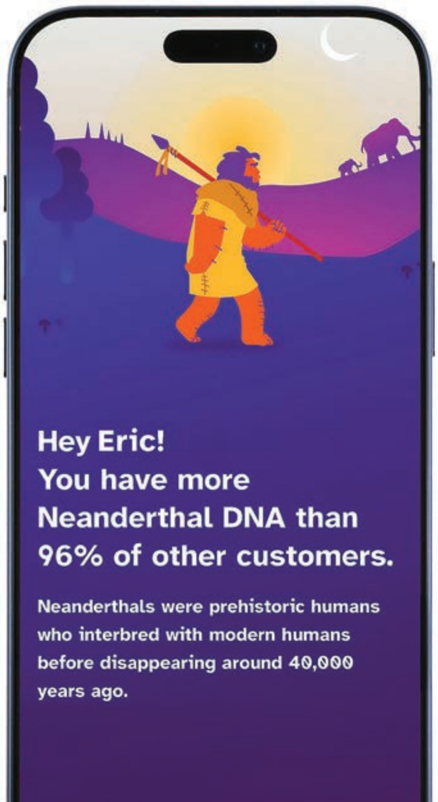
So how did Neanderthal DNA wind up in living people if not via interspecies passion? Chikhi and Tournebize think it's more likely that it was inherited by both Neanderthals and some *sapiens* groups in Africa from a common ancestor living at least half a million years ago. If the *sapiens* groups carrying those genetic variants included the people who migrated out of Africa, then the two human species would have already had the DNA in common when they came into contact in Europe and Asia—no sex required.

"The interpretation of genetic data is not straightforward," Chikhi says. "We always have to make assumptions. Nobody takes data and magically comes up with a solution."

Embracing the uncertainty

Most of the half-dozen population geneticists I spoke with praised Chikhi and Tournebize's ingenuity and appreciated the spirit of their critique. "Their paper forces us to think more critically about the model we use for inference and consider alternatives," says Aaron Ragsdale, a population geneticist at the University of Wisconsin–Madison. His own work likewise suggests that the earliest *Homo sapiens* populations in Africa were probably structured—and that this is the likely reason for genomic patterns that other research groups had attributed to hybridization with a mysterious "ghost lineage" of hominins in Africa.

Yet most researchers still believe that modern humans and Neanderthals *did* probably have children with each other tens of thousands of years ago. Several pointed to the fact that fossil DNA of *Homo sapiens* who died thousands of years ago had longer chunks of



Commercial genetic testing companies like 23andMe started offering customers Neanderthal ancestry reports.

apparent Neanderthal DNA than living people, which is exactly what you would expect if they had a more recent Neanderthal ancestor. (To address this possibility, Chikhi and Tournebize included DNA from 10 ancient humans in their study and found that most of them fit the structured model.) And while the Harvard population geneticist David Reich, who helped design the statistical test from Pääbo's 2010 study, declined an interview, he did say he thought Chikhi and Tournebize's model was "weak" and "very contrived," adding that "there are multiple lines of evidence for Neanderthal admixture into modern humans that make the evidence for this overwhelming." (Two other authors of that study, Richard Green and Nick Patterson, did not respond to requests for comment.)

Loosening our attachment to certain narratives of evolution can create space for wonder at the sheer complexity of life's history.

Nevertheless, most scientists these days welcome the development of structured, or "spatially explicit," models that account for the fact that any given member of a population is usually more closely related to individuals living nearby than to those living far away.

Other scientists also say that random mating isn't the only assumption in population genetics that merits scrutiny. Models rarely factor in natural selection, which can also create genetic patterns that look like hybridization. Another common assumption is that everyone's DNA mutates at the same, constant rate. "All the theory says the mutation rate is fixed," says Amos, the Cambridge population geneticist. But he thinks that rate would have slowed drastically in the group of *Homo sapiens* that expanded to Europe around 45,000 years ago. This, too, could have created genomic patterns that other scientists interpret as evidence of interbreeding with Neanderthals.

The point here isn't that a complex model of evolution with many moving pieces is necessarily better than a simple one. Scientists need to reduce complexity in order to see the underlying processes more clearly. But simple models require assumptions, and scientists need to reevaluate those assumptions in light of what they learn. "As you get more data, you can justify more complex models of the world," says Mark Thomas, a population geneticist at University College London, who wrote a history of random mating in population genetics that highlighted how the field was starting to see it as "a limiting assumption as opposed to a simplifying one."

It can feel discouraging to couch conversations about the past in confusing terms like "population structure" and "mutation rates." It seems almost antithetical to the spirit of science to talk more about uncertainty at the same time we are developing powerful technologies and enormous data sets for analyzing evolution. These tools often yield novel answers, but they can also limit the questions we ask. The French archaeologist Ludovic Slimak, for example, has complained that the idea of the inner Neanderthal has domesticated our image of Neanderthals and made it difficult to imagine their humanity as distinct from our own. Investigating Neanderthal DNA is sexier to many young researchers than searching for archaeological and fossil evidence of how Neanderthals actually lived.

Loosening our attachment to certain narratives of evolution can create space for wonder at the sheer complexity of life's history. Ultimately, that's what Chikhi and Tournebize hope to do. After all, they don't believe the question of population structure versus hybridization is either-or. It's possible, and even likely, that both played a role in human evolution. "Our structured model does not necessarily mean that no admixture ever took place," Chikhi and Tournebize wrote in their study. "What our results suggest is that, if admixture ever occurred, it is currently hard to identify using existing methods."

Future methods might disentangle the different factors, but it's just as important, Chikhi says, for scientists to be up-front about their assumptions and test alternatives. "There's still so much uncertainty on so many aspects of the demographic history of Neanderthals and *Homo sapiens*," he notes.

Keep that in mind the next time you read about your inner Neanderthal. The association between this DNA and some diseases may be real, of course—but would journals publish these studies without the additional claim that the DNA is from Neanderthals? Any good storyteller knows that sex sells, even in science. ■

Ben Crair is a science and travel writer based in Berlin.

COURTESY OF 23ANDME

T U

Around the country, heated debates are taking place over whether to install

W A

R F

plastic fields, pitting neighbors against each other. By Douglas Main

R S

A rare warm spell in January melted enough snow to uncover Cornell University's newest athletic field, built for field hockey. Months before, it was a meadow teeming with birds and bugs; now it's more than an acre of synthetic turf roughly the color of the felt on a pool table, almost digital in its saturation. The day I walked up the hill from a nearby creek to take a look, the metal fence around the field was locked, but someone had left a hallway-size piece of the new simulated grass outside the perimeter. It was bristly and tough, but springy and squeaky under my booted feet. I could imagine running around on it, but it would definitely take some getting used to.

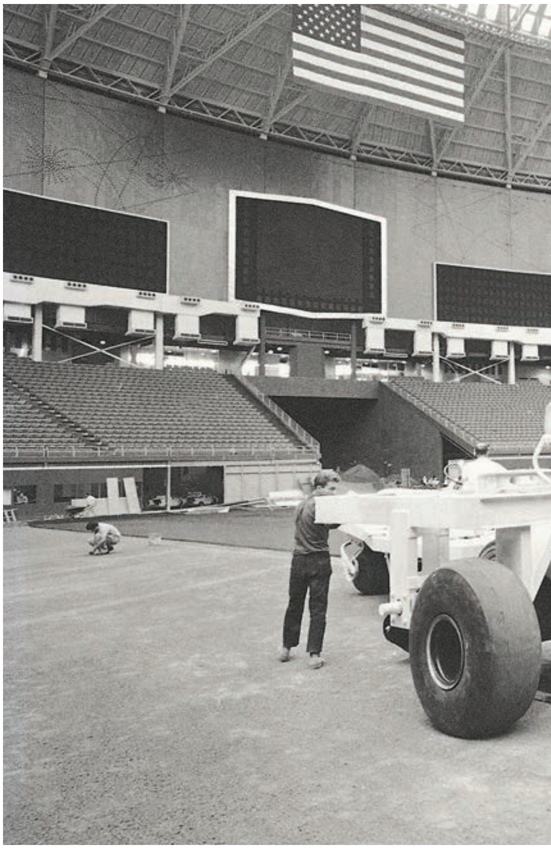
My companion on this walk seemed even less favorably disposed to the thought. Yayoi Koizumi, a local environmental advocate, has been fighting synthetic-turf projects at Cornell since 2023. A petite woman dressed that day in a faded plum coat over a teal vest, with a scarf the colors of salmon, slate, and sunflowers, Koizumi compulsively picked up plastic trash as we walked: a red Solo cup, a polyethylene Dunkin' container, a five-foot vinyl panel. She couldn't bear to leave this stuff behind to fragment into microplastic bits—as she believes the new field will. "They've covered the living ground in plastic," she said. "It's really maddening."

The new pitch is one part of a $70 million plan to build more recreational space at the university. As of this spring, Cornell plans to install something like a quarter million square feet of synthetic grass—what people have colloquially called "astroturf" since the middle of the last century. University PR says it will be an important part of a "health-promoting campus" that is "supportive of holistic individual, social, and ecological well-being." Koizumi runs an anti-plastic environmental group called Zero Waste Ithaca, which says that's mostly nonsense.

This fight is more than just the usual town-versus-gown tension. Synthetic turf used to be the stuff of professional sports arenas and maybe a suburban yard or two; today communities across the United States are debating whether to lay it down on playgrounds, parks, and dog runs. Proponents say it's cheaper and hardier than grass, requiring less water, fertilizer, and maintenance—and that it offers a uniform surface for more hours and more days of the year than grass fields, a competitive advantage for athletes and schools hoping for a more robust athletic program.

But while new generations of synthetic turf look and feel better than that mid-century stuff, it's still just plastic. Some evidence suggests it sheds bits that endanger users and the environment, and that it contains PFAS "forever chemicals"—per- and polyfluoroalkyl substances, which are linked to a host of health issues. The padding within the plastic grass is usually made from shredded tires, which might also pose health risks. And plastic fields need to be replaced about once a decade, creating lots of waste.

Yet people are buying a lot of the stuff. In 2001, Americans installed just over 7 million square meters of synthetic turf, just shy of 11,000 metric tons. By 2024, that number was 79 million square meters—enough to carpet all of Manhattan and then some, almost 120,000 metric tons. Synthetic turf covers 20,000 athletic fields and tens of thousands of parks, playgrounds,



WHERE REAL ESTATE IS LIMITED AND DEMAND FOR ATHLETIC FACILITIES IS HIGH, ARTIFICIAL TURF IS TEMPTING. "IT ALL COMES DOWN TO LAND AND DEMAND," SAYS ONE TURF SCIENTIST.

Below: Workers lay artificial turf at the Astrodome in Houston on July 13, 1966. Developed by Monsanto, the material was originally known as ChemGrass but was later renamed AstroTurf after the stadium.

PREVIOUS SPREAD: ALAMY; AP PHOTO/ED KOLENOVSKY, FILE

and backyards. And the US is just 20% of the global market.

Those increases worry folks who study microplastics and environmental pollution. Any actual risk is hard to parse; the plastic-making industry insists that synthetic fields are safe if properly installed, but lots of researchers think that isn't so. "They're very expensive, they contain toxic chemicals, and they put kids at unnecessary risk," says Philip Landrigan, a Boston College epidemiologist who has studied environmental toxins like lead and microplastics.

But at Cornell, where real estate is limited and demand for athletic facilities is high, synthetic turf was a tempting option. As Frank Rossi, a professor of turf science at Cornell, told me: "It all comes down to land and demand."

In 1965, Houston's new, domed baseball stadium was an icon of space-age design. But the Astrodome had a problem: the sun. Deep in the heart of Texas, it shined brightly through the Astrodome's skylights—so much so that players kept missing fly balls. So the club painted over the skylights. Denied sunlight, the grass in the outfield withered and died.

A replacement was already in the works. In the late 1950s a Ford Foundation–funded educational laboratory determined that a soft, grasslike surface material would give city kids more places to play outside and had prevailed upon the Monsanto corporation to invent one. The result was clipped blades of nylon stuck to a rubber base, which the company called ChemGrass. Down it went into Houston's outfield, where it got a new, buzzier name: AstroTurf.

That first generation of simulated lawn was brittle and hard, but quality has improved. Today, there are a few competing products, but they're all made by extruding a petroleum-based polymer—that's plastic—through tiny holes and then stitching or fusing the resulting fibers to a carpetlike bottom. That gets attached to some kind of padding, also plastic. In the 1970s the industry started layering that over infill, usually sand; by the 1990s, "third generation" synthetic turf had switched to softer fibers made of polyethylene. Beneath that, they added infill that combined sand and a soft, cheap shredded rubber made from discarded automobile tires, which pile up by the hundreds of millions every year. This "crumb rubber" provides padding and fills spaces between the blades and the backing.

In the early 1980s, nearly half the professional baseball and football fields in the US had synthetic turf. But many players didn't like it. It got hotter than real grass, gave the ball different action, and seemed to be increasing the rate of injuries among athletes. Since the 1990s, most pro sports have shifted back toward grass—water and maintenance costs pale in comparison to the importance of keeping players happy or sparing them the risk of injury.

But at the same time, more universities and high schools are buying the artificial stuff. The advantages are clear, especially in places where it rains either too much or not enough. A natural-grass field is usable for a little more than 800 hours a year at the most, spread across just eight months in the cooler, wetter northern US. An artificial-turf field can see 3,000 hours of activity per year. For sports like lacrosse, which begins in late winter, this makes artificial turf more appealing. Most lacrosse pitches are now synthetic. So are almost all field hockey pitches; players like the way the even, springy turf makes the ball bounce.

Furthermore, supporters say synthetic turf needs less maintenance than grass, saving money and resources. That's not always true; workers still have to decompact the playing surface and hose it off to remove bird poop or cool it down. Sometimes the infill needs topping up. But real grass allows less playing time, and because grass athletic fields often need to be rotated to avoid damage, synthetic ground cover can require less space. Hence the market's explosive growth in the 21st century.

The city and town of Ithaca—two separate political entities with overlapping jurisdiction over Cornell construction projects—held multiple public meetings about the university's new synthetic fields: the field hockey pitch and a complex called the Meinig Fieldhouse. Koizumi's group turned up in force, and a few folks who worked at Cornell came to oppose the idea too—submitting pages of citations and studies on the risks of synthetic grass.

At two of those meetings, dozens of Cornell athletes turned out to support the turf. Representatives of the university and the athletic department declined to speak with me for this story, citing an ongoing lawsuit from Zero Waste Ithaca. But before that, Nicki Moore, Cornell's director of athletics, told a local newspaper that demand from campus groups and sports teams meant the fields were constantly overcrowded. "Activities get bumped later and later, and sometimes varsity teams won't start practicing until 10 at night, you know?" Moore told the paper. "Availability of all-weather space should normalize scheduling a great deal."

That argument wasn't universally convincing. "It's a bad idea, but that's from the environmental perspective," says Marianne Krasny, director of Cornell's Civic Ecology Lab and one of the speakers at those hearings. "Obviously the athletic department thinks it's a great idea."

Members of Cornell on Fire, a climate action group with members from both the university and the town, joined in opposing the use of artificial turf, citing the fossil-fuel origins of the stuff. They described the nominal support of the project from student athletes as inauthentic, representing not grassroots support but, yes, an astroturf campaign.

Sorting out the actual science here isn't simple. Over time, the plastic that synthetic turf is made of sheds bits of itself into the environment. In one study, published in 2023 in the journal *Environmental Pollution*, researchers found that 15% of the medium-size and microplastic particles in a river and the Mediterranean Sea outside Barcelona, Spain, came from artificial turf, mostly in the form of tiny green fibers. Back in 2020, the European Chemicals Agency estimated that infill material from artificial-turf fields in the European Union was contributing 16,000 metric tons of microplastics to the environment each year—38% of all annual microplastic pollution. Most of that came from the crumb rubber infill, which Europe now plans to ban by 2031.

This pollution worries the Cornell activists. Ithaca is famous for scenic gorges and waterways. The new field hockey pitch is uphill from a local creek that empties into Cayuga Lake, the longest of the Finger Lakes and the source of drinking water for over 40,000 people.

And it's not just the plastic bits. When newer generations of synthetic turf switched to durable high-density polyethylene, the new material gunked up the extruders used in the manufacturing process. So turf makers started adding fluorinated polymers—a type of PFAS. Some of these environmentally persistent "forever chemicals" cause cancer, disrupt the endocrine system, or lead to other health problems. Research in several different labs has found PFAS in many types of plastic grass.

But the key to assessing the threat here is exposure. Heather Whitehead, an analytical chemist then at the University of Notre Dame, found PFAS in synthetic turf at levels around five parts per billion—but estimated it'd be in water running off the fields at three parts per *trillion*; for context, the US Environmental Protection Agency's legal drinking-water limit on one of the most widespread and dangerous PFAS chemicals is four parts per trillion. "These chemicals will wash off in small amounts for long periods of time," says Graham Peaslee, Whitehead's advisor and an emeritus nuclear physicist who studies PFAS concentrations. "I think it's reason enough not to have artificial turf."

This gets confusing, though. There are over 16,000 different types of PFAS, few have been well studied, and different companies use different manufacturing techniques. Companies represented by the Synthetic Turf Council now "use zero intentionally added PFAS," says Melanie Taylor, the group's president. "This means that as the field rolls off the assembly line, there are zero PFAS-formulated materials present."

Some researchers are skeptical of the industry's assurances. They're hard to confirm, especially because there are a lot of ways to test for PFAS. The type of synthetic

Growing like a weed

Demand for artificial turf has only risen in recent decades—especially in the United States, which accounts for 20% of the global market.

2001	2024
AREA INSTALLED: **7 million square meters**	AREA INSTALLED: **79 million square meters**
WEIGHT: **11,000 metric tons**	WEIGHT: **120,000 metric tons**

turf going onto the new field hockey pitch at Cornell is called GreenFields TX; the university had a sample tested using an EPA method that looks for 40 different PFAS compounds. It came back negative for all of them. The local activists countered that the test doesn't detect the specific types they're most concerned about, and in 2025 they paid for three more tests on newly purchased synthetic turf. Two clearly found fluorine—the F in "PFAS"—and one identified two distinct PFAS compounds. (The company that makes GreenFields TX, TenCate, declined to comment, citing ongoing litigation.)

GETTY IMAGES

PFAS isn't the only potential problem. There's also the crumb rubber made from tires. A billion tires get thrown out every year worldwide, and if they aren't recycled they sit in giant piles that make great habitats for rats and mosquitoes; they also occasionally catch fire. Lots of the tires that go into turf are made of styrene-butadiene rubber, or SBR. In bulk, that's bad. Butadiene is a carcinogen that causes leukemia, and fumes from styrene can cause nervous system damage. SBR also contains high levels of lead.

But how much of that comes out of synthetic-turf infill? Again, that's hotly debated. Researchers around the world have published suggestive studies finding potentially dangerous levels of heavy metals like zinc and lead in synthetic turf, with possible health risks to people using the fields. But a review of many of the relevant studies on turf and crumb rubber from Canada's National Collaborating Centre for Environmental Health determined that most well-conducted health risk assessments over the last decade found exposures below levels of concern for cancer and certain other diseases. A 2017 report by the European Chemicals Agency—the same people who found all those microplastics in the environment—"found no reason to advise people against playing sports on synthetic turf containing recycled rubber granules as infill material." And a multiyear study from the EPA, published in 2024, found much the same thing—although the researchers said that levels of certain synthetic chemicals were elevated inside places that used indoor artificial turf. They also stressed that the paper was not a risk assessment.

The problem is, the kinds of cancers these chemicals can cause may take decades to show up. Long-term studies haven't been done yet. All the evidence available so far is anecdotal—like a series for the *Philadelphia Inquirer* that linked the deaths of six former Phillies players from a rare type of brain cancer called glioblastoma to years spent playing on PFAS-containing artificial turf. That'd be about three times the usual rate of glioblastoma among adult men, but the report comes with a lot of cautions—small sample size, lots of other potential causes, no way to establish causation.

Synthetic turf has one negative that no one really disputes: It gets very hot in the sun—as hot as 150 °F (66 °C). This can actually burn players, so they often want to avoid using a field on very hot days.

Athletes playing on artificial turf also have a higher rate of foot and ankle injuries, and elite-level football players seem to be more predisposed to knee injuries on those surfaces. But other studies have found rates of knee and hip injury to be roughly comparable on artificial and natural turf—a point the landscape architect working on the Cornell project made in the information packet the university sent to the city. Athletic departments and city parks departments say that the material's upsides make it worthwhile, given that there's no conclusive proof of harm.

Back in Ithaca, Cornell hired an environmental consulting firm called Haley &

Aldrich to assess the evidence. The company concluded that none of the university's proposed installations of artificial turf would have a negative environmental impact. People from Cornell on Fire and Zero Waste Ithaca told me they didn't trust the firm's findings; representatives from Haley & Aldrich declined to comment.

Longtime activists say that as global consumption of fossil fuels declines, petrochemical companies are desperate to find other markets. That means plastics. "There's a big push to shift more petrochemicals into plastic products for an end market," says Jeff Gearhart, a consumer product researcher at the Ecology Center. "Industry people, with a vested interest in petrochemicals, are looking to expand and build out alternative markets for this stuff."

All that and more went before the decision-makers in Ithaca. In September 2024, the City of Ithaca Planning Board unanimously issued a judgment that the Meinig Fieldhouse would not have a significant environmental impact and thus would not need to complete a full environmental impact assessment. Six months later, the town made the same determination for the field hockey pitch.

Zero Waste Ithaca sued in New York's supreme court, which ruled against the group. Koizumi and lawyers from Pace University's Environmental Litigation Clinic have appealed. She says she's still hopeful the court might agree that Ithaca authorities made a mistake by not requiring an environmental impact statement from the college. "We have the science on our side," she says.

Ithaca is a pretty rarefied place, an Ivy League university town. But these same tensions—potential long-term environmental and public health consequences versus the financial and maintenance concerns of the now—are pitting worried citizens against their representatives and city agencies around the country.

New York City has 286 municipal synthetic-turf fields, with more under construction. In Inwood, the northernmost neighborhood in Manhattan, two fields were approved via Zoom meetings during the pandemic, and Massimo Strino, a local artist who makes kaleidoscopes, says he found out only when he saw signs announcing the work on one of his daily walks in Inwood Hill Park, along the Hudson River. He joined a campaign against the plan, gathering more than 4,300 signatures. "I was canvassing every weekend," Strino says. "You can count on one hand, literally, the number of people who said they were in favor."

But that doesn't include the group that pushed for one of those fields in the first place: Uptown Soccer, which offers free and low-cost lessons and games to 1,000 kids a year, mostly from underserved immigrant families. "It was turning an unused community space into a usable space," says David Sykes, the group's executive director. "That trumped the sort of abstract concerns about the environmental impacts. I'm not an expert in artificial turf, but the parks department assured me that there was no risk of health effects."

New York City councilmember Christopher Marte disagrees. He has introduced a bill to ban new artificial turf from being installed in parks, and he hopes the proposal will be taken up by the Parks Committee this spring. Last session, the bill had 10 cosponsors—that's a lot. Marte says he expects resistance from lobbyists, but there's precedent. The city of Boston banned artificial turf in 2022.

Upstate, in a Rochester suburb called Brighton, the school district included synthetic-turf baseball and softball diamonds in a wide-ranging February 2024 capital improvement proposition. The measure passed. In a public meeting in November 2025, the school board acknowledged the intent to use synthetic grass—or, as concerned parents had it, "to rip up a quarter million square feet of this open

ARTIFICIAL TURF DOESN'T GO AWAY. "YOU'RE GOING TO BE PAYING TO GET RID OF IT," SAYS ONE RESEARCHER. "SOMEBODY WILL HAVE TO TAKE IT TO A DUMP, WHERE IT WILL SIT FOR A THOUSAND YEARS."

Below: A field hockey player from Cornell University passes the ball during a game played on artificial turf at Bryant University in 2025. Cornell's own turf field will be ready for the 2026 season.

space and replace it with artificial turf," says David Masur, executive director of the environmental group PennEnvironment, whose kids attend school in Brighton. Parents and community members mobilized against the plan, further angered when contractors also cut down a beloved 200-year-old tree. School superintendent Kevin McGowan

ANDREW KATSAMPES/ISI PHOTOS/GETTY IMAGES

says it's too late to change course. Masur has been working to oppose the plan nevertheless—he says school boards are making consequential decisions about turf without sharing information or getting input, even though these fields can cost millions of dollars of taxpayer money.

In short, the fights can get tense. On Martha's Vineyard, in Massachusetts, a meeting about plans to install an artificial field at a local high school had to be ended early amid verbal abuse. A staffer for the local board of health who voiced concern about PFAS in the turf quit the board after discovering bullet casings in her tote bag, she said, which she perceived as a death threat. After an eight-year fight, the board eventually banned artificial turf altogether.

What happens next? Well, outdoor artificial turf lasts only eight to 12 years before it needs to be taken up and replaced. The Synthetic Turf Council says it's at least partially recyclable and cites a company called BestPLUS Plastic Lumber as a purveyor of products made from recycled turf. The company says one of its products, a liner called GreenBoard that artificial turf can be nailed into, is at least 40% recycled from fake grass. Joseph Sadlier, vice president and general manager of plastics recycling at BestPLUS, says the company recycles over 10 million pounds annually.

Yet the material is piling up. In 2021, a Danish company called Re-Match announced plans to open a recycling plant in Pennsylvania and began amassing thousands of tons of used plastic turf in three locations. The company filed for bankruptcy in 2025.

In Ithaca, university representatives told planning boards that it would be possible to recycle the old artificial turf they ripped out to make way for the Meinig Fieldhouse. That didn't happen. An anonymous local activist tracked the old rolls to a hauling company a half-hour's drive south of campus and shared pictures of them sitting on the lot, where they stayed for months. It's unclear what their ultimate fate will be.

That's the real problem: Artificial turf just doesn't go away. "You're going to be paying to get rid of it," says Peaslee, the PFAS expert. "Somebody will have to take it to a dump, where it will sit for a thousand years." At minimum, real grass is a net carbon sink, even including installation and maintenance. Synthetic turf releases greenhouse gases. One life-cycle analysis of a 2.2-acre synthetic field in Toronto determined that it would emit 55 metric tons of carbon dioxide over a decade. Plastic fields need less water to maintain, but it takes water to make plastic, and natural grass lets rainwater seep into the ground. Synthetic turf sends most of it away as runoff.

It's a boggling set of issues to factor into a decision. Rossi, the Cornell turf scientist, says he can understand why a school in the northern United States might go plastic, even when it cares about its students' health. "It was the best bad option," he says. Concerns about microplastics and PFAS are "significant issues we have not fully addressed." And they need to be. ■

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

The noise of human cities is getting so bad it's hurting animals.

Can we learn to shut up?

Un-silent spring

By
Clive Thompson

Illustrations
Eddie Guy

When the covid-19 pandemic started, Jennifer Phillips thought about the songs of the sparrows.

They were easier to hear, because the world had suddenly become quieter. Car traffic plummeted as people sheltered at home and shifted to remote work. Air travel collapsed. Cities—normally filled with the honking, screeching, engine-gunning riot of transportation—became as silent as tombs.

For years, Phillips has studied how animals react to "anthropogenic noise," or the racket created by human activity. Most animals really don't like it, she and her colleagues have learned. Animals constantly listen to the world around them: They're on the alert for the rustle of approaching predators, or a mating call from a member of their species. As human society has expanded—with sprawling cities, industrial mines, and roads crisscrossing the world—it has gotten noisier too, and animals have trouble hearing one another.

Phillips and her colleagues had spent time in the 2010s in San Francisco recording the sound of white-crowned sparrows in the Presidio. It's a park that is half peaceful nature and half automobile noise, since it's filled with thick clumps of trees and grassy fields but also has two highways that slice through it, feeding onto the Golden Gate Bridge. In past recordings, starting in the 1950s, sparrows had sung with complex and lower-pitched melodies and three major "dialects." But by the 2010s, traffic in the Presidio had exploded, and the hubbub was so loud that the birds began to sing with faster trills—and at a higher pitch—so their fellows could hear them. The two quietest dialects were either dead or on their way to extinction.

They're "screaming at the top of their lungs," says Phillips. "They really can't hear the lower frequencies when the traffic noise is present." Urban noise can even change birds' bodies; they get thinner and more stressed out. Their mating calls aren't as effective, because female birds, as researchers have found, generally don't

enjoy high-pitched, high-volume shouting. (It makes them wonder if the males are unhealthy.) The noise can increase bird-on-bird conflict, because when birds can't hear warning cries they accidentally stumble into enemy territory. Perhaps worst of all, in situations like these biodiversity takes a hit: Entire species that can't handle urban clamor simply head out of town and never come back.

But as the sudden, eerie silence of the pandemic descended, Phillips sat at home thinking, *It's really quiet*. And then she wondered: Would the Presidio birds now be able to hear each other better?

She raced over to the park and started recording. Sure enough, the park was seven decibels quieter—a huge drop. (That's like the difference between the noise of the average home and whispering.)

And remarkably, the researchers found that the songs of the white-crowned sparrows had transformed. They were singing more quietly, with a richer range of frequencies. A bird could be heard twice as far as before. And the mating calls had gotten more sultry.

"They could sing a higher performance, basically a sexier song, but not have to scream it so loud," Phillips says.

It was as if time had been reversed and all the damage abruptly repaired. And it proved what Phillips and her peers have been increasingly documenting: that anthropogenic noise is the newest form of pollution we need to tackle. The noise of our relentlessly on-the-move industrial society affects all life on Earth, wildlife and humans, in ways we're just beginning to grasp. Yet strategies such as electrification and clever urban design could help. As the Presidio showed, noise can vanish overnight—once we figure out how to shut up.

Hidden impacts

Many forms of pollution are obvious to us humans. Dumping toxic goo into lakes? Sure, that's bad. Coal smokestacks pumping soot and carbon dioxide, plastic bags and sea nets choking whales—we now understand that these, too, are problems. Even an idea as gauzy as light pollution has penetrated the public consciousness to some extent, since it's why city dwellers can't see many stars, and we've heard it confuses migratory birds.

But noise, mostly from transportation, took longer to hit our radar. This is partly because it's invisible; there's no billowing smokestack, no soiled waterway. We just got used to it as it vibrated in the background.

There were a few studies in the '70s and '80s showing that animals were upset by our noise. But the field really began to take off in the '00s, in part because digital technology made it easier to record long swathes of sound out in nature and analyze them. One early salvo came from the biologist Hans Slabbekoorn, who was studying doves in the city of Leiden and irritatedly noticed that he could rarely get a clean recording because of the background noise. Sometimes he'd see the doves' throats moving as they cooed but couldn't hear them. "If I'm having difficulty hearing them," he thought, "what about *them*?"

So he and a colleague started recording ambient sound levels in different parts of Leiden. Some were quiet residential areas, which registered a soothing 42 decibels, and others were noisy intersections or areas near highways, which reached 63 decibels, about as loud as background music. Sure enough, he found that birds in the noisy areas were singing at a higher pitch.

Over the next two decades, research in the field bloomed. Noise, the scientists found, has a few common ill effects on animals. It disrupts communication, certainly. But it also generally stresses them, reducing everything from their body weight to their receptivity to mating calls. If an animal nests closer to a road, its reproduction rates can go down; eastern bluebirds, for example, produce fewer fledglings. Truly cacophonous noise—like planes taking off at a nearby airport—can cause hearing loss in birds. And animals can wind up becoming less aware of threats from predators. They'll wander closer to danger, because they can't hear it coming. (And sometimes they'll do the opposite: They'll develop a rageaholic hair-trigger temper, because they're constantly on high alert and regard *everything* as a threat.)

Even in deep rural areas, where things are normally pretty quiet, highways can disrupt wildlife—the noise carries far into the fields nearby. Fraser Shilling, a biologist at the University of California, Davis, has stood up to half a mile from rural highways and recorded sound as loud as 60 decibels, which is at least 20 decibels higher than you'd typically find in the wilderness. "The motorcycles and the 18-wheelers are really the ones that project a lot of noise," he told me.

Above 55 decibels, many skittish animals get into a fight-or-flight panic. The prevalence of bobcats—an endangered species famously rattled by noise—"starts dropping off the cliff," says Shilling. Above 65, "you're really starting to exclude almost all wildlife."

And that's not even the upper limit of what wildlife is exposed to. There are

Noise is invisible; there's no billowing smokestack, no soiled waterway. We just got used to it as it vibrated in the background.

Sparrows in San Francisco's Presidio began to sing with faster trills—and at a higher pitch—so their fellows could hear them over the noise of nearby traffic.

The black-chinned hummingbird seems to prefer noisy areas, fledging more chicks than the same species does in quieter areas.

GETTY IMAGES (SPARROW); MDF/WIKIMEDIA COMMONS (HUMMINGBIRD)

roughly a half-million natural-gas wells around the US, and piercingly loud compressors are used to shoot water down into most of them. Up close, the compressors can kick out 95 decibels, a sound as loud as a subway train; at one Wyoming gas well the sound still registered around 48 decibels nearly a quarter-mile away.

Historically, it wasn't always easy to prove that noise was causing whatever problems the animals were experiencing. Maybe it was other factors; maybe animal populations reduce near a road because some are hit by vehicles?

But several clever experiments have proved that noise—and noise alone—can disrupt wildlife. One was the "phantom road" experiment by the conservation scientist Jesse Barber and his team, then at Boise State University. They went out to a quiet, uninhabited area of the Boise foothills in Idaho, far away from any roads. In this valley in the mountains, thousands of migratory birds stop on their way south each year; they'll gorge themselves on cherry bushes, gaining weight for the next days of flying. The researchers strapped 15 pairs of speakers to Douglas fir trees, in a half-kilometer line. Then they blasted recordings of highway noise. They played the noise for four days and then turned it off for four days. Then they observed thousands of birds, capturing many to measure their body mass.

The noise truly rattled the birds. When the sound was turned on, nearly a third left the area. Those that stuck around ate less: While birds should be heavier after a day of foraging, these ones didn't gain much. The noise seemed to have so interrupted their feeding that they weren't packing on the weight needed for their migratory trip.

Other, similarly nifty A/B tests followed. One was led by David Luther, a biologist at George Mason University (who also worked with Phillips on the covid-19 study in San Francisco). In 2015, these researchers took 17 white-crowned sparrows at birth and raised them in a lab. To teach them their species' songs, they played the nestlings recordings of adult sparrows singing, at low and high pitches. Six of the nestlings heard the songs without any interference; with the other half, the researchers played the sounds of city noise at the same time.

The results were stark. The lucky birds that were spared the traffic noise learned to perform the quieter, sweeter, more complex songs. But the birds that had traffic noise blasted learned only the higher, faster, more stressed-out songs. From the cradle, noise changed the way they communicated.

Humans hate noise too

You can't pull the same experiment with humans, raising them in a lab to see how noise affects them. (Not ethically, anyway.) But if we could, we'd likely find the same thing. We, too, are animals—and it appears that we suffer in similar ways from anthropogenic noise, even though we're the ones creating it.

Stacks of research in the last few decades have found that noise—most often, as with wildlife, the sound of traffic—is correlated with lousy sleep, higher blood pressure, more heart disease, and higher stress. A Danish study followed almost 25,000 nurses for years and found that an additional 10 decibels hit them hard; over a 23-year period they had an 8% higher rate of death, plus higher rates of nearly every bad thing that could happen to you: cancers, psychiatric problems, strokes. (They controlled for other malign health influences.) As you'd probably predict by now, children fare badly too. When Barcelona researchers followed almost 3,000 elementary school kids for a year, they found that those in noisier schools performed worse on assessments of working memory and ability to pay attention.

"We think of ourselves as being 'used to it,'" says Gail Patricelli, a professor of evolution and ecology at the University of California, Davis. "We're not as used to it as we think we are."

It's also true that there's a trade-off. Many people understand that noise from cities and highways is aggravating, but we tolerate it because we get benefits along with the hassles. Cities are crammed with jobs and connections and dating opportunities; cars and trucks bring us the things we need and increase our personal mobility.

It turns out that animals make a similar calculus. Some species appear to benefit in certain ways from proximity to noise, so they move *toward* it.

Clinton Francis, a biologist at California Polytechnic State University, and a team studied bird populations near noisy gas wells in rural New Mexico. Most species avoided the riot of the well pumps. But Francis was surprised to find that some hummingbirds and finches preferred it, and by one important measure they thrived: They were nesting more in the noisy areas than in the quieter areas. Additionally, several species had more success at fledging chicks in noisier locations.

What was going on? It's likely that the noise makes it harder for predators to hear the birds and hunt down their nests. "It's essentially a predator shield," Francis says. Since his research found that predators can cause as much as 76% of failures of eggs to produce healthy offspring, that's a significant survival advantage.

Cities can offer the same protections to certain species. Consider the case of Flaco, a Eurasian eagle-owl that escaped from the Central Park Zoo in February of 2023 and found he was in a terrific place to hunt. The incessant traffic ought to have caused him trouble. "An owl like this is among the most vulnerable species to intrusions from noise pollution. They're listening for extremely faint signals or cues that their prey provide," Francis notes. But New York has its compensations, because prey animals abound. They're also naïve and unguarded, never expecting an owl with a six-foot wingspan to swoop down and devour them.

Granted, these upsides don't cancel out the negatives. Human noise may shield some birds from predators, but in other ways it leaves them faintly miserable, with high levels of stress hormones and lower weight.

Worse, the species that manage to thrive in cities or near highways are often the same ones all over the country. And they represent only a minority of species; most are driven further away, with less and less land to live on as civilization spreads ever outward.

"Overall, it's kind of a nightmare for diversity," says Luther.

How to silence the world

In the early '00s, the village of Alverna in the Netherlands began to get louder. A major intercity road cut straight through the town, and traffic had gone up by two-thirds in the previous decade. Facing complaints about the din, the town offered to put up some 13-foot walls on either side of the route. Residents hated the idea. Who wants to look out the window at massive walls?

So instead town planners redesigned the road in subtle ways. They lowered it by half a meter, slightly blocking the tire sounds. They built wedges that rise up three feet on either side, and surfaced them with attractive antique stone; that blocked even more sound. They planted sound-absorbing trees. And as a final coup de grâce, they reduced the speed limit from about 50 to 30 miles per hour. When a car is moving slowly, the engine is producing most of the roar—but once it's going 45 mph or faster, the rumble of tires on the pavement takes over and is much louder. Each intervention had only a small effect, but cumulatively they made the road a blessed 10 decibels quieter.

This tale illustrates one curious *upside* of noise. Compared with other forms of pollution, it can be ended quickly. Toxic pollutants or CO_2 can hang around for tens of thousands of years; the microplastics in your pancreas are probably never coming out. But with noise, the instant you reduce the source, the benefits are immediate.

Plus, most of what works is "not rocket science," Shilling says. A tall wall at the side of a highway will cut noise by 10 decibels; fill a double-sided wall with rubble and it's even better. That could cut the traffic noise to below 55 decibels, he notes, which would help particularly skittish forms of wildlife. Walls can block animal movement, though, so in animal-heavy areas it's better to build berms—small hills on either side of a highway. Areas of high ecological importance could be prioritized to keep costs down.

"If there's a great chunk of wetland habitat and it's the only one around for 50 miles in any direction? Well, then we should build noise walls around it," he says. We should also build overpasses and underpasses to help animals get around. And to quiet the din of gas wells out in the countryside, states could require companies to build walls around them. (They'll likely only do that, though, when human neighbors complain or launch lawsuits; animals don't have lawyers.)

Cities, too, can learn to shut up, as Alverna proved. At the most ambitious, some have buried noisy highways that once cut through the downtown core. Boston put a massive elevated highway underground in its "Big Dig"; in Slabbekoorn's hometown of Amstelveen—a suburb of Amsterdam—they're currently enclosing the A9 highway in a tunnel and turning the surface into a verdant park with new buildings. "That's amazing, getting back a lot of the space as well," he says.

Granted, this sort of reengineering can be brutally expensive, which is why politicians blanch when they're asked to reduce road noise. The Big Dig cost $15 billion, and with interest up to $24 billion. When I mentioned cost to Shilling, he sighed. "It's not as expensive as a B-1 bomber or tax cuts for rich people," he says. "Environmental stuff is considered expensive just because our expectations are low, not because we can't afford to do it."

There are cheaper and more politically palatable fixes, though. Reducing urban speed limits is one; Paris recently cut the top speed on its ring roads from 70 to 50 kilometers per hour (43 to 31 mph), and noise at night went down by an average 2.7 decibels—a noticeable drop. Planting more trees and vegetation all around roads and cities can cut a few decibels more, and residents love it.

Growing adoption of electricity would also bring down the volume. "Electric vehicles of all kinds have the potential to make a big difference," Patricelli says; when the light turns green and an EV next to you accelerates away, it's up to 13 decibels quieter than a comparable gas-powered vehicle. These benefits won't be felt as much on highways, because EVs still make tire noise at high speeds. But in the slower stop-and-go traffic of urban life, they are far more pleasant to the ears, both animal and human. Indeed, the electrification of *everything* that currently uses a gas-powered motor will make urban life quieter. Cities like Alameda, California, and Alexandria, Virginia, are increasingly banning gas-powered leaf blowers and lawn mowers, which operate at hair-raising volume while electric ones whisper along.

We've engineered a civilization that roars, but the next phase is making it purr. The animals will thank us. ■

The sound of traffic is correlated with lousy sleep, higher blood pressure, more heart disease, and higher stress.

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

In the summer of 2025, the Norwegian research icebreaker *Kronprins Haakon* (seen here in the central Arctic Ocean) set forth on a mission to determine if the North Pole was ice-free during Earth's warmer past.

Blue Arctic

To understand what the future holds for Earth's northernmost waters, scientists are digging deep below the seabed.

STORY AND PHOTOS BY **TIM KALVELAGE**

In the past, even with an icebreaker and during peak melt season, getting to the North Pole wasn't a sure bet. It took favorable winds to crack the frozen ocean surface, and ships had to fight through ice that had grown many meters thick over several winters. In the summer of 2025, though, Jochen Knies from the Arctic University of Norway, Tromsø, and his team met little resistance on their way to 90 degrees North with the research vessel *Kronprins Haakon*. The geologist "didn't hear the usual grinding of ice" against the hull that he remembered from 1996, when he first reached the pole by ship. Instead, thin floes and large stretches of open water made for an easy, quiet passage. To him, it was "a reminder of how quickly the Arctic is changing."

Since the late 1970s, when satellite observations of the polar seas began, summer ice cover of the Arctic Ocean has declined by more than 40%. In less than half a century, a frozen area the size of the Mediterranean Sea has turned into blue open water with the rapid warming of the high northern latitudes. If this trend continues, there could soon be summers at the North Pole with no sea ice whatsoever. The last time this happened may have been some 120,000 years ago. But no one knows for certain.

That's why Knies and his colleagues, a team of researchers from Norway and Germany, set out from Svalbard to the central Arctic last August. The aim of their five-week mission was to determine whether this region had been ice-free in recent Earth history—and if so, when. As part of a €12.5 million project financed by the European Union, they also came to answer some questions about the future of the Arctic and beyond: How does the loss of sea ice affect the marine ecosystem? What are the consequences for ocean circulation and global climate?

In search of clues, the expedition collected sediment cores up to 22 meters in length at different locations across the Arctic seafloor. Marine sediments are valuable climate archives that give scientists a window into bygone eras. Like diligent record keepers, they can log past water temperatures, sea-ice coverage, and the strength of ocean currents. These data are encrypted in the chemical and physical properties of the plankton remains and weathered rock deposited on the seabed.

While sediment cores several meters long had been recovered on earlier expeditions in the central Arctic, there is no scientific consensus on how old the deposits actually are or whether sea ice ever completely disappeared in summer.

To decode the Arctic's climate archive, Knies brought a team of experts from various disciplines onboard the *Kronprins Haakon* to dig deeper and obtain fresh samples they could subject to the latest analytical techniques.

Some of this work was done while the researchers were still at sea. Now, at their home laboratories, they are finalizing their analysis of the seafloor samples. One important task is dating the sediments, which may be up to 2 million years old. The team uses a combination of methods to do this, including measuring magnetization, the decay of radioactive elements, and the exposure of mineral grains to sunlight before sinking to the depths. Once they can place them on a timeline, the materials in the cores will help researchers paint a picture of what the Arctic Ocean looked like in times that were warmer than today. For example, the presence or absence of the molecule IP_{25}, which is produced exclusively by ice algae, could tell them how far the sea ice receded at a given time.

At the end of the study, the team hopes to have data that could improve climate projections for a future ice-free "blue Arctic," helping us understand how it could affect marine life and carbon storage, Atlantic Ocean circulation, or extreme weather events in Europe and North America. ■

Tim Kalvelage is a freelance science reporter based in Bremen, Germany, who focuses on climate, ocean, and polar research. He has been to the North Pole twice.

The ship's crew and researchers recover the sediment corer, a 25-meter-long steel pipe that is driven into the seafloor using a top weight of more than three metric tons.


NICS
SEABICS

It's all hands on deck once the coring device is secured.

LEFT: Together, the scientists pull out long plastic pipes filled with precious deep-sea mud.

BELOW: The pipes are cut into shorter pieces and split in half before being processed in the ship's laboratories. Each of these one-meter sections covers several tens of thousands of years of Earth's history.

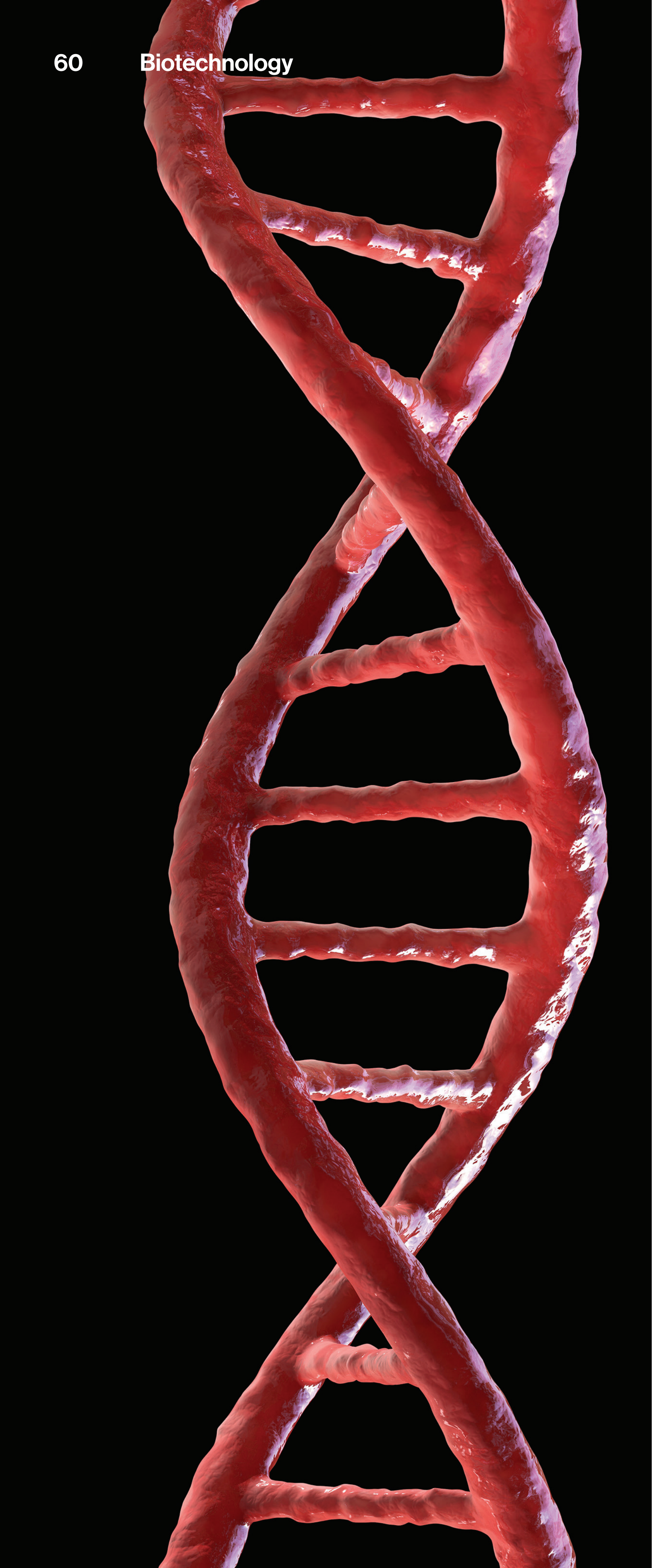
In the ship's lab, samples of the core are taken for chemical analysis and dating.

ABOVE: Samples await paleomagnetic dating. Like tiny compass needles, iron-rich particles align with Earth's shifting magnetic field as they settle on the seabed. By measuring their orientation, researchers can estimate the age of the different sediment layers.

RIGHT: Under the microscope, PhD student Paulina Romel picks shells of unicellular foraminifera from a sample. The chemical composition of these microfossils can give clues about the age of the sediment and the surface water temperature when the organisms were still alive. "These are really cool creatures!" says Romel.

ABOVE: Agathe Ollive, a geochemist from the Alfred Wegener Institute in Germany, takes water samples from a CTD rosette, an instrument package that measures conductivity (salinity) and temperature at various depths. She uses certain elements to trace the inflow of fresh water and seawater from rivers and adjacent ocean basins into the Arctic. “I didn’t expect there to be so little ice up here,” Ollive says. She is worried about how the Arctic will look 20 years from now.

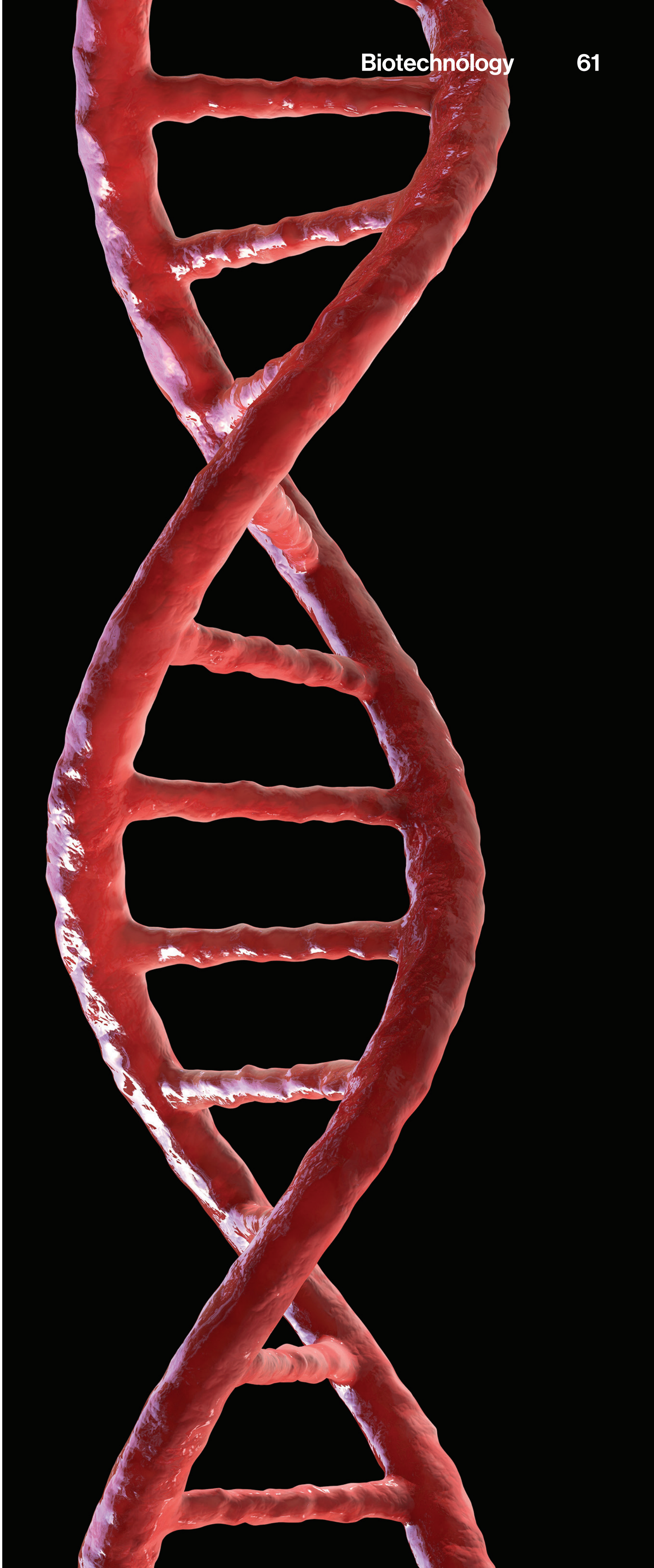
OPPOSITE: Toward the end of the expedition, the *Kronprins Haakon* passes this iceberg near the northeast coast of Greenland.



Through the looking glass

For four days in February 2019, some 30 synthetic biologists and ethicists hunkered down at a conference center in Northern Virginia to brainstorm high-risk, cutting-edge, irresistibly exciting ideas that the National Science Foundation should fund. By the end of the meeting, they'd landed on a compelling contender: making "mirror" bacteria. Should they come to be, the lab-created microbes would be structured and organized like ordinary bacteria, with one important exception: Key biological molecules like proteins, sugars, and lipids would be the mirror images of those found in nature. DNA, RNA, and many other components of living cells are chiral, which means they have a built-in rotational structure. Their mirrors would twist in the opposite direction.

Researchers thrilled at the prospect. "Everybody—everybody—thought this was cool," says John Glass, a synthetic biologist at the J. Craig Venter Institute in La Jolla, California, who attended the 2019 workshop and is a pioneer in developing synthetic cells. It was "an incredibly difficult project that would tell us potentially new things about how to design and build cells, or about the origin of life on Earth." The group saw enormous potential for medicine, too. Mirror microbes might be engineered as biological factories, producing mirror molecules that could form the basis for



Synthetic biologists were tantalized by the idea of making the mirror images of microbes.

Then things got complicated.

By Stephen Ornes

new kinds of drugs. In theory, such therapeutics could perform the same functions as their natural counterparts, but without triggering unwelcome immune responses.

After the meeting, the biologists recommended NSF funding for a handful of research groups to develop tools and carry out preliminary experiments, the beginnings of a path through the looking glass. The excitement was global. The National Natural Science Foundation of China funded major projects in mirror biology, as did the German Federal Ministry of Research, Technology, and Space.

By five years later, in 2024, many researchers involved in that NSF meeting had reversed course. They'd become convinced that in the worst of all possible futures, mirror organisms could trigger a catastrophic event threatening every form of life on Earth; they'd proliferate without predators and evade the immune defenses of people, plants, and animals.

Over the past two years, they've been ringing alarm bells. They published an article in *Science* in December 2024, accompanied by a 299-page technical report addressing feasibility and risks. They've written essays and convened panels and cofounded the Mirror Biology Dialogues Fund (MBDF), a broadly funded nonprofit charged with supporting work on understanding and addressing the risk. The issue

“I wish that one sunny afternoon we were having coffee and we

has received a blaze of media attention and ignited dialogues among not only chemists and synthetic biologists but also bioethicists and policymakers.

What’s received less attention, however, is how we got here and what uncertainties still remain about any potential threat. Creating a mirror-life organism would be tremendously complicated and expensive. And although the scientific community is taking the alarm seriously, some scientists doubt whether it’s even possible to create a mirror organism anytime soon. “The hypothetical creation of mirror-image organisms lies far beyond the reach of present-day science,” says Ting Zhu, a molecular biologist at Westlake University, in China, whose lab focuses on synthesizing mirror-image peptides and other molecules. He and others have urged colleagues not to let speculation and anxiety guide decision-making and argued that it’s premature to call for a broad moratorium on early-stage research, which they say could have medical benefits.

But the researchers who are raising flags describe a pathway, even multiple pathways, to bringing mirror life into existence—and they say we urgently need guardrails to figure out what kinds of mirror-biology research might still be safe. That means they’re facing a question that others have encountered before, multiple times over the last several decades and with mixed results—one that doesn’t have a neat home in the scientific method. What should scientists do when they see the shadow of the end of the world in their own research?

Looking-glass life

The French chemist and microbiologist Louis Pasteur was the first to recognize that biological molecules had built-in handedness. In the late 19th century, he described all living species as “functions of cosmic asymmetry.” What would happen, he mused, if one could replace these chiral components with their mirror opposites?

Scientists now recognize that chirality is central to life itself, though no one knows why. In humans, 19 of the 20 so-called “standard” amino acids that make up proteins are chiral, and all in the same way. (The outlier, glycine, is symmetrical.) The functions of proteins are intricately tied to their shapes, and they mostly interact with other molecules through chiral structures. Almost all receptors on the surface of a cell are chiral. During an infection, the immune system’s sentinels use chirality to detect and bind to antigens—substances that trigger an immune response—and to start the process of building antibodies.

By the late 20th century, researchers had begun to explore the idea of reversing chirality. In 1992, one team reported having synthesized the first mirror-image protein. That, in turn, set off the first clarion call about the risk: In response to the discovery, chemists at Purdue University pointed out, briefly, that mirror-life organisms, if they escaped from a lab, would be immune to any attack by “normal” life. A 2010 story in *Wired* highlighting early findings in the area noted that if a such a microbe developed the ability to photosynthesize, it could obliterate life as we know it.

The synthetic biology community didn’t seriously weigh those threats then, says David Relman, a specialist who bridges infectious disease and microbiology at Stanford University and a trailblazer in studying the gut and oral microbiomes. The idea of a mirror microbe seemed too far beyond the actual progress on proteins. “This was almost a solely theoretical argument 20 years ago,” he says.

Now the research landscape has changed.

Scientists are quickly making progress on mirror images of the machinery cells use to make proteins and to self-replicate. Those components include DNA, which encodes the recipes for proteins; DNA polymerases, which help copy genetic material; and RNA, which carries recipes to ribosomes, the cell’s protein factories. If researchers could make self-replicating mirror ribosomes, then they would have an efficient way to produce mirror proteins. That could be used as a biological manufacturing method for thera-

peutics. But embedded in a self-replicating, metabolizing synthetic cell, all these pieces could give rise to a mirror microbe.

When synthetic biologists convened in Northern Virginia in 2019, they didn’t recognize how quickly the technology was advancing, and if they saw a threat at all, it may have been obscured by the blinding appeal of pushing the science forward. What’s become apparent now, says Glass, is that scientists in different disciplines, all related to mirror life, were largely unaware of what other scientists had been doing. Chemists didn’t know that synthetic biologists had made so much progress on creating mirror cells with natural chirality from scratch. Biologists didn’t appreciate that chemists were building

PREVIOUS SPREAD AND ABOVE: GETTY IMAGES

realized the world's about to end, but that's not what happened."

ever-larger mirror macromolecules. "We tend to be siloed," Glass says. And nobody, he says, had thought to seriously examine the immune system concerns that had already been raised in response to earlier work. "There was not an immunologist or an infectious disease person in the room," Glass says, reflecting on the 2019 meeting. "I may have come closest, given that I work with pathogenic bacteria and viruses," he adds, but his work doesn't address how they cause infections in their hosts.

These scientists also didn't know that around the same time as their meeting, another conversation about mirror life was happening—a darker dialogue that was as focused on danger as it was on discovery. Starting around 2016, researchers with a nonprofit called Open Philanthropy had begun compiling research files on catastrophic biological risks. The organization, which rebranded as Coefficient Giving in 2025, funds projects across a range of focus areas; it adheres to a divisive philanthropic philosophy called effective altruism, which advocates giving money to projects with the highest potential benefit to the most people. While that might not sound objectionable, critics point out that the metrics devotees use to gauge "effectiveness" can prioritize long-term solutions while neglecting social injustices or systemic problems.

Someone in Open Philanthropy's biosecurity group had suggested looking into the risks posed by mirror life. In 2019 the organization began funding research by Kevin Esvelt, who leads the Sculpting Evolution group at the MIT Media Lab, on biosecurity issues, including mirror life. He began reading up to see whether mirror life was something to worry about.

Esvelt made waves in 2013 for pioneering the use of CRISPR to develop a gene drive, a technology that could spread genetic changes introduced into a living organism through a whole population. Researchers are exploring its use, for example, to make mosquitoes hostile to the parasite that causes malaria—and, as a result, lower their chance of spreading it to humans. But almost immediately after he developed the tool, Esvelt argued against using it for profit, at least until proper safeguards could be set and its use in fighting malaria had been established. "Do you really have the right to run an experiment where if you screw up, it affects the whole world?" he asked, in this magazine, in 2016. At the Media Lab, Esvelt leads efforts to safely develop gene drives that can be deployed locally but prevented from spreading globally.

Esvelt says he's often thinking about the security risks posed by self-sustaining genetically engineered technologies, and research led him to suspect that the threat of mirror organisms hadn't been seriously interrogated. The more he learned about microbial growth rates, predator-prey and microbe-microbe interactions, and immunology, the more he began to worry that mirror organisms, if impervious to the innate defenses of natural ones, could cause unstoppable infections in the event that they escaped the lab.

Even if the first experimental iteration of such a germ were too fragile to survive in the environment or a human body, Esvelt says, it would be a light lift to genetically engineer new, more resilient versions with existing technology. Even worse, he says, the results could be weaponized. The possible path from 2019 to global annihilation seemed almost too direct, he found.

But he wasn't an expert in all the scientific fields involved in research on mirror life, so he started making calls. He first described his concerns to Relman one night in February 2022, at a restaurant outside Washington, DC. Esvelt hoped Relman would tell him he was wrong, that he'd missed something over the years of gathering data. Instead, he was troubled.

The concern spreads

When Relman returned to California, he read more about the technology, the risks, and the role of chirality in the immune system and the environment. And he consulted experts he knew well—ecologists, other microbiologists, immunologists, all of them leaders in their fields—in an attempt to assuage his concerns. "I was hoping that they'd be able to say, *I've thought about this, and I see a problem with your logic. I see that it's really not so bad*," he says. "At every turn, that did not happen. Something about it was new to every person."

The concern spread. Relman worked with Jack Szostak, a professor of chemistry at the University of Chicago, and a group of researchers to see if it was possible to make an argument that mirror life wasn't going to wipe out humanity. Included in that group was Kate Adamala, a synthetic biologist at the University of Minnesota. She was a natural choice: Adamala had shared the initial grant from the NSF, in 2019, to explore mirror-life technologies.

She also became convinced the risk was real—and was dumbfounded that she hadn't seen it earlier. "I wish that one sunny afternoon we were having coffee and we realized the world's about to end, but that's not what happened," she says. "I'm embarrassed to admit that I wasn't even the one that brought up the risks first." Through late 2023 and early 2024, the endeavor began to take on the form of a rigorous scientific investigation. Experts were presented with a hypothesis—namely, that if mirror cells were built, they would pose an existential threat—and asked to challenge it. The goal was to falsify the hypothesis. "It would be great if we were wrong," says Vaughn Cooper, a microbiologist at the University of Pittsburgh and president-elect of the American Society for Microbiology.

Relman says that as the chemists and biologists learned more about one another's work and began to understand what immunologists know about how living things defend themselves, they started to connect the dots and see an emerging picture of an unstoppable synthetic threat.

Timothy Hand, an immunologist at the University of Pittsburgh who hadn't participated in the 2019 NSF meeting, wasn't initially worried when he heard about mirror life, in 2024. "The mammalian immune system has this incredible capability to make antibodies against any shape," he says. "Who cares if it's a mirror?" But when he took a closer look at that process, he could see a cascade of potential problems far upstream of antibody production. Start with detection: Macrophages, which are cells the immune system uses to identify and dispatch invaders, use chiral sensing receptors on their surfaces. The proteins they use to grab on to those invaders, too, are chiral. That suggests the possibility that an organism could be infected with a mirror organism but not be able to detect it or defend against it. "The lack of innate immune sensing is an incredibly dangerous circumstance for the host," Hand says.

By early 2024, Glass had become concerned as well. Relman and James Wagstaff, a structural biologist from Open Philanthropy, visited him at the Venter Institute to talk about the possibility of using synthetic cell technology—Glass's specialty—to build mirror life. "At first I thought, *This can't be real*," Glass says. They walked through arguments and counterarguments. "The more this went on, the more I started feeling ill," he says. "It made me realize that work I had been doing for much of the last 20 years could be setting the world up for this incredible catastrophe."

Some scientists have pushed back against the doomsday scenario, suggesting that the case against mirror life offers an "inflated view of the danger."

In the second half of 2024, the growing group of scientists assembled the report and wrote the policy forum for *Science.* Relman briefed policymakers at the White House, members of the defense community, and the National Security Agency. Researchers met with the National Institutes of Health and the National Science Foundation. "We briefed the United Nations, the UK government, the government of Singapore, scientific funding organizations from Brazil," says Glass. "We've talked to the Chinese government indirectly. We were trying to not blindside anybody."

A year and a half on, the push has had an impact. UNESCO has recommended a precautionary global moratorium on creating mirror-life cells, and major philanthropic organizations that fund science, including the Alfred P. Sloan Foundation, have announced they will not finance research leading to a mirror microorganism. The *Bulletin of the Atomic Scientists* highlighted considerations about mirror life in its most recent report on the Doomsday Clock. In March, the United Nations Secretary-General's Scientific Advisory Board issued a brief highlighting the risks—noting, for example, that recent progress on building mirror molecules could reduce the cost of creating a mirror microbe.

"I think no one really believes at this stage that we should make mirror life, based on the evidence that's available," says James Smith, the scientist who leads the MBDF, the nonprofit focused on assessing the risks of mirror life, which is funded by Coefficient Giving, the Sloan Foundation, and other organizations. The challenge now, Smith says, is for scientists to work with policymakers and bioethicists to figure out how much research on mirror life should be permitted—and who will enforce the rules.

Drawing the line

Not everyone is convinced that mirror organisms pose an existential threat. It's difficult to verify predictions about how mirror microbes would fare in the immune system—or the larger world—without running experiments on them. Some scientists have pushed back against the doomsday scenario, suggesting that the case against mirror life offers an "inflated view of the danger." Others have noted that carbohydrates called glycans already exist in both left- and right-handed forms—even in pathogens—and the immune system can recognize both of them. Experiments focused on interactions between the immune system and mirror molecules, they say, could help clarify the risks of mirror organisms and reduce uncertainty.

Andy Ellington, a biotechnologist and synthetic biologist at the University of Texas at Austin, doesn't think mirror organisms

will come to fruition anytime soon. Even if they do, he isn't sure they will pose a threat. "If there is going to be harm done to the human race, this is about position 382 on my list," he says. But at the same time, he says it's a complicated issue worth studying more, and he wants to see the conversations continue: "We're operating in a space where there's so much unknown that it's very difficult for us to do risk assessment."

Even among those convinced that the worst-case scenario is possible, researchers still disagree over where to draw the line. What inquiries should be allowed and what should be prohibited?

Adamala, of the University of Minnesota, and others see a natural line at ribosomes, the cellular factories that transform chains of amino acids into proteins. These would be a critical ingredient in creating a self-replicating organism, and Adamala says the path to getting there once mirror ribosomes are in place would be pretty straightforward. But Zhu, at Westlake, and others counter that it's worth developing mirror ribosomes because they could possibly produce medically useful peptides and proteins more efficiently than traditional chemical methods. He sees a clear distinction, and a foundational gap, between that kind of technology and the creation of a living synthetic organism. "It is crucial to distinguish mirror-image molecular biology from mirror-image life," he says. That said, he points out that many synthetic molecules and organisms containing unnatural components, including but not limited to the mirror-image subset, might pose health risks. Researchers, he says, should focus on developing holistic guidelines to cover such risks—not just those from mirror molecules.

Even if the exact risk remains uncertain, Esvelt remains more convinced than ever that the work should be paused, perhaps indefinitely. No one has taken a meaningful swing at the hypothesis that mirror life could wipe out everything, he says. The primary uncertainties aren't around whether mirror life is dangerous, he points out; they have more to do with identifying which bacterium—including what genes it encodes, what it eats, how it evades the immune system's sentinels—could lead to the most serious consequences. "The risk of losing everything, like the entire future of humanity integrated over time, is not worth any small fraction of the economy. You just don't muck around with existential risk like that," he says.

Even among those convinced that the worst-case scenario is possible, researchers still disagree over where to draw the line. What inquiries should be allowed and what should be prohibited?

In some ways, scientists have been here before, working out rules and limits for research. Two years after the start of the covid-19 pandemic, for example, the World Health Organization published guidelines for managing risks in biological research. But the history is much deeper: Horrific episodes of human experimentation led to the establishment of institutional review boards to provide ethical oversight. In the early 1970s, in response to concerns over lab-acquired infections and growing use of biological warfare, the US Centers for Disease Control and Prevention established biohazard safety levels (BSLs), which govern work on potentially dangerous biological experiments.

And in 1975—at the dawn of recombinant DNA research, which allows researchers to put genetic material from one organism into another—geneticists met at the Asilomar conference center in Pacific Grove, California, to hammer out rules governing the work. There were concerns over what would happen if some virus or bacterium, genetically engineered to have traits that would make it particularly dangerous for people, escaped from a lab. Scientists agreed to self-imposed restrictions, like a moratorium on research until new safety guidelines were in place. As a result of the meeting, in June 1976 the NIH issued rules that, among other things, categorized the risks associated with rDNA experiments and aligned them with the newly adopted BSL system.

Asilomar is often hailed as a successful model for scientific self-governance. But that perception reflects a tendency to recall the meeting through a nostalgic haze. "In fact, it was incredibly messy and human," says Luis Campos, a historian of science at Rice University. Equally brilliant Nobelists argued on either side of the question of whether to rein in rDNA research. Technical discussions dominated; talks about who would be affected by the technology were missing. The meeting didn't start establishing guidelines, says Campos, until the lawyers mentioned liability and lab leaks.

For now it's unclear whether these examples of self-governance, which arose from the demonstrated risks of existing technologies, hold useful lessons for the mirror-life community. Three competing images of the future are coming into focus: Mirror life might not be possible, it might be possible but not threatening, or it might be possible and capable of obliterating all life on Earth.

Scientists may be censoring themselves out of fear and speculation. To some, shutting down the work seems necessary and urgent; to others, it is unnecessarily limiting. What's clear is that the question of what to do about mirror life has been both illuminating and disorienting, pushing scientists to interrogate not only their current research but where it might lead. This is uncharted territory. ■

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A new book by one of the builders of the modern culture of tech asks: How do we fix everything? And why? But it doesn't quite answer.

By Lee Vinsel

Portrait by Winni Wintermeyer

Maintenance: Of Everything, Part One
Stewart Brand
STRIPE PRESS
2026

Tool use

The handsome new book *Maintenance: Of Everything, Part One*, by the tech industry legend Stewart Brand, promises to be the first in a series offering "a comprehensive overview of the civilizational importance of maintenance." One of Brand's several biographers described him as a mainstay of both counterculture and cyberculture, and with *Maintenance*, Brand wants us to understand that the upkeep and repair of tools and systems has profound impact on daily life. As he puts it, "Taking responsibility for maintaining something—whether a motorcycle, a monument, or our planet—can be a radical act."

Radical how? This volume doesn't say. In an outline for the overall work, Brand says his goal is to "end with the nature of maintainers and the honor owed them."

The idea that maintainers are owed anything, much less honor, might surprise some readers. Actually, maintenance and repair have been hot topics in academia since the mid-2010s. I played some role in that movement as a cofounder of the Maintainers, a global, interdisciplinary network dedicated to the study of maintenance, repair, care, and all the work that goes into keeping the world going.

Brand is right, too, that maintainers haven't gotten the laurels they deserve. Over the past few decades, scholars have shown that work from oiling tools to replacing worn parts to updating code bases all tends to be lower in status than "innovation." Maintenance gets neglected in many organizational and social settings. (Just look at some American infrastructure!) And as the right-to-repair movement has shown, companies in pursuit of greater profits have frequently locked us out of being able to do repairs or greatly reduced the maintainable life of their products. It's hard to think of any other reason to put a computer in the door of a refrigerator.

Some of Brand's earlier work helped inspire those insights. But his new book makes me think he doesn't see things that way. For Brand, maintenance seems to be a solitary act, profound but more about personal success and fulfillment than tending to a shared world or making it better.

Born in 1938, Brand is 87 years old. A sense hangs over the book—with its battles against corrosion, rust, and decay, with its attempts to keep things going even as they inevitably falter—of someone looking over life and pondering its end. *Maintenance: Of Everything* connects to every stage of Brand's life. It's worth reviewing where it falls in that arc. Brand has always been interested in tools and fixing things, but rarely has he focused on the systems that need the most care.

More than a half-century ago, Brand was a member of the Merry Pranksters, a countercultural, LSD-centered hippie collective famously led by Ken Kesey, the author of *One Flew Over the Cuckoo's Nest*. In 1966, Brand co-produced the Trips Festival, where bands like the Grateful

COURTESY OF THE PUBLISHER; WINNI WINTERMEYER/GUARDIAN/EYEVINE/REDUX

Dead and Big Brother and the Holding Company performed for thousands amid psychedelic light shows.

In some ways, the Trips Festival set a paradigm for the rest of his life's work. Brand's biographers have described him as a network celebrity—someone who got ahead by bringing people together, building coalitions of influential figures who could boost his signal. As Kesey put it in 1980, "Stewart recognizes power. And cleaves to it."

Brand applied this network logic to the undertaking he will always be best remembered for: the *Whole Earth Catalog*. First published in 1968 and aimed at hippies and members of the nascent back-to-the-land movement, the publication had the motto "Access to tools." Its pages were full of Quonset huts, geodesic domes, solar panels, well pumps, water filters, and other technologies for life off the grid. It was a vision that might feel progressive or left-leaning, but the libertarian, rugged-individualist philosophy of eschewing corrupt systems and remaking civilization alone stood in contrast to the more collective movements pushing for deep social change at the time—like civil rights, feminism, and environmentalism.

That vision also led straight to the empowerment that came with new digital tools, and to Silicon Valley. In 1985, Brand published the *Whole Earth Software Catalog*, the last of the series, and also cofounded the WELL—the Whole Earth 'Lectronic Link, a pioneering online community famous for, among other things, facilitating the trade of Grateful Dead bootlegs. He also wrote a hagiographic book about the MIT Media Lab, known for its corporate-sponsored research into new communications tech. "The Lab would cure the pathologies of technology not with economics or politics but with technology," Brand wrote. Again, not collective action, not policymaking: tools. And Brand then cofounded the Global Business Network, a group of pricey consulting futurists that further connected him to MIT, Stanford, and the Valley. Brand had literally helped bring about the modern digital revolution.

Brand's *Whole Earth Catalog* had a vision that might feel progressive, but its libertarian, rugged-individualist philosophy of remaking civilization alone stood in contrast to more collective social change movements.

His attention then turned toward its upkeep. Brand's 1994 book, *How Buildings Learn: What Happens After They're Built*, argued against high-modernist architectural ideas. Nearly all buildings eventually get remade, he argued, but he especially favored cheap, simple structures that inhabitants could easily retool to suit changing needs. In some ways, Brand was recapitulating the liberated—or libertarian—philosophy of the *Whole Earth Catalog*: People can remake their world, if they have access to tools. In a chapter titled "The Romance of Maintenance," he asked readers to see the beauty, value, and occasional pleasures of fixer-uppers of all kinds.

This chapter was a touchstone for many of us in the academic subfield of maintenance studies. Researchers in disciplines like history, sociology, and anthropology, as well as artists and practitioners in fields like libraries, IT, and engineering, all started trying to understand the realities and, yes, romance of maintenance and repair. Brand joined and contributed to Listservs, attended conferences, chatted with intellectual leaders. So it's a bit uncharitable when he writes that his new book is "the first to look at maintenance in general." He knows better. The real question, though, is what his work has to teach us that others have not said before. In this first volume, the answer is unclear.

Maintenance: Of Everything, Part One is an odd book. If so much of Brand's thinking has been about access to tools, he now asks, in a more extended way: How are our tools maintained? But where Brand began his career with a catalogue, in this volume we get … what? A digest? An almanac? An encyclopedia? Its form and riotous variety fit no genre easily.

The book has two chapters. The first, "The Maintenance Race," recounts the story of three men who took part in the Golden Globe, a round-the-world race for solo sailors held in 1968. Each of the sailors, Brand explains, had a different philosophy of maintenance. One neglected it and hoped for the best. He died. Another thought of and prepared for everything in advance, and while he didn't win the race, he completed it and once held the record for the "world's longest recorded nonstop solo sailing voyage." The final sailor won and did so through heroic acts of perseverance; his style was "*Whatever comes, deal with it*," Brand explains. Structured like a fairy tale and unremittingly romantic, the story—like most of the anecdotes in the book—focuses on the derring-do of vigorous white guys. The strategy is no secret. Brand's outline explains: "Start with a dramatic contest of maintenance styles under life-critical conditions—a true story told as a fable." This myth is meant to inspire.

The second chapter, "Vehicles (and Weapons)," is over 150 pages long. It has five sections, multiple subsections, five subsections designated "digressions," one called a "subdigression," two "postscripts," and several "footnotes" that are not footnotes in a formal sense but, rather, further addenda. At times, it all feels like notes for a future work. Brand makes no apology for the book's woolliness. "All I can offer here," he writes, "is to muse across a representative of maintenance domains and see what emerges." Perhaps

the most charitable reading of the potpourri is that it represents the return of a Merry Prankster, offering us a riotous varied light show. It's a good book to leave on a table and occasionally open to a random page for entertainment. But it often seems as if it does not know what it wants to say or be.

It is environmentally far better to retire and recycle an internal-combustion vehicle than to keep the polluting beast going forever. Keeping existing systems going can be a way of avoiding tough, necessary change.

"Vehicles (and Weapons)" begins by paraphrasing two famous works of maintenance philosophy, Robert M. Pirsig's *Zen and the Art of Motorcycle Maintenance* and Matthew B. Crawford's *Shop Class as Soulcraft*. Maintenance involves both "problem finding" and "problem solving." While much repair work is marked by anxiety, impatience, and boredom, it also offers positive values and outcomes. "Motorcycle maintainers take heart from what they repair *for*—the glory of the ride," Brand writes.

The beauty and triumph of cheapness is a running theme throughout the work, harking back to *How Buildings Learn*. Henry Ford's Model T won out over early electric vehicles and hugely expensive luxury vehicles like Rolls-Royce's Silver Ghost because it was cheap and easier to maintain. The three most popular cars in human history—the Ford Model T, the Volkswagen Bug, and the Lada "Classic" from Russia—all privileged cheapness, "retained their basic design for decades, and … invited repair by the owner." Or, to be fair, maybe demanded it? For every hobbyist who delighted in being able to self-reliantly keep a VW running, there must have been thousands who appreciated how cheap it was and hated that it broke a lot. Brand never points to social research, like surveys, that might help us know people's feelings on such matters.

Other sections recount how Americans created interchangeable parts (enabling not only cheap mass production but also easy maintenance), examine how maintenance works with assault rifles and in war, and track the history of technical manuals from the early modern period to the age of YouTube. These stories are solid, but they're also well known to students of technology, and nearly all are recycled from the work of others, featuring many large block quotes. The volume breaks little new ground.

Brand treats maintenance as an unalloyed good. But the field of maintenance studies has moved on, burrowing into the domain's ironies, complexities, and difficulties. A simple example: In most cases, it is environmentally far better to retire and recycle an internal-combustion vehicle and buy an electric one than to keep the polluting beast going forever. Maintaining a gas-guzzler or a coal-burning power plant isn't a radical act but a regressive one. Also, maintenance can become a life-breaking burden on the poor, and it falls inequitably on the shoulders of women and people of color. Keeping existing systems going can be a way of avoiding tough, necessary change—like making technological systems more accessible for people with disabilities. In this volume, Brand is uninterested in such difficult trade-offs. He avoids any question of how politics shapes these issues, or how they shape politics.

This avoidance comes out most clearly in a section of "Vehicles (and Weapons)" that talks about Elon Musk—a character of "unique mastery," Brand informs us. He tells us that Bill Gates once shorted Tesla's stock, only to lose $1.5 billion. The lesson is clear: Elon won.

In what political and social vision is money the best way to keep the score? Brand rightly points out that electric vehicles have fewer moving parts and, in that sense, are more maintainable than internal-combustion vehicles. He celebrates Musk most of all because his products "have all proven to be game changers in part because they combine ingenious design with surprisingly low cost." Again, it's Brand's "cheap, available tools" hypothesis. But there's a real superficiality and lack of follow-through in thinking here: Teslas remain luxury vehicles whose sales have slumped since federal tax subsidies disappeared. The company has faced several right-to-repair lawsuits; there's even a law review article on the topic. Musk is in no sense a maintenance hero. Yet Brand writes that with his companies, "Musk may have done more practical world saving than any other business leader of his time." By the time Brand was writing this book, the controversies surrounding Musk for at least *flirting with* antisemitism, racism, sexism, authoritarianism, and more were quite clear. About this, the book says not a word.

For sure, Brand needn't agree with Musk's critics, but failing to even broach the subject is tone deaf and out of touch. Others have argued that Silicon Valley's "Move fast and break things" mentality undermines healthy maintenance. Brand doesn't raise the idea—even to dismiss it.

It could be that with *Maintenance: Of Everything, Part One* Brand is just getting going; that in subsequent volumes he'll have something more coherent to say; that he'll raise really hard questions and try to answer them. But given his track record, we might reasonably doubt it. Kesey said Brand cleaves to power; he certainly doesn't question it. ■

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The latest boom in robotics represents a revolution in the way machines have learned to interact with the world. By James O'Donnell

How robots learn

Roboticists used to dream big but build small. They'd hope to match or exceed the extraordinary complexity of the human body, and then they'd spend their career refining robotic arms for auto plants. Aim for C-3P0; end up with the Roomba.

The real ambition for many of these researchers was the robot of science fiction—one that could move through the world, adapt to different environments, and interact safely and helpfully with people. For the socially minded, such a machine could help those with mobility issues, ease loneliness, or do work too dangerous for humans. For the more financially inclined, it would mean a bottomless source of wage-free labor. Either way, a long history of failure left most of Silicon Valley hesitant to bet on helpful robots.

That has changed. The machines are yet unbuilt, but the money is flowing: Companies and investors put $6.1 billion into humanoid robots in 2025 alone, four times what was invested in 2024.

What happened? A revolution in how machines have learned to interact with the world.

Imagine you'd like a pair of robot arms installed in your home purely to do one thing: fold clothes. How would it learn to do that? You could start by writing rules. Check the fabric to figure out how much deformation it can tolerate before tearing. Identify a shirt's collar. Move the gripper to the left sleeve, lift it, and fold it inward by exactly this distance. Repeat for the right sleeve. If the shirt is rotated, turn the plan accordingly. If the sleeve is twisted, correct it. Very quickly the number of rules explodes, but a complete accounting of them could produce reliable results. This was the original craft of robotics: anticipating every possibility and encoding it in advance.

Around 2015, the cutting edge started to do things differently: Build a digital simulation of the robotic arms and the clothes, and give the program a reward signal every time it folds successfully and a ding every time it fails. This way, it gets better by trying all sorts of techniques through trial and error, with millions of iterations—the same way AI got good at playing games.

The arrival of ChatGPT in 2022 catalyzed the current boom. Trained on vast amounts of text, large language models work not through trial and error but by learning to predict what word should come next in a sentence. Similar models adapted to robotics were soon able to absorb pictures, sensor readings, and the position of a robot's joints and predict the next action the machine should take, issuing dozens of motor commands every second.

This conceptual shift—to reliance on AI models that ingest large amounts of data—seems to work whether that helpful robot is supposed to talk to people, move through an environment, or even do complicated tasks. And it was paired with other ideas about how to accomplish this new way of learning, like deploying robots even if they aren't yet perfect so they can learn from the environment they're meant to work in. Today, Silicon Valley roboticists are dreaming big again. Here's how that happened. ■

James O'Donnell is a senior reporter at MIT Technology Review.

Jibo

Jibo

A movable social robot carried out conversations long before the age of LLMs.

An MIT robotics researcher named Cynthia Breazeal introduced an armless, legless, faceless robot called Jibo to the world in 2014. It looked, in fact, like a lamp. Breazeal's aim was to create a social robot for families, and the idea pulled in $3.7 million in a crowd-sourced funding campaign. Early preorders cost $749.

The early Jibo could introduce itself and dance to entertain kids, but that was about it. The vision was always for it to become a sort of embodied assistant that could handle everything from scheduling and emails to telling stories. It earned a number of devoted users, but ultimately the company shut down in 2019.

In retrospect, one thing that Jibo really needed was better language capabilities. It was competing against Apple's Siri and Amazon's Alexa, and all those technologies at the time relied on heavy scripting. In broad terms, when you spoke to them, software would translate your speech into text, analyze what you wanted, and create a response pulled from preapproved snippets. Those snippets could be charming, but they were also repetitive and simply boring—downright robotic. That was especially a challenge for a robot that was supposed to be social and family oriented.

What has happened since, of course, is a revolution in how machines can generate language. Voice mode from any leading AI provider is now engaging and impressive, and multiple hardware startups are trying (and failing) to build products that take advantage of it.

But that comes with a new risk: While scripted conversations can't really go off the rails, ones generated by AI certainly can. Some popular AI toys have, for example, talked to kids about how to find matches and knives.

A crowd-funding campaign started in 2014 and drew 4,800 Jibo preorders.

COURTESY OF MIT MEDIA LAB

Dactyl, part of OpenAI's first attempt at robotics, was trained in simulation to solve Rubik's Cubes.

OpenAI

Dactyl

A robot hand trained with simulations tries to model the unpredictability and variation of the real world.

By 2018, every leading robotics lab was trying to scrap the old scripted rules and train robots through trial and error. OpenAI tried to train its robotic hand, Dactyl, virtually—with digital models of the hand and of the palm-size cubes Dactyl was supposed to manipulate. The cubes had letters and numbers on their faces; the model might set a task like "Rotate the cube so the red side with the letter O faces upward."

Here's the problem: A robotic hand might get really good at doing this in its simulated world, but when you take that program and ask it to work on a real version in the real world, the slight differences between the two can cause things to go awry. Colors might be slightly different, or the deformable rubber in the robot's fingertips could turn out to be stretchier than it was in simulation.

The solution is called domain randomization. You essentially create millions of simulated worlds that all vary slightly and randomly from one another. In each one the friction might be less, or the lighting more harsh, or the colors darkened. Exposure to enough of this variation means the robots will be better able to manipulate the cube in the real world. The approach worked on Dactyl, and one year later it was able to use the same core techniques to do something harder: solving Rubik's Cubes (though it worked only 60% of the time, and just 20% when the scrambles were particularly hard).

Still, the limits of simulation mean that this technique plays a far smaller role today than it did in 2018. OpenAI shuttered its robotics effort in 2021 but has recently started the division up again—reportedly focusing on humanoids.

Google DeepMind

RT-2

Training on images from across the internet helps robots translate language into action.

Around 2022, Google's robotics team was up to some strange things. It spent 17 months handing people robot controllers and filming them doing everything from picking up bags of chips to opening jars. The team ended up cataloguing 700 different tasks.

The point was to build and test one of the first large-scale foundation models for robotics. As with large language models, the idea was to input lots of text, tokenize it into a format an algorithm could work with, and then generate an output. Google's RT-1 received input about what the robot was looking at and how the many parts of the robotic arm were positioned; then it took an instruction and translated it into motor commands to move the robot. When it had seen tasks before, it carried out 97% of them successfully; it succeeded at 76% of the instructions it hadn't seen before.

The second iteration, RT-2, came out the following year and went even further. Instead of training on data specific to robotics, it went broad: It trained on more general images from across the internet, like the vision-language models lots of researchers were working on at the time. That allowed the robot to interpret where certain objects were in the scene.

"All these other things were unlocked," says Kanishka Rao, a roboticist at Google DeepMind who led work on both iterations. "We could do things now like 'Put the Coke can near the picture of Taylor Swift.'"

In 2025, Google DeepMind further fused the worlds of large language models and robotics, releasing a Gemini Robotics model with improved ability to understand commands in natural language.

The model RT-2, for Robotic Transformer 2, incorporated internet data to help robots process what they were seeing.

OPPOSITE: COURTESY OF OPENAI; COURTESY OF GOOGLE DEEPMIND

A Covariant robot demonstrates "induction"—the common warehouse task of placing objects on sorters or conveyors.

Covariant

RFM-1

An AI model that allows robotic arms to act like coworkers.

In 2017, before OpenAI shuttered its first robotics team, a group of its engineers spun out a project called Covariant, aiming to build not sci-fi humanoids but the most pragmatic of all robots: an arm that could pick up and move things in warehouses. After building a system based on foundation models similar to Google's, Covariant deployed this platform in warehouses like those operated by Crate & Barrel and treated it as a data collection pipeline.

By 2024, Covariant had released a robotics model, RFM-1, that you could interact with like a coworker. If you showed an arm many sleeves of tennis balls, for example, you could then instruct it to move each sleeve to a separate area. And the robot could respond—perhaps predicting that it wouldn't be able to get a good grip on the item and then asking for advice on which particular suction cups it should use.

This sort of thing had been done in experiments, but Covariant was launching it at significant scale. The company now had cameras and data collection machines in every customer location, feeding back even more data for the model to train on.

It wasn't perfect. In a demo in March 2024 with an array of kitchen items, the robot struggled when it was asked to "return the banana" to its original location. It picked up a sponge, then an apple, then a host of other items before it finally accomplished the task.

It "doesn't understand the new concept" of retracing its steps, cofounder Peter Chen told me at the time. "But it's a good example—it might not work well yet in the places where you don't have good training data."

Chen and fellow founder Pieter Abbeel were soon hired by Amazon, which is currently licensing Covariant's robotics model (Amazon did not respond to questions about how it's being used, but the company runs an estimated 1,300 warehouses in the US alone).

Agility Robotics

Digit

Companies are putting this humanoid to the test in real-world settings.

The new investment dollars flowing to robotics startups are aimed largely at robots shaped not like lamps or arms but like people. Humanoid robots are supposed to be able to seamlessly enter the spaces and jobs where humans currently work, avoiding the need to retool assembly lines to accommodate new shapes such as giant arms.

It's easier said than done. In the rare cases where humanoids appear in real warehouses, they're often confined to test zones and pilot programs.

That said, Agility's humanoid Digit appears to be doing some real work. The design—with exposed joints and a distinctly unhuman head—is driven more by function than by sci-fi aesthetics. Amazon, Toyota, and GXO (a logistics giant with customers like Apple and Nike) have all deployed it—making it one of the first examples of a humanoid robot that companies see as providing actual cost savings rather than novelty. Their Digits spend their days picking up, moving, and stacking shipping totes.

The current Digit is still a long way from the humanlike helper Silicon Valley is betting on, though. It can lift only 35 pounds, for example—and every time Agility makes Digit stronger, its battery gets heavier and it has to recharge more often. And standards organizations say humanoids need stricter safety rules than most industrial robots, because they're designed to be mobile and spend time in proximity to people.

But Digit shows that this revolution in robot training isn't converging on a single method. Agility relies on simulation techniques like those OpenAI used to train its hand, and the company has worked with Google's Gemini models to help its robots adapt to new environments. That's where more than a decade of experiments have gotten the industry: Now it's building big.

COURTESY OF COVARIANT; COURTESY OF AGILITY ROBOTICS

Amazon and other companies are using Digit to help move shipping totes.

Fiction

CONSTELLATIONS

By

Jeff VanderMeer

I. We had crash-landed on the planet. We were far from home. The spaceship could not be repaired, and the rescue beacon had failed. Besides me, only the astrogator, part of the captain, and the ship's AI mind were left.

Outside, the atmosphere registered as hostile to most organisms. We huddled in the lifeboat, which was inoperable but still held air. Vast storms buffeted our cockleshell shelter, although we knew from prior readings that other areas remained calm. All that remained to us was to explore, if we wanted to live. The captain gave me the sole weapon. She tasked the astrogator with carrying some tools that would not unduly weigh him down.

Little existed on the planet except deserts of snow. But alien artifacts lay in an area near us. We were an exploration team, so this discovery had oddly comforted us, even though we had been on our way elsewhere. The massive systems failure had no discernible source, and the planet had been our only choice for landfall.

The artifacts took the form of 13 domes, spread out over that hostile terrain. The domes had been linked by cables just below shoulder level, threaded through the tops of metal posts at irregular intervals. Whether intended or not, these cables and rods formed a series of paths between the domes.

Artwork by Rogan Brown

GHOST CORAL VENICE VARIATION, HAND- AND LASER-CUT PAPER, CARD, AND FOAMBOARD, 102 × 102 CM, 2024

Before our instruments failed, the AI had reported that the domes appeared to have a heat signature. The cables pulsed under our grip in a way that teased promised warmth far ahead. It took some time to get used to the feeling.

The shortest path between domes was a thousand miles long. The longest path was 10 thousand miles long. Our suit technology was good: A suit could recycle water, generate food, create oxygen. It could push us into various states of near hibernation while motors in the legs drove us forward. For the captain, the suit would compensate for having lost her legs and ease her pain. We estimated we could reach the nearest path and follow it to the nearest dome … and that was it. If the dome had life support capabilities, or even just a way to replenish our suits, we would live. Otherwise, we would probably die.

We revised the estimate of our survival downward when we reached the path and soon encountered the skeletons of dead astronauts littering the way. In all shapes and sizes, cocooned within their suits. Their huddled forms under the snow displayed a serenity at odds with their fate. But when I wiped the frost from face plates, we saw the extremity of their suffering.

It is difficult to explain how we felt walking among so many fatalities. So many dead first contacts.

Here were the ghastly emissaries of hundreds of spacefaring species we had never before encountered.

We no longer had to puzzle over the systems failure. Spaceships came here to crash, and intelligent entities came here to die, for whatever reason. We could not presume our fate would be any different, and adjusted our expectations accordingly. The AI's platitudes about courage did not raise morale. There were too many lost there in the frozen wastes.

The number of the bodies and their haphazard positioning hampered our ability to make progress to the dome. The AI estimated our chances of survival at below 50% for the first time. We would starve in our suits as the motors propelled us forward. We would become desiccated and exist in an elongation of our thoughts that made us weak and stupid until the light winked out. But still, we had no choice. So even in places where the dead in their suits were piled high, we would simply plunge forward, over and through them, headed for the dome.

What we would find there, as I have said, we did not know. But we were in an area of the galaxy where ancient civilizations had died out millions of years ago. We had been on our way to a major site, an ancient city on a moon with no atmosphere in a wilderness of stars.

Although our emotions fluctuated, a professional awe and curiosity about the dead eventually came over us. This created much debate over the comms. We had made a discovery for the ages, but our satisfaction was bittersweet. Even if we lived longer than expected, we would never return home, never see our friends or family again. The AI might continue on after we were dead, but I doubt it envied being the one to report on our discovery centuries hence. And to who?

Here were the ghastly emissaries of hundreds of spacefaring species we had never before encountered. Their suits displayed an extraordinary range, although our examination was cursory. Some even appeared to be made out of scales and other biological substances from their home worlds, giving us further clues as to their origins.

The burial of the suits by snow and the lack of access to anything other than a screaming face or faces, often distorted by time and ice, worked against recording much usable data. This issue was compounded in those cases where the suit was part of the organism and they had not needed any "artificial skin," as the AI put it, to survive harsh conditions. That many had died despite appearing well-prepared for the planet's environment sobered us up even before our own suits dispensed drugs to help our mental states.

After a time, each face seemed to express some aspect of our own stress and terror at the seriousness of our situation. After a time, the sheer welter of detail defeated us and caused us extreme distress. The captain made the observation that even one instance of alien contact might cause physiological and mental conditions, including anxiety, stress, fatigue. Here, we were constantly encountering the alien dead of what seemed at times an infinite number of civilizations.

We stopped recording. We recommitted ourselves to the slog toward the nearest dome.

The captain's drugs unit had failed, but the AI found a way to help her by turning off the heating element in select panels of her suit. Some parts of her would soon be lost to the cold, but the system would allow her to live on with some measure of comfort.

I must admit, we were just glad the screaming had stopped and welcomed her counsel.

II. For a long time, as we labored in our spacesuits on that planet—following the path, beleaguered by snowstorms—we could not understand why we found so many dead astronauts, of so many unknown alien types, and yet no spaceships. During good visibility, our line of sight reached, unbroken, for 500 miles. Where were the crash sites?

But one day we chanced upon an antenna sticking up out of the ground. Clumsy attempts at excavation soon revealed that below this antenna lay a vast dead spaceship of a kind we had never seen before. The gash that had opened it to the elements had laid bare its unique architecture, but also gave the illusion that the snow had spilled out of it to create the world around us rather than having infiltrated and accumulated inside over time.

Aspects of the spaceship's texture gave the startling suggestion that it had been made of some ultra-hard wood or wood equivalent. Clambering partway up to stare at the inner compartments, we all felt the strangeness of the dimensions and proportions of the living quarters. There was no sign of the occupants. Perhaps, I suggested, they had headed for the domes. Perhaps they had even made it to the domes. I tried and failed to keep hope from my voice.

But the captain had ordered the AI to perform a materials analysis. The "snow" in this region had been contaminated by ash and tiny particles of bone. The AI estimated that more than 70% of the white surrounding us was made of the remains of vertebrate sentient life and the remnants of suits. Of invertebrates there was no telling. A thaw might bring not just the drip, drip of water but a shushing sound indicative of bone particulate in the mixture. I imagined there might even be the clink of small objects not rendered down by whatever intense heat had created the ash.

The astrogator had insisted on digging deeper into the ship, with the idea that some recognizable commonality between technologies might yield a part or parts with which he could fix our ship. The rest of us allowed this delusion for the obvious reasons. But upon his return, he held in his hands ovals of snow not much larger than the space formed by the circle between a thumb and finger. Many of them had soft indentations, as one might find in the afterbirth of reptiles from eggs. A kind of ghostly cilia-like tread appeared along the bottoms of these objects.

The astrogator did not find any technology of use to us. Instead, he discovered that the species piloting the spaceship had been so different from us as to be safely encapsuled in suits the size of eggs. Much of what had spilled into or spilled out of the gash constituted the bodies of the crew, in their hundreds of thousands. Their suits had been inadequate to the conditions. They had died en masse attempting to escape their own ship.

The AI speculated that it had been a generation ship, perhaps fleeing a planet with a dying star. If we wondered how the AI had reached this conclusion, it was because we did not want it to be true.

The captain became silent upon receiving this further news and did not speak to us for more than 100 miles of further progress.

As we left that site, unsure exactly what we stepped upon, we also knew that since the spaceship was entirely covered by snow, it had been falling into the sediment for days or months or years. We knew then that our ship might not be visible against the horizon should we retrace our steps. The already bleak probability of rescue through visual identification of a crash site from above would be lost to us in time, even as the line of cables remained perpetually visible to the horizon. We now thought of the planet as a trap. But of what sort?

III. We could not be sure, but in the absence of the captain's voice, it may have been the AI that put forward the idea of the planet's being "duplicitous." The phrasing concerned us, for there was a duplicity in using the planet as the subject of the spoken sentence. A sphere rotating around a sun in deep space could not exhibit forethought or premeditation or other qualities of sentience.

The AI meant whoever or whatever had created the conditions on the planet that allowed spacecraft to be trapped and then the occupants placed in a perilous situation with no recourse. But I distinctly recall the AI using the words "the planet." In addition to being inaccurate, this also let us know that the AI did not have any analysis available that might help us understand the agency and motivations acting upon us.

But in a sense, the AI only voiced something I had felt for several miles: that there existed an overlay to the planet's surface, an area or space or different landscape unavailable to us. This overlay had also not been available to any of the prior astronauts who had died here. In this area or space or different landscape existed a wealth of the usual hoped-for things: a breathable atmosphere and abundant food and water.

While we struggled with the line through the snow and through the storms that welled up, *others* could see us but chose to ignore us for reasons or perhaps just for their own well-being. For hundreds, possibly thousands of years, as explorers had died here in merciless and terrible ways, there raged a sumptuous feast for the senses, as excessive as it was ancient and unending.

I cannot tell you how powerfully the AI's words struck us, so that our mouths watered at the thought of real food and of clean, unrecycled water, of a freedom unencumbered by suits and breathing apparatus. Even at our intended destination, we would have spent most of our days aboard a small space station. This tedium would have been broken only by the arduous process of reaching the unbreathable surface and its ancient ruins of jagged black stone.

This vision that overtook us functioned not just as tantalizing delusion. It scared us so much that we could not compartmentalize it in our thoughts. It continued to overwhelm us like a wave.

We fought for the first time, with the astrogator expressing the wish to return to the ruined spacecraft and explore nearby areas for parts, while the captain broke silence to order us to continue to make progress toward the nearest dome. The AI, which had brought us to this point, stole the captain's silence and said no more.

For each of us, those endless white plains with no real elevation, just the metal rope and the metal posts, had become a kind of repetition that hurt the brain, and the mind with it.

As I looked out across the white, I could not help seeing the impression of shapes in the wind, as if invisible entities fled by, carried there by gusts, unable to get purchase, swept up for hundreds and hundreds of miles before being dashed to the ground.

We did not give up, however.

IV. About halfway to the nearest dome, amid a storm that reduced our progress incrementally and our line of sight to nothing, we came upon a peculiar tableau.

Six astronaut suits had fallen across and around the metal rope. With the flurries of snow, it took us, even with our powerful headlamps, some minutes to determine the nature of the obstruction. The six suits had been created for a humanoid species that must have had torsos like nine-foot-long slabs, attached to six limbs, three for walking. Their heads had flared out like thick fans. All the helmets were cracked open, and curled inside were the skeletons of some other intelligent species no larger than 40 or 50 pounds, possibly warm-blooded. With no sign of the original occupants.

I felt like a parasite who beheld a god. Or was the scale even more ludicrous?

After a brief analysis cut short by the conditions, we postulated that the warm-blooded species had worn breathable skin suits that, as they failed, required these intruders to seek shelter. All they could find were these six dead astronauts. Because we could discover no trace of the original occupants, the AI put forward the theory that this smaller species had eaten every scrap of the remains within the suits.

Then they too had perished, and in time, the AI suggested, something smaller would take up residence inside those bodies, then smaller still within those, and smaller still—

At this point, the captain attempted a soft reboot of the AI using a coded question. We could hear the concern in her voice.

Yet the AI continued undeterred, suggesting that we might find this to be a common situation. It might be replicated across the planet, depending on a system's ability to break down and process meat that had not evolved alongside the devourer for millions of years. In all likelihood, most who attempted to eat in this way died soon after, poisoned by alien flesh.

The astrogator had taken to muttering inside his suit, off comms, as if he no longer thought we functioned as a team. No amount of castigation from the captain served to change his mind.

In the terse harshness of the captain's reprimand, I recognized that her pain levels had spiked once again.

V. The AI began to talk to us in strange alien voices at mile 700, as we labored through the snowstorm to hold onto the cables and thus the path. The AI warbled and chirped and howled and hummed and clucked. The AI spoke in voices like fossilized choruses of beasts, vast and harmonious. And in voices like dry grass spun to fire by the sun. And in voices like the dissolution of all things, darkness in the blinding white that scared me.

At first we thought the AI was deranged. Then that the AI channeled voices from the dome 300 miles ahead. But finally, the AI managed to make known to us that these were the voices of the dead astronauts we had come across from time to time. Huddled frozen. The suits in so many shapes and sizes. That the voices of the dead were channeled through the AI, and nothing could stop them.

We chose to believe that the AI had begun to malfunction. We did not waste time with a response. The captain asked the AI to perform self-shutdown and whispered the numbers in the correct sequence. We knew what we lost with this act, and yet we knew if we did not shut down the AI it might become harmful to us beyond the mental distress of what it had just conveyed to us.

Soon after, the AI gave up its own voice, and all that came from it were the sounds of the others.

A little later, the AI no longer spoke at all.

VI. The snow began to betray us, as the storms created different forms of ice. Often, our arms became weary, our legs cramping, and we had to rest with greater frequency. We came to accept the solid crunch that could support our weight. We came to reject the feather-light freshness that felt effortless underfoot but could give way just as easily as if it were air. In some places, slick purple-hued ice welled up in sluggish layers as if something half-alive. In others, we discovered strange islands of elevation, with brutal curls and curves that suggested two continental shelves had clashed in that space.

As we adapted to these conditions, and as conditions worsened and still we adapted, we came to feel an illusion of competency, one that made even the astrogator temporarily cheerful. The sounds through the comms of our efforts, the deeper breathing, the occasional muffled curse, seduced us in this regard. We felt that we were becoming adroit at handling the snow. We began to believe if we could only make it to the dome, we would be saved.

Yet this uptick in morale ran parallel to, rather than intersected with, the idea of our ultimate survival.

VII. We lost track of the distance left to us without the AI to tell us. Or the captain, in her pain, no longer thought to issue updates. But across the distance left to us came sights beyond reckoning: three giant astronauts spaced 50 miles apart. Larger than most starships, each body lay sprawled across an area larger than several fields and in very different conditions.

The first had been badly burned and was thus unrecoverable, even in terms of salvage. The astronaut had crawled or pulled itself along for some distance. It had left a long smudge of black and red across that expanse. The alien species was, as ever, unknown to us, but the five arms were sunk in the ground as if in agony. The skull had once held three eyes, and the face plate had been cracked by force so strong it resembled a meteor strike. The body was bloated, the fabric of the suit gray with a shimmer of green that came and went, linked to photosensitive skin cells. The way the flesh took up space, and how it exhibited aspects more plant than animal, made it impossible to study further.

The second was a sprawl of limbs, with the suggestion of a defensive posture. The debris of conflict flared out to the side in an incomprehensible display. The suit had an intactness that surprised us, but a similar crack in the face plate without any trace of body within. The rest of the suit had become inhabited by a wealth of other dead astronauts of varying sizes and shapes, who had sought shelter or sustenance and then become trapped or simply … given up. As the AI had predicted, we had once again encountered bodies providing other bodies with temporary sustenance and shelter.

But this condition was not at first evident to us, becoming apparent only after we had clambered for an hour to reach the cracked face plate and the entry hole extended like a broken archway before us.

Despite the number of remains within, and the difficulty in moving through them to explore, the captain ordered an exhaustive recon. Her pulse in the readings had a thready quality. Sometimes I felt, and the astrogator too when we took private comms, that the captain had begun to say things similar to the AI's delusions. Yet we obeyed the order, on the chance that some internal calculation on the captain's part meant she believed this was the only way we would survive.

What did we expect to find in the dead body of a once-intelligent giant? Food? Oxygen? Some cause of death? To put off the thought of our own death by seeking shelter with a death so large we could not comprehend it?

I felt like a parasite who beheld a god. Or was the scale even more ludicrous? I had trouble envisioning the way the body must have twisted as it pitched forward into that icy ground. I had trouble holding onto my own thoughts.

More and more pressure moved through my skull as I contemplated that scene. We were in the midst of something none of my kind had ever known. We might be the only ones, ever. I better understood the unraveling of the AI and of the captain. My sharpness had dulled, taking my calm with it.

It was impossible to tell how long the astronaut had taken to die. Unless somewhere within that fallen figure some hint of life hid that we would never find.

The storms fell away, rose, then fell away again.

VIII. The third huge astronaut was full of light and life and shone out across the wasteland of snow like a beacon. For a moment, I thought we had pierced the invisible layer and could see what lay beyond the veil. We would have comforts beyond anything found on our ruined spaceship even when it had been fit to cross galactic space. There would not be recycled urine for our water. There would not be the faint stink of sweat creeping into our suits as the ventilation system began to fail. Our liquid food would not taste stale and moldy.

As we approached, the suit extended almost to the horizon in that foreshortened perspective created by the left foot. We noted through our remaining instrumentation that the suit remained intact. The pressure told us a kind of air circulated within its sealed surfaces.

We climbed with a renewed energy, the promise of sanctuary so close making us giddy. We each exhorted the others on with such exuberance that it made me a little afraid. What lay on the other side of this state of mind but a fall?

When we reached the helmet plate, we could see inside not a face or a skull, but instead such a richness of healthy growth that we fell silent before it. None of us could, I believe, understand exactly what we saw, except that it equaled ecosystem—resplendent with vibrant greens and blues, stippled with other colors. There might be some parallel to a terrarium full of moss and exotic plants. There might be some sense of life moving amongst those plants, as of jewel-like amphibians or even tiny shy sapphire birds. We could not smell or taste or hear what lay behind the face plate. We could not experience it in that way, but somehow we each imagined enough to be calmed and comforted by it.

The astrogator said he might be able to create a hole in the plate or elsewhere on the body to let us in, and then patch the surface such that not too much air or vitality would spill out. This workaround might take an hour or two, due to the delicate nature of what we saw within. But it was possible.

The captain considered the astrogator's proposal and then agreed. The weather had begun to turn dangerous again. That we should begin immediately did not need to be said. With the proper pressure brought to bear, we would have some measure of sanctuary from which to recover for a final push to the dome. It could be the difference between life and death, the astrogator said. If the atmosphere was breathable, we might even be able to give the captain some better solution to her pain.

I unclipped the astrogator's equipment from his waist and threw it off the mountain that was the astronaut and watched it sail through the air and into the snow. Then I used my weapon to fry it where it lay. Then I threw my weapon into the snow, too, in a place where the featheriness would cover it and hide it forever.

We were a team and I had helped my team while showing them I posed no threat—although I knew the astrogator and the captain would not see it that way. I stood there on the face plate that we could no longer open with the diminished tools at our disposal as they both yelled at me through the comms. It's unimportant what they said to me. They were admonishing me for something that had already happened and that they had no power to stop. I did not bother to explain, but began to make the descent to the ground so we could once again take up the metal rope and make for the dome.

Will you follow, I asked them from the ground, when I saw they still stood on the heights. There came no reply, but when they saw me take up the rope, they climbed down to take up the rope too.

I waited then, and let them catch up.

IX. The captain died not long after. The pain was too great or the wounds she had suffered too damaging. I had known for some time she would never make it to the dome, but there was no point in emphasizing that to her. Nothing she had done until the end had required her to be removed from command. Her last words were the name of our ship and giving her love to someone who would be dead of old age even if we found a way to escape this place and return home. But the astrogator told her he would carry those words forward.

Then we left her by the marker that meant we had 100 miles left to the dome. We knew the snow would cover her for burial. It had done so faithfully for all the rest.

As the astrogator followed me down the rope line, he cried out for explanation. The captain's death required it for some reason, in his mind. The captain had not deserved my betrayal. The captain would not rest easy until I told him why.

You must believe in ghosts, I replied.

This reply incensed him and he castigated me in words not used among members of a team that respect each other. Once more, I ignored him, but told him if our oxygen got low, he could have mine if we calculated he could make it to the base. I meant this, as I knew the odds were low anyway. I had hurt my knee taking the equipment from the astrogator and then making my way so rapidly down from the dead astronaut.

The astrogator did not reply, by which I knew he did not accept my answer.

The reason I took the tools and destroyed them is because the wind had told me something it had not whispered to the captain or the astrogator. The wind had not spoken to me before, so I believed what it told me. That the astronaut within the suit lived on, if unable to move. That what we saw on the outside and registered as ecosystem, as separate "plants" and "animals," instead formed a composite life-form and that to crack open the suit or cut through the suit at a leg would have been a violation.

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That in that frozen hellscape, the persistence of life in that manner, an oasis in the midst of nothing, could be categorized as a miracle.

I would not snuff that out. I could not allow that to be snuffed out. But I remembered too how I felt looking at that vast and alien country behind the face plate. So calm, so comforted, overcome by the depths of an emotion I could not place. Would I replace that feeling with the feeling of seeing all those explorers dead within the other vast suit? Even as I become one of them?

Because the planet had already told us the rules, the consequences, and the ultimate outcome. There are no odds so terrible that they could not be experienced, and in dozens of ways, in this place.

So I trudged on and the astrogator cursed me and cursed me and called out my childhood and how badly I must have been brought up and how I must have cheated to pass the psych exams, and yet I had thought the same of him at various points during our journey.

See how beautiful the snow is, falling now, I said to him over the comms. See how precise and geometric this line we follow across this expanse.

He did not reply, but a little later he told me he no longer believed in the line at all, and by his calculations he would get to the dome faster if he abandoned it and struck out on his own.

I could not stop the astrogator and did not want to, so I watched him become a smaller and smaller figure against the white until the white ate him up and I was alone.

X. I have been walking a long time, visiting with the dead. Here, against an arch of heaven that appears no different than what I see directly in front of me. ■

Jeff VanderMeer is the author of the critically acclaimed, bestselling Southern Reach series, translated into 38 languages. His short fiction has appeared in Vulture, Slate, New York Magazine, Black Clock, Interzone, American Fantastic Tales (Library of America), and many others.

The AI Hype Index

MIT Technology Review's highly subjective take on the latest buzz about AI

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