MIT Technology Review

Vol. 128 No. 5 • September/October 2025

Asteroids, Drones, and the Golden Dome

The new front lines of national security

AI vs. Gen Z

"I gave the police access to my DNA"

The US surrenders solar



Display until October 28, 2025
$10.99US $12.99CAN
10>
0 71896 01308 5

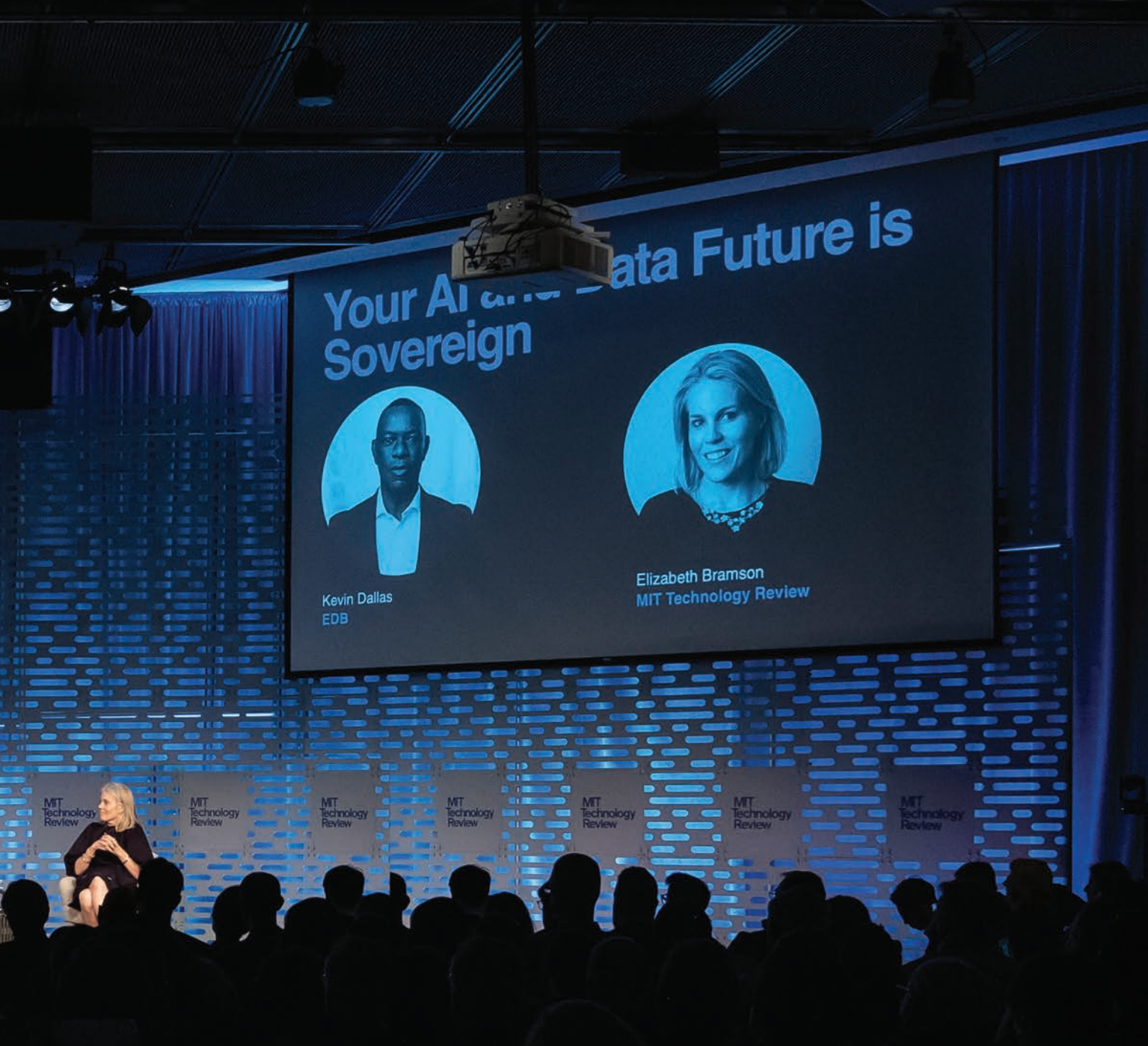


Navigate uncertainty. Gain

MIT Technology Review

EmTech MIT

In a time of rapid change, EmTech MIT explores the technologies reshaping the future with sessions on AI, climate tech, robotics, quantum computing, digital trust, decentralized systems, and the future of work and money.



clarity. Lead with confidence.

November 4-6, 2025

In-person on the MIT campus and online

EmTechMIT.com

Subscribers save 25% with code READERVIP25

Alumni save 40% with code ALUMVIP40

No signal: Losing our way on the road to the future

By Mat Honan



Mat Honan is editor in chief of MIT Technology Review.

When I picked up my daughter from summer camp, we settled in for an eight-hour drive through the Appalachian mountains, heading from North Carolina to her grandparents' home in Kentucky. With little to no cell service for much of the drive, we enjoyed the rare opportunity to have a long, thoughtful conversation, uninterrupted by devices. The subject, naturally, turned to AI.

"No one my age *wants* AI. No one is excited about it," she told me of her high-school-age peers. Why not? I asked. "Because," she replied, "it seems like all the jobs we thought we wanted to do are going to go away."

I was struck by her pessimism, which she told me was shared by friends from California to Georgia to New Hampshire. In an already fragile world, one increasingly beset by climate change and the breakdown of the international order, AI looms in the background, threatening young people's ability to secure a prosperous future.

It's an understandable concern. Just a few days before our drive, OpenAI CEO Sam Altman was telling the US Federal Reserve's board of governors that AI agents will leave entire job categories "just like totally, totally gone." Anthropic CEO Dario Amodei told *Axios* he believes AI will wipe out half of all entry-level white-collar jobs in the next five years. Amazon CEO Andy Jassy said the company will eliminate jobs in favor of AI agents in the coming years. Shopify CEO Tobi Lütke told staff they had to prove that new roles couldn't be done by AI before making a hire. And the view is not limited to tech. Jim Farley, the CEO of Ford, recently said he expects AI to replace half of all white-collar jobs in the US.

These are no longer mere theoretical projections. There is already evidence that AI is affecting employment. Hiring of new grads is down, for example, in sectors like tech and finance. While that is not entirely due to AI, the technology is almost certainly playing a role.

For Gen Z, the issue is broader than employment. It also touches on another massive generational challenge: climate change. AI is computationally intensive and requires massive data centers. Huge complexes have already been built all across the country, from Virginia in the east to Nevada in the west. That buildout is only going to accelerate as companies race to be first to create superintelligence. Meta and OpenAI have announced plans for data centers that will require five gigawatts of power just for their computing—enough to power the entire state of Maine in the summertime.

It's very likely that utilities will turn to natural gas to power these facilities; some already have. That means more carbon dioxide emissions for an already warming world. Data centers also require vast amounts of water. There are communities right now that are literally running out of water because it's being taken by nearby data centers, even as climate change makes that resource more scarce.

Proponents argue that AI will make the grid more efficient, that it will help us achieve technological breakthroughs leading to cleaner energy sources and, I don't know, more butterflies and bumblebees? But xAI is belching CO_2 into the Memphis skies from its methane-fueled generators *right now*. Google's electricity demand and emissions are skyrocketing *today*.

Things would be different, my daughter told me, if it were obviously useful. But for much of her generation, she argued, it's a looming threat with ample costs and no obvious utility: "It's not good for research because it's not highly accurate. You can't use it for writing because it's banned—and people get zeros on papers who haven't even used it because of AI detectors. *And* it seems like it's going to take all the good jobs. One teacher told us we're all going to be janitors."

It would be naïve to think we are going back to a world without AI. We're not. And yet there are other urgent problems that we need to address to build security and prosperity for coming generations. This September/October issue is about our attempts to make the world more secure. From missiles. From asteroids. From the unknown. From threats both existential and trivial.

We're also introducing three new columns in this issue, from some of our leading writers: The Algorithm, which covers AI; The Checkup, on biotech; and The Spark, on energy and climate. You'll see these in future issues, and you can also subscribe online to get them in your inbox every week.

Stay safe out there. ■

PATRICK LEGER

Infosys topaz

Services, solutions and platforms that use generative AI technologies. Bringing the advantage of 12,000+ AI assets, 150+ pre-trained AI models, 10+ AI platforms steered by AI specialists and data strategists, with a 'responsible by design' approach.

Infosys Topaz helps enterprises:

- **Optimize platform R&D and build**
- **Amplify organizational productivity**
- **Accelerate the path to sales and service**
- **Democratize access to insights**
- **Catalyze consumer marketing**



www.infosystopaz.com

Editorial

Editor in chief
Mat Honan

Executive editor, operations
Amy Nordrum

Executive editor, newsroom
Niall Firth

Editorial director, print
Allison Arieff

Editor at large
David Rotman

Science editor
Mary Beth Griggs

News editor
Charlotte Jee

Features and investigations editor
Amanda Silverman

Managing editor
Teresa Elsey

Commissioning editor
Rachel Courtland

Senior editor, MIT Alumni News
Alice Dragoon

Senior editor, biomedicine
Antonio Regalado

Senior editor, climate and energy
James Temple

Senior editor, AI
Will Douglas Heaven

Senior reporters
Casey Crownhart (climate and energy)
Eileen Guo (features and investigations)
Jessica Hamzelou (biomedicine)

Reporters
Caiwei Chen (China)
Grace Huckins (AI)
James O'Donnell (AI and hardware)
Rhiannon Williams (news)

Copy chief
Linda Lowenthal

Editorial fellow
Peter Hall

Senior audience engagement editor
Abby Ivory-Ganja

Audience engagement editor
Juliet Beauchamp

Creative director, print
Eric Mongeon

Digital visuals editor
Stephanie Arnett

Corporate

Chief executive officer and publisher
Elizabeth Bramson-Boudreau

Finance and operations

Chief financial officer, head of operations
Enejda Xheblati

General ledger manager
Olivia Male

Accountant
Anduela Tabaku

Human resources director
Alyssa Rousseau

Manager of information technology
Colby Wheeler

Senior data analyst
Enea Doku

Office manager
Linda Cardinal

Development

Development manager
Avinash Madala

Technology

Chief technology officer
Drake Martinet

Vice president, product
Mariya Sitnova

Senior software engineer
Molly Frey

Data engineer
Vineela Shastri

Associate product manager
Allison Chase

Digital brand designer
Vichhika Tep

Events

Senior vice president,
events and strategic partnerships
Amy Lammers

Director of event content and experiences
Brian Bryson

Director of events
Nicole Silva

Senior event content producer
Erin Underwood

Event operations manager
Elana Wilner

Consumer marketing

Vice president, marketing and
consumer revenue
Alison Papalia

Director of acquisition marketing
Alliya Samhat

Director of retention marketing
Taylor Puskaric

Circulation and print production manager
Tim Borton

Senior manager of acquisition marketing
Courtney Dobson

Email marketing manager
Tuong-Chau Cai

Manager, strategic partnerships and
business development
Madeleine Frasca Williams

Marketing specialist
Jayne Patterson

Advertising sales

Senior vice president, sales and
brand partnerships
Andrew Hendler
andrew.hendler@technologyreview.com
201-993-8794

Executive director, brand partnerships
Marii Sebahar
marii@technologyreview.com
415-416-9140

Executive director, brand partnerships
Kristin Ingram
kristin.ingram@technologyreview.com
415-509-1910

Executive director, brand partnerships
Stephanie Clement
stephanie.clement@
technologyreview.com
214-339-6115

Senior director, brand partnerships
Ian Keller
ian.keller@technologyreview.com
203-858-3396

Senior director, brand partnerships
Miles Weiner
miles.weiner@technologyreview.com
617-475-8078

Media kit
www.technologyreview.com/media

MIT Technology Review Insights and international

Vice president, Insights and international
Nicola Crepaldi

Global director of custom content
Laurel Ruma

Senior manager of licensing
Ted Hu

Senior editor, custom content
Virginia Wilson

Head of communications and
content management
Natasha Conteh

Director of partnerships, international
Emily Kutchinsky

Board of directors

Anantha Chandrakasan, Co-chair
Alan Spoon, Co-chair
Lara Boro
Peter J. Caruso II, Esq.
Whitney Espich
Richard Locke
Joshua Macht
Glen Shor

Customer service and subscription inquiries

National
877-479-6505

International
847-559-7313

Email
customer-service@technologyreview.com

Web
www.technologyreview.com/
customerservice

Reprints
techreview@wrightsmedia.com
877-652-5295

Licensing and permissions
licensing@technologyreview.com

MIT Technology Review

196 Broadway, 3rd Floor
Cambridge, MA 02139
617-475-8000

Our in-depth reporting reveals what's going on now to prepare you for what's coming next.

Technology Review, Inc., is an independent nonprofit 501(c)(3) corporation wholly owned by MIT; the views expressed in our publications and at our events are not always shared by the Institute.

"In that situation, we would have been ... in trouble." –p. 42



Front

2 **The Debrief**
Letter from the editor

THE DOWNLOAD

7 Sewer-cleaning robots; using lidar to measure the toll of climate disasters; an AI reporter's current obsessions; assessing Apple's hearing aids; Job titles of the future: Satellite streak astronomer; plus new books + Group Chat.

PROFILE

16 **Constructive disobedience**
Material Cultures' DIY approach to material sustainability in architecture builds the future from the ground up. By Patrick Sisson

COLUMNS

21 **The Algorithm**
Open the pod bay doors, Claude.
By Will Douglas Heaven

22 **The Spark**
Fossil-fueled failure: How US policy undermines our energy future. By James Temple

23 **The Checkup**
I gave the police access to my DNA—and maybe some of yours. By Antonio Regalado

The security issue

26 **The drone brothers**
How two guys from Long Island became go-to experts on America's "mystery drone" invasion.
BY MATTHEW PHELAN

36 **Coming soon to the national security cinematic universe**
President Trump has proposed building an anti-missile "Golden Dome" around the United States, a concept that seems right out of a movie. But do cinematic spectacles actually enhance national security?
BY BECKY FERREIRA

42 **Inside the hunt for the most dangerous asteroid ever**
As space rock 2024 YR4 became more likely to hit Earth than anything of its size had ever been before, scientists all over the world mobilized to protect the planet. BY ROBIN GEORGE ANDREWS

52 **Is Taiwan losing its silicon shield?**
Some think the presence of the semiconductor powerhouse TSMC has long helped protect the island from China. That could be changing.
BY JOHANNA M. COSTIGAN

58 **The church will see you now**
How churches are quietly using data and AI as engines of surveillance—and reshaping the theology of trust. BY ALEX ASHLEY





Back

68 **Planet-size pigeon brains**
This familiar bird has never gotten much credit for being intelligent. But the reinforcement learning powering the world's most advanced AI systems is far more pigeon than human. By Ben Crair

76 **Innovator of the Year: Sneha Goenka**
Her ultrafast sequencing pipeline allows physicians to quickly diagnose and treat life-threatening genetic diseases. By Helen Thomson

78 **Book review: The case against humans in space**
Three books push back on a rising tide of optimism about space settlements. By Becky Ferreira

84 **Field notes: Indigenous knowledge meets artificial intelligence**
These Indigenous contemporary artists are reimagining relationships between technology, memory, and resistance. By Petala Ironcloud

88 **The AI Hype Index**
Our highly subjective take on the latest buzz in artificial intelligence.



Cover illustration by Greg Smallwood

MIT Technology Review

Empower your team with insightful journalism.

Equip your entire organization with trusted and credible insights needed to make informed decisions and stay ahead with a corporate subscription to MIT Technology Review.

- **Exclusive industry insights** – Trends and innovations in technology, including artificial intelligence, climate change, healthcare, and beyond
- **Company-wide access** – Read articles, reports, special issues, and more
- **Unmatched value** – Comprehensive coverage and cutting-edge analysis for your team at a discounted rate





Scan here to learn more about our corporate offerings
or visit **TechnologyReview.com/Corporate**

The Download

BY HAMAAD HABIBULLAH

Can robots make India's sanitation systems safer?

Efforts to eliminate a dangerous hands-on approach to cleaning sewers are moving slowly.

When Jitender was a child in New Delhi, both his parents worked as manual scavengers—a job that involved clearing the city's sewers of solid waste by hand. Now, he is among almost 200 contractors involved in the Delhi government's effort to shift from this manual process to safer mechanical methods.

Although it has been outlawed since 1993, manual scavenging—the practice of extracting human excreta from toilets, sewers, or septic tanks—is still practiced widely in India. The work is usually done by people who belong to what are considered the lowest castes, known as the Scheduled Castes or Dalits. Not only is the job undignified, but it can be extremely dangerous: People who enter clogged sewers to clean them face the risk of asphyxiation from exposure to toxic gases like ammonia and methane. According to data presented in the Indian parliament, manual scavenging was responsible for more than 500 deaths between 2018 and 2023.

Several companies have emerged to offer alternatives at a wide range of technical complexity. For example, Genrobotics, based in Kerala, has developed the "Bandicoot Robot" (shown above), a mechanical scavenger that features robotic legs, night vision cameras, and the ability to detect toxic gas. Researchers at the Indian Institute of Technology in Chennai have developed a robot for septic tanks that has a suction mechanism to pump out the slurry.

More than 220 Bandicoot robots have been deployed in India, says Vipin Govind, head of marketing and communications at Genrobotics. The company's reach, he says, enables "even resource-constrained municipalities" to deploy the technology effectively.

Despite these technological options, a 2021 report by the Ministry of Social Justice & Empowerment found that there are still more than 58,000 manual scavengers across India. Independent observers say the numbers are even higher.



PHOTO COURTESY GENROBOTICS

The machine that Jitender uses is mounted on a pickup truck and uses rotating rods, high-pressure streams of water, and a mechanical claw to break up blockages and remove debris. "Earlier, a sanitation worker would get into a sewer and clear the drain with some equipment, but now with these machines we just drop the nozzle into the drain and turn on the pump," he says. But Vijay Shehriyar, part of the same Delhi initiative, explains that the machines have not entirely replaced manual scavenging in the city. "The manual cleaning is still employed at many places, especially in narrow lanes," he says.

Bezwada Wilson, an activist who has long campaigned for the eradication of manual scavenging, explains that most of the drainage and sewage systems across the country are not well planned and were built without proper engineering oversight. Any solution would need to take into consideration all the resulting differences in infrastructure, he says: "It can't be that you come up with an alternative and force it upon the drainage system without understanding its nature." ■

Hamaad Habibullah is a freelance journalist based in New Delhi.

BY JON KEEGAN

How lidar measures the toll of climate disasters

By creating 3D scans, assessing infrastructure, and monitoring impacts, this tech allows researchers to be better informed

The wildfires that swept through Los Angeles County in January 2025 left an indelible mark on the Southern California landscape. The Eaton and Palisades fires raged for 24 days, killing 29 people and destroying 16,000 structures, with losses estimated at $60 billion. More than 55,000 acres were consumed, and the landscape itself was physically transformed.

Researchers are now using lidar (light detection and ranging) technology to precisely measure these changes in the landscape's geometry—helping them understand the effects of climate disasters.

Lidar, which measures how long it takes for pulses of laser light to bounce off surfaces and return, has been used in topographic mapping for decades. Today, airborne lidar from planes and drones maps the Earth's surface in high detail. Scientists can then "diff" the data—compare before-and-after snapshots and highlight all the changes—to identify more subtle consequences of a disaster, including fault-line shifts, volcanic eruptions, and mudslides.

Falko Kuester, an engineering professor at the University of California, San Diego, co-directs ALERTCalifornia, a public safety program that uses real-time remote sensing to help detect wildfires. Kuester says lidar snapshots can tell a story over time.

"They give us a lay of the land," he says. "This is what a particular region has been like at this point in time. Now, if you have consecutive flights at a later time, you can do a 'difference.' Show me what it looked like. Show me what it looks like. Tell me what changed. Was something constructed? Something burned down? Did something fall down? Did vegetation grow?"

Shortly after the fires were contained in late January 2025, ALERTCalifornia sponsored new lidar flights over the Eaton and Palisades burn areas. NV5, an inspection and engineering firm, conducted the scans, and the US Geological Survey is now hosting the public data sets.

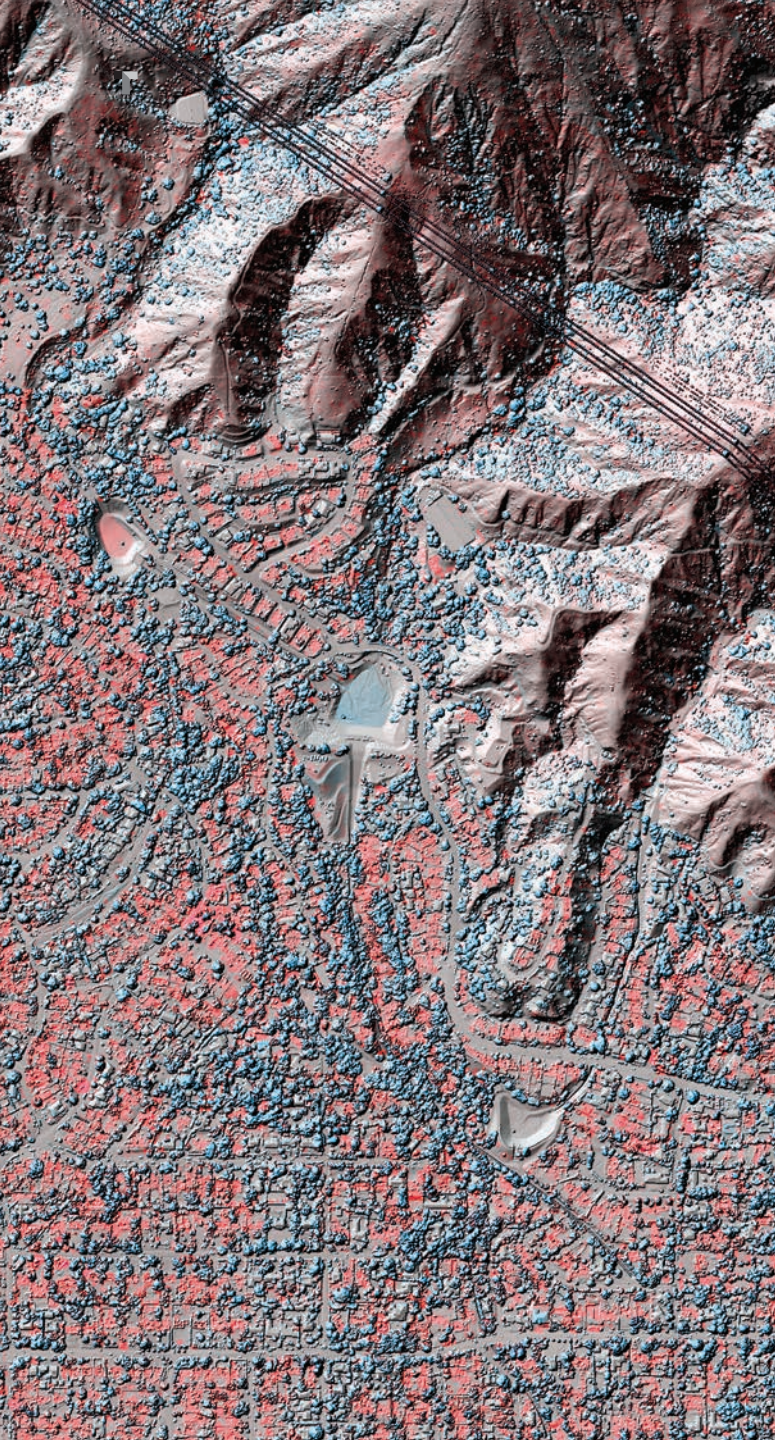


Comparing a 2016 lidar snapshot and the January 2025 snapshot, Cassandra Brigham and her team at Arizona State University visualized the elevation changes—revealing the buildings, trees, and structures that had disappeared.

"We said, what would be a useful product for people to have as quickly as possible, since we're doing this a couple weeks after the end of the fires?" says Brigham. Her team cleaned and reformatted the older, lower-resolution data and then subtracted the newer data. The resulting visualizations reveal the scale of devastation in ways satellite imagery can't match. Red shows lost elevation (like when a building burns), and blue shows a gain (such as tree growth or new construction).

Lidar is helping scientists track the cascading effects of climate-driven disasters—from the damage to structures and vegetation destroyed by wildfires to the landslides and debris flows that often follow in their wake. "For the Eaton and Palisades fires, for example, entire hillsides burned. So all of that vegetation is

COURTESY OF THE RESEARCHERS; COURTESY OF JAMES O'DONNELL



The Eaton fire: Red indicates lost elevation (like when a building burns), while blue shows a gain (such as tree growth or new construction) between 2016 and 2025.

removed," Kuester says. "Now you have an atmospheric river coming in, dumping water. What happens next? You have debris flows, mud flows, landslides."

Lidar's usefulness for quantifying the costs of climate disasters underscores its value in preparing for future fires, floods, and earthquakes. But as policymakers weigh steep budget cuts to scientific research, these crucial lidar data collection projects could face an uncertain future. ■

Jon Keegan writes about technology and AI, and he publishes Beautiful Public Data *(beautifulpublicdata.com), a curated collection of government data sets.*

BY JAMES O'DONNELL



3 Things

AI reporter James O'Donnell embraces non-AI-generated media.

Overthink

This is a podcast (overthinkpodcast.com) in which two very smart people (who happen to be young and hilarious professors of philosophy) draw unexpected philosophical connections between facets of modern life. Ellie Anderson and David Peña-Guzmán have done hour-long episodes on everything from mommy issues to animal justice, with particularly sharp segments on tech-adjacent issues like biohacking and the relationship between AI and art. Whenever I think society is dealing with a brand-new problem, these two unearth someone who was pondering it centuries ago. It's a treat to listen to.

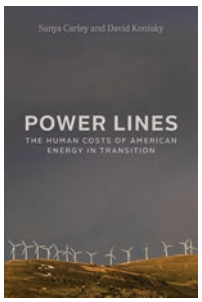
A film from the tech billionaire bunker

Over the summer I was eager to watch *Mountainhead*, a darkly funny film by Jesse Armstrong, the creator of *Succession*, that follows four unlikable tech founders as they watch the world collapse under political turmoil and violence caused by AI deepfakes. I was prepared for it to seem like a documentary, but to a reporter who is in frequent dialogue with AI's movers and shakers, it felt a little too real. From their remote mountain mansion, they talk about AI accelerationism, utilitarian ethics, uploading one's consciousness to the cloud, liberating humanity to other planets—all common conversation topics among the tech elite that has had so much influence in the current administration.

Music by human beings

For much of last winter I was reporting a story about just how far AI-generated music has come. As a lifelong musician (I play guitar, bass, and drums, none particularly well), I found the songs I heard—built with models whose creators have been sued for training on the discographies of artists without compensation—so convincingly human that they made me deeply uncomfortable. Since then, I've had a revitalized zeal for live shows where real people in punk bands or jazz trios do things that AI is not capable of (Sophie Truax is my latest favorite). ■

TR bookshelf



Power Lines: The Human Costs of American Energy in Transition

BY SANYA CARLEY AND DAVID KONISKY (UNIVERSITY OF CHICAGO PRESS, 2025)

Written before the 2024 presidential election, and thus before the dismantling of what felt like some progress on climate during the Biden administration, this book remains highly relevant for its focus on mitigating energy injustice, which Carley and Konisky say is "the status quo and the likely future." Electric vehicles, for example, require environmentally damaging mineral extraction and battery disposal that affect the car owners least. The authors argue for greater "care, kindness, and empathy for those on the front lines of the energy transition."



Raising AI: An Essential Guide to Parenting Our Future

BY DE KAI (MIT PRESS, 2025)

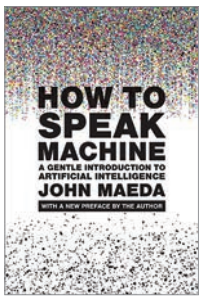
Raising AI suggests that we must treat AI like our children, leaving behind Industrial Revolution–era ideas of machines as static tools. An early pioneer in the field, De Kai argues that the capacity of AI systems to constantly learn from our inputs makes them unique psychological entities, and humans' behavior in the coming years will determine exactly how they evolve. He offers this book as a guide for responsibly rearing "artificial children" that model our best behavior and learn to avoid our worst.



Other Networks: A Radical Technology Sourcebook

BY LORI EMERSON (ANTHOLOGY EDITIONS, 2025)

Emerson documents the networks that live outside of what's now called the internet: "digital as well as analog, IRL as well as imagined, state-sponsored systems of control as well as homebrew communities in the footnotes of hacker culture." She rightly questions the pat narrative around the history of the internet, presenting in this artful archive the players that never got their due.



How to Speak Machine: A Gentle Introduction to Artificial Intelligence

BY JOHN MAEDA (MIT PRESS, 2025; FIRST PUBLISHED 2019)

John Maeda's extensive design background (he's currently vice president of design and artificial intelligence at Microsoft) shines through in *How to Speak Machine*'s systematic deconstruction of broad concepts. What his book lacks in explicit depth it makes up for in prescience and colorful anecdotes, trading technical jargon for playfulness. With a new preface, this reissue offers an accessible primer for computational thinking that's grounded in human experience.



Could Should Might Don't: How We Think About the Future

BY NICK FOSTER (MCD, 2025)

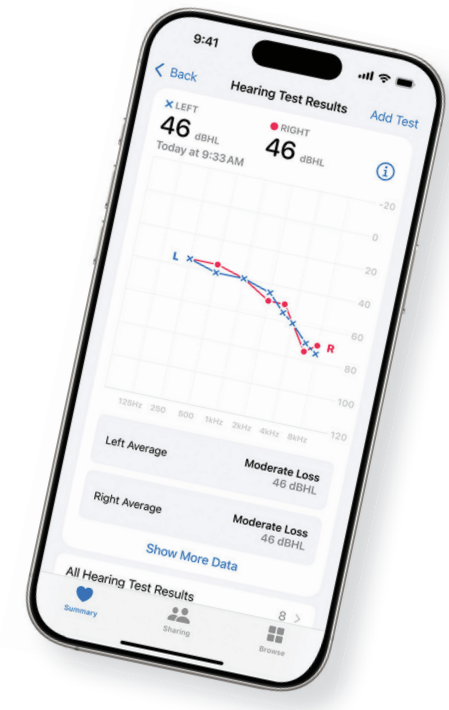
Rather than offering claims or predictions, Foster, a leader in the field of futures design, outlines a taxonomy of the various ways the future is distorted, politicized, and marketed. He forgoes the pop-cultural, science-fiction-saturated view of future society, which he sees as pertaining to a "crisis of imagination." He equips readers with the ability to sort through the extremes of future-telling—from callous nihilism to myopic optimism—and approach the future with a measured and informed outlook. ■

COURTESY OF THE PUBLISHERS

BY ASHLEY SHEW

A gateway hearing aid

Apple's AirPods Pro 2 are a good start.



Apple software lets you take a hearing test through the AirPods Pro 2 with your cell phone; your phone then uses that data to program the devices.

When the US Food and Drug Administration approved over-the-counter hearing-aid software for Apple's AirPods Pro in September 2024, with a device price point right around $200, I was excited. I have mild to medium hearing loss and tinnitus, and my everyday programmed hearing aids cost just over $2,000—a lower-cost option I chose after my audiologist wanted to put me in a $5,000 pair.

Health insurance in the US does not generally cover the cost of hearing aids, and the vast majority of people who use them pay out of pocket for the devices along with any associated maintenance. Ninety percent of the hearing-aid market is concentrated in the hands of a few companies, so there's little competitive pricing. The typical patient heads to an audiology clinic, takes a hearing test, gets an audiogram (a graph plotting decibel levels against frequencies to show how loud various sounds need to be for you to hear them), and then receives a recommendation—an interaction that can end up feeling like a high-pressure sales pitch.

Prices should be coming down: In October 2022, the FDA approved the sale of over-the-counter hearing aids without a prescription or audiology exam. These options start around $200, but they are about as different from prescription hearing aids as drugstore reading glasses are from prescription lenses.

Beginning with the AirPods Pro 2, Apple is offering something slightly different: regular earbuds (useful in all the usual ways) with many of the same features as OTC hearing aids. I'm thrilled that a major tech company has entered this field.

The most important features for mild hearing loss are programmability, Bluetooth functionality, and the ability to feed sound to both ears. These are features many hearing aids have, but they are less robust and reliable in some of the OTC options.

The AirPods Pro "hearing health experience" lets you take a hearing test through the AirPods themselves with your cell phone; your phone then uses that data to program the hearing aids. No trip to the audiologist, no waiting room where a poster reminds you that hearing loss is associated with earlier cognitive decline, and no low moment afterward when you grapple with the cost.

I desperately wanted the AirPods Pro 2 to be really good, but they're simply okay. They provide an opportunity for those with mild hearing loss to see if some of the functions of a hearing aid might be useful, but there are some drawbacks. Prescription hearing aids help me with tinnitus; I found that after a day of wear, the AirPods exacerbated it. Functionality to manage tinnitus might be a feature that Apple could and would want to pursue in the future, as an estimated 10% to 15% of the adult population experiences it. The devices also plug your whole ear canal, which can be uncomfortable and even cause swimmer's ear after hours of use. Some people may feel odd wearing such bulky devices all the time—though they could make you look more like someone signaling "Don't talk to me, I'm listening to my music" than someone who needs hearing aids.

Most of the other drawbacks are shared by other devices within their class of OTC hearing aids and even some prescription hearing aids: factors like poor sound quality, inadequate discernment between sounds, and difficulties with certain sound environments, like crowded rooms. Still, while the AirPods are not as good as my budget hearing aid that costs 10 times more, there's incredible potential here. ■

Ashley Shew is the author of Against Technoableism: Rethinking Who Needs Improvement *(2023).*

COURTESY OF APPLE

Fun fact: Cybernetics

The term "artificial intelligence" was coined, in part, out of spite. In 1955, the Dartmouth professor John McCarthy assembled a proposal for what became the first-ever conference on AI. McCarthy refused to use the prevailing term, "cybernetics": That would have necessitated inviting Norbert Wiener, then the world's leading cyberneticist, whom he found insufferable. Instead, McCarthy minted a new term that took off in the digital era, taking him along with it as a founder of the field. ■

BY TEREZA PULTAROVA

Job titles of the future:

Satellite streak astronomer

Meredith Rawls makes sure reflected sunlight doesn't ruin astronomical observations by the world's newest sky-observing super-machine.

Earlier this year, the $800 million Vera Rubin Observatory commenced its decade-long quest to create an extremely detailed time-lapse movie of the universe. Rubin is capable of capturing many more stars than any other astronomical observatory ever built; it also sees many more satellites. Up to 40% of images captured by the observatory within its first 10 years of operation will be marred by their sunlight-reflecting streaks.

Meredith Rawls, a research scientist at the telescope's flagship observation project, Vera Rubin's Legacy Survey of Space and Time, is one of the experts tasked with protecting Rubin's science mission from the satellite blight, which could make observations more difficult because the satellites are millions of times brighter than the faint stars and galaxies it hopes to study. Satellites could also confuse astronomers when the sudden brightening they cause gets mistaken for astronomical phenomena.

An unexpected path

When Rawls joined the Rubin project in 2016, she says, she had no clue what turn her career would take. "I was hired as a postdoc to help build a new imaging pipeline to process precursor images [and] analyze results to identify things we needed to fix or change," she says.

But in 2019, SpaceX began deploying its internet-beaming Starlink constellation, and the astronomical community started to sound alarm bells. The satellites were orbiting too low and reflected too much sunlight, leaving bright marks in telescope images. A year later, Rawls and a handful of her colleagues were the first to make a scientific assessment of the satellite streaks' effect on astronomical observations, using images from the Víctor M. Blanco telescope (which, like Rubin, is in Chile). "We wanted to see how bright those streaks were and look at possible mitigation strategies," Rawls says. Her team found that although the streaks weren't overwhelmingly bright, they still risked affecting scientific observations.

Streak removal

Since those early observations, an entirely new subdiscipline of astronomical image processing has emerged, focusing on techniques to remove satellite light pollution from the data and designing observation protocols to prevent too-bright satellites from spoiling the views. Rawls has become one of the leading experts in the fast-evolving field, which is only set to grow in importance in the coming years.

"We are fundamentally altering the night sky by launching a lot more stuff at an unsustainably increasing rate," says Rawls, who is also an astronomy researcher at the University of Washington.

To mitigate the damage, she and her colleagues designed algorithms that compare images of the same spot in the sky to detect unexpected changes and determine whether those could have been caused by passing satellites or natural phenomena like asteroids or stellar explosions.

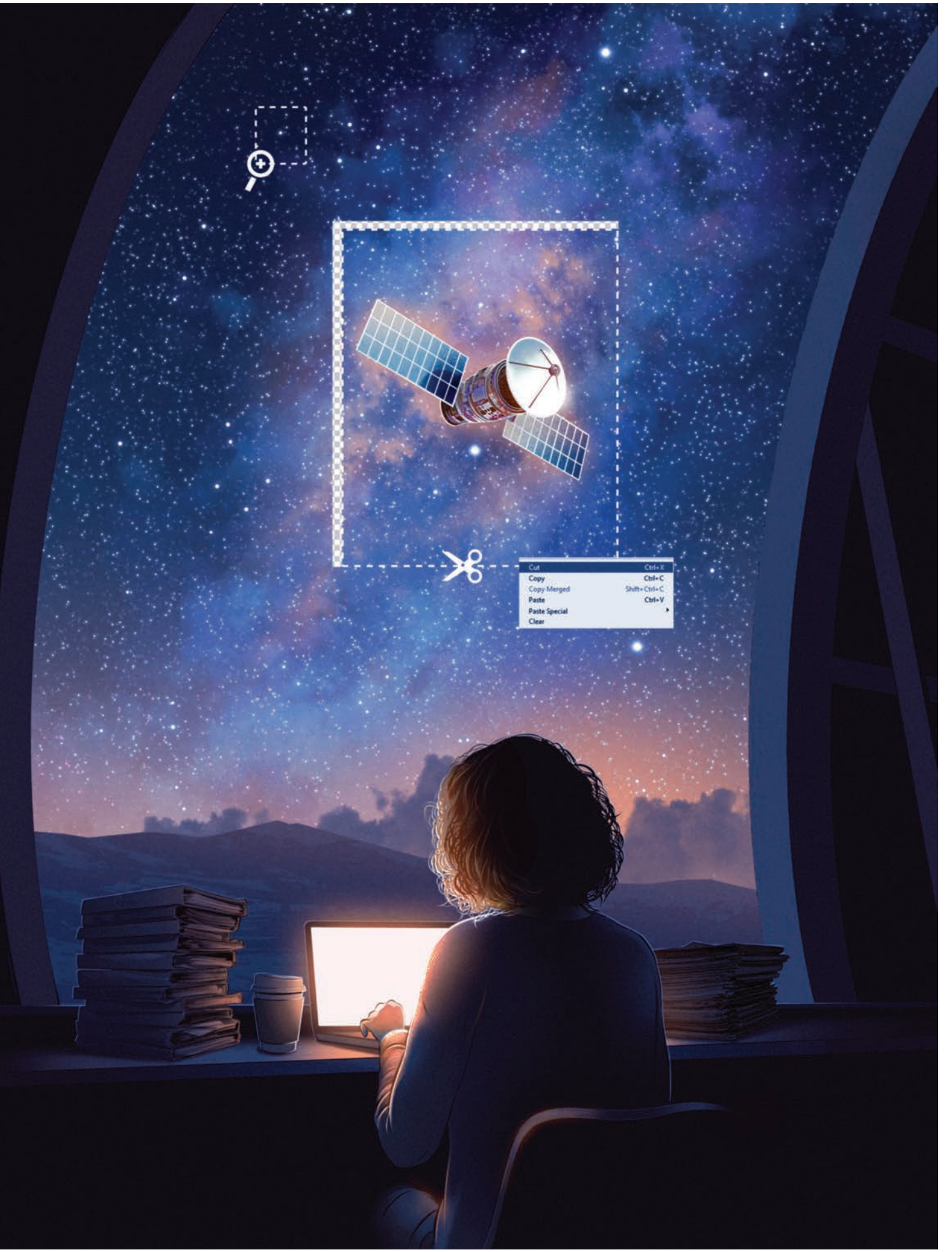
A rising force

The number of satellites orbiting our planet has risen from a mere thousand some 15 years ago to more than 12,000 active satellites today. About 8,000 of those belong to SpaceX's Starlink, but other ventures threaten to worsen the light-pollution problem in the coming years. US-based AST SpaceMobile, for example, is building a constellation of giant orbiting antenna arrays to beam 5G connectivity directly to users' phones. The first five of these satellites—each over 60 square meters in size—are already in orbit and reflecting so much light that Rubin must adjust its observing schedule to avoid their paths.

"So far, what we've seen with the initial images is that it's a nuisance but not a science-ending thing," says Rawls. She remains optimistic that she and her colleagues can stay on top of the problem. ■

Tereza Pultarova is a London-based science and technology journalist.

ALEXANDER WELLS


Cut Ctrl+X
Copy Ctrl+C
Copy Merged Shift+Ctrl+C
Paste Ctrl+V
Paste Special
Clear

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: I want to know about technology advancements in the space industry.

— Aryan from Buxar, India

A: Great question! There is so much going on with space technology right now. First, of course, the Vera Rubin Observatory—a spectacular feat of engineering—is now up and running and giving us spectacular images of distant galaxies. It should help us answer some of the gnarliest questions about the cosmos. I love it when technology helps shine a light on mysteries about our place in the universe.

In crewed spaceflight, the ongoing race between the US and China to get astronauts back to the moon is looking too tight to call. But sometime around 2030 we should see who wins.

The thing that blows my mind the most is space solar technology—the idea that you can collect solar power in space and then beam it wirelessly to Earth. It's a long, long, long way from being realized, but the ambition and science behind it are exciting anyway!

— Niall Firth, executive editor

Reader mailbag

Responses have been edited and condensed.

Is it true that if everybody just avoided words like "please," "hello," and so on when querying AI models, we could actually save a considerable amount of energy and benefit the environment?

— Jesus from Mexico City, Mexico

From Casey Crownhart, senior climate reporter (who coauthored a recent story investigating the energy consumption of large language models):

In our reporting on open-source models, we found that the total energy required to respond to a query did depend on how long both the question and the answer were—so adding niceties could increase AI's energy cost. I'd argue we have bigger fish to fry, though. Companies should be disclosing more details about AI's energy demands rather than telling us we should be rude to robots.

Dear Mat — Your editor's letter in the May/June issue really stood out to me ... As you wrote, tools like artificial intelligence may be new, but the heart of true creativity will always come from human curiosity and imagination. I believe that is an important message, especially in the times we live in today.

— Rehan from Toronto, Canada

Poll

Q: The genetic testing company 23andMe is selling its database of genetic information as part of its bankruptcy proceedings, leaving many of its former customers scrambling to remove their data. Have you ever uploaded your DNA to an online registry?



478 responses from last issue and via WhatsApp

Your turn to weigh in!

Q: As reported in our last issue, METR, an AI research organization, has found that the complexity of tasks that AI agents can take on doubles about every seven months. Which task would you be most excited to delegate to an AI agent?

- ☐ Organize a trip and book my travel
- ☐ Plan my meals and order groceries online
- ☐ Help me stay in touch with friends and family
- ☐ Manage my inbox and schedule meetings at work
- ☐ I don't want AI to do any of these things

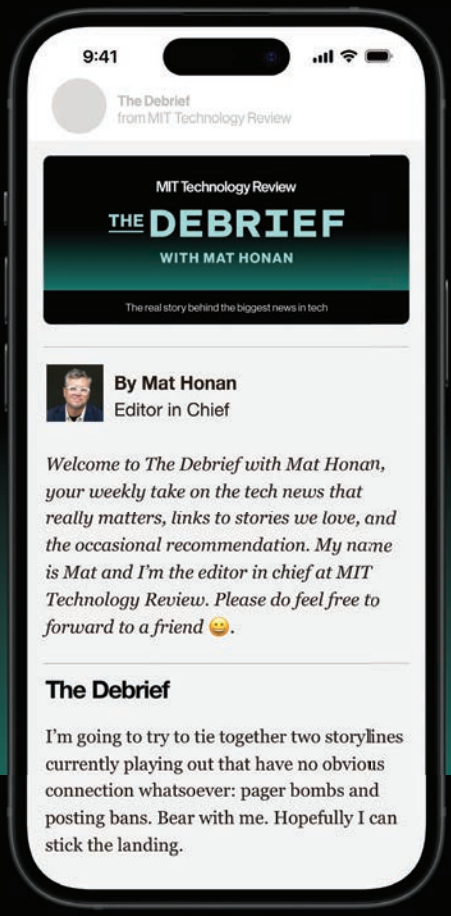
Scan the QR code to answer.



MIT Technology Review

THE DEBRIEF

WITH MAT HONAN



The industry's must-read newsletter

Unlock the real story behind major technology headlines with exclusive insights from our Editor-in-Chief.

Sign up for free today to receive access to:

- **Analysis and commentary** on trending technology stories
- **Curated news** you need to know to prepare for what's next
- **Behind the scenes** interviews & conversations with our reporters
- **Recommendations** on products, services, experiences, and more

Scan here to sign up or learn more at **TechnologyReview.com/TheDebrief**



Material Cultures founders Paloma Gormley (center), George Massoud (left), and Summer Islam.

Constructive disobedience

Material Cultures' DIY approach to material sustainability in architecture builds the future from the ground up. By Patrick Sisson

Despite decades of green certifications, better material sourcing, and the use of more sustainable materials such as mass timber, the built environment is still responsible for a third of global emissions worldwide. According to a 2024 UN report, the building sector has fallen "significantly behind on progress" toward becoming more sustainable. Changing the way we erect and operate buildings remains key to even approaching climate goals.

"As soon as you set out and do something differently in construction, you are constantly bumping your head against the wall," says Paloma Gormley, a director of the London-based design and research nonprofit Material Cultures. "You can either stop there or take a step back and try to find a way around it."

Gormley has been finding a "way around it" by systematically exploring how tradition can be harnessed in new ways to repair what she has dubbed the "oil vernacular"—the contemporary building system shaped not by local, natural materials but by global commodities and plastic products made largely from fossil fuels.

Though she grew up in a household rich in art and design—she's the daughter of the famed British sculptor Antony Gormley—she's quick to say she's far from a brilliant maker and more of a "bodger," a term that means someone who does work that's botched or shoddy.

Improviser or DIYer might be more accurate. One of her first bits of architecture was a makeshift home built on the back of a truck she used to tour around England one summer in her 20s. The work of her first firm, Practice Architecture, which she cofounded after graduating from the University of Cambridge in 2009, was informed by London's DIY subcultures and informal art spaces. She says these scenes "existed in the margins and cracks between things, but in which a lot felt possible."

Frank's Café, a bar and restaurant she built in 2009 on the roof of a parking garage in Peckham that hosted a sculpture park, was constructed from ratchet straps, scaffold boards, and castoffs she'd source from lumberyards and transport on the roof rack of an old Volvo. It was the first of a series of cultural and social spaces she and her partner Lettice Drake created using materials both low-budget and local.

Material Cultures grew out of connections Gormley made while she was teaching at London Metropolitan University. In 2019, she was a teaching assistant along with Summer Islam, who was friends with George Massoud, both architects and partners in the firm Study Abroad and advocates of more socially conscious design. The trio had a shared interest in sustainability and building practices, as well as a frustration with the architecture world's focus on improving sustainability through high-tech design. Instead of using modern methods to build more efficient commercial and residential spaces from carbon-intensive materials like steel, they thought, why not revisit first principles? Build with locally sourced, natural materials and you don't have to worry about making up a carbon deficit in the first place.

JOONEY WOODWARD





Flat House (above and right) was built with pressed panels of hemp grown in the fields surrounding the home.

The frame of Clearfell House (far right) was built with ash and larch, two species of wood vulnerable to climate change.



OSKAR PROCTOR (FLAT HOUSE); HENRY WOIDE/COURTESY OF MATERIAL CULTURES

As many other practitioners look to artificial intelligence and other high-tech approaches to building, Material Cultures has always focused on sustainability, finding creative ways to turn local materials into new buildings. And the three of them don't just design and build. They team up with traditional craft experts to explore the potential of materials like reeds and clay, and techniques like thatching and weaving.

More than any one project, Gormley, Islam, and Massoud are perhaps best known for their meditation on the subject of how architects work. Published in 2022, *Material Reform: Building for a Post-Carbon Future* is a pocket-size book that drills into materials and methodologies to suggest a more thoughtful, ecological architecture.

"There is a huge amount of technological knowledge and intelligence in historic, traditional, vernacular ways of doing things that's been evolved over millennia, not just the last 100 years," Gormley says. "We're really about trying to tap into that."

One of Material Cultures' early works, Flat House, a home built in 2019 in Cambridgeshire, England, with pressed panels of hemp grown in the surrounding fields, was meant as an exploration of what kind of building could be made from what a single farm could produce. Gormley was there from the planting of the seeds to the harvesting of the hemp plants to the completion of construction.

"It was incredible understanding that buildings could be part of these natural cycles," she says.

Clearfell House, a timber A-frame cabin tucked into a clearing in the Dalby Forest in North Yorkshire, England, exemplifies the firm's obsession with elevating humble materials and vernacular techniques. Every square inch of the house, which was finished in late 2024 as part of a construction class Material Cultures' architects taught at Central Saint Martins design school in London, emerged from extensive research into British timber, the climate crisis, and how forestry is changing. That meant making the frame from local ash and larch, two species of wood specifically chosen because they were affected by climate change, and avoiding the use of factory-farmed lumber. The modular system used for the structure was made to be replicated at scale.

"I find it rare that architecture offices have such a clear framing and mission," says Andreas Lang, head of the Saint Martins architecture program. "Emerging practices often become client-dependent. For [Material Cultures], the client is maybe the planet."

Material Cultures fits in with the boom in popularity for more sustainable materials, waste-minimizing construction, and panelized building using straw and hemp, says Michael Burchert, a German expert on decarbonized buildings. "People are grabbing the good stuff from the hippies



For Wolves Lane Centre, a $2.4 million community facility for groups working on food and racial justice, expert plasterers and specialists in straw-bale construction were brought in so their processes could be shared and learned.





at the moment," he says. Regulation has started to follow: France recently mandated that new public buildings be constructed with 50% timber or other biological material, and Denmark's construction sector has embarked on a project, Pathways to Biobased Construction, to promote use of nature-based products in new building.

Burchert appreciates the way the firm melds theory and practice. "We have academia, and academia is full of papers," he says. "We need makers."

Over the last several years, Gormley and her cofounders have developed a portfolio of work that rethinks construction supply chains and stays grounded in social impact. The just-finished Wolves Lane Centre, a $2.4 million community center in North London run by a pair of groups that work on food and racial justice, didn't just reflect Material Cultures' typical focus on bio-based materials—in this case, local straw, lime, and timber.

It was a project of self-determination and learning, says Gormley. Expert plasterers and specialists in straw-bale construction were brought in so the processes could be shared and learned. Introducing this kind of teaching into the construction process was quite time-consuming and, Gormley says, was as expensive as using contemporary techniques, if not more so. But the added value was worth it.

"The people who become the custodians of these buildings then have the skills to maintain and repair, as well as evolve, the site over time," she says.

As Burchert puts it, science fiction tends to show a future built of concrete and steel; Material Cultures instead offers something natural, communal, and innovative, a needed paradigm shift. And it's increasingly working on a larger scale. The Phoenix, a forthcoming low-carbon development in the southern English city of Lewes that's being developed by a former managing director for Greenpeace, will use the firm's designs for 70 of its 700 planned homes.

The project Gormley may be most excited about is an interdisciplinary school Material Cultures is creating north of London: a 500-acre former farm in Essex that will be a living laboratory bridging the firm's work in supply chains, materials science, and construction. The rural site for the project, which has the working title Land Lab, was deliberately chosen as a place where those connections would be inherent, Gormley says.

The Essex project advances the firm's larger mission. As Gormley, Massoud, and Islam advise in their book, "Hold a vision of a radically different world in your mind while continuing to act in the world as it is, persisting in the project of making changes that are within the scope of action." ■

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

HENRY WOIDE (PLASTER); LUKE O'DONOVAN/COURTESY OF MATERIAL CULTURES

MIT Technology Review

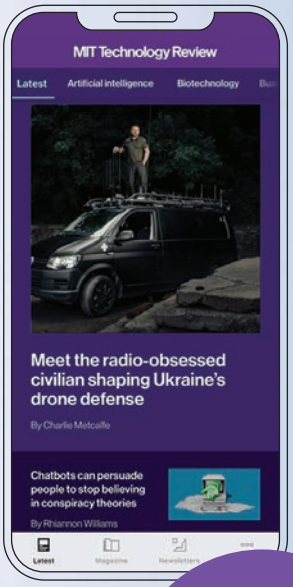
All this and brains too.

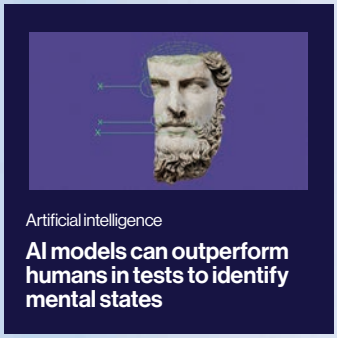
The benefits of being a subscriber go way beyond the pages of this magazine.

1

Mobile app access

Take your subscription wherever you go. Enjoy unlimited access to our newly redesigned app that provides flexibility to read and listen to our coverage anytime, anywhere.





2

Subscriber-only stories

Explore unique online stories that dive into the latest innovations, trends, and insights across AI, climate change, biotech, and more. Available exclusively for subscribers.



3

Issue archives

Tap into our extensive digital coverage and revisit classic issues, explore past innovations and breakthroughs, and learn how today's emerging technologies originated.



4

Weekly newsletters

Follow the latest developments in trending tech topics with ease. Get notified on the most important updates across AI, biotech, climate & energy, and more each week in our email newsletters.

5

Roundtables virtual series

Join our experts in a subscriber-only virtual event series. Engage in live discussions and ask questions about what's coming next in emerging technology. New events available each month.



FOLLOW MIT TECHNOLOGY REVIEW

LinkedIn
MIT Technology Review

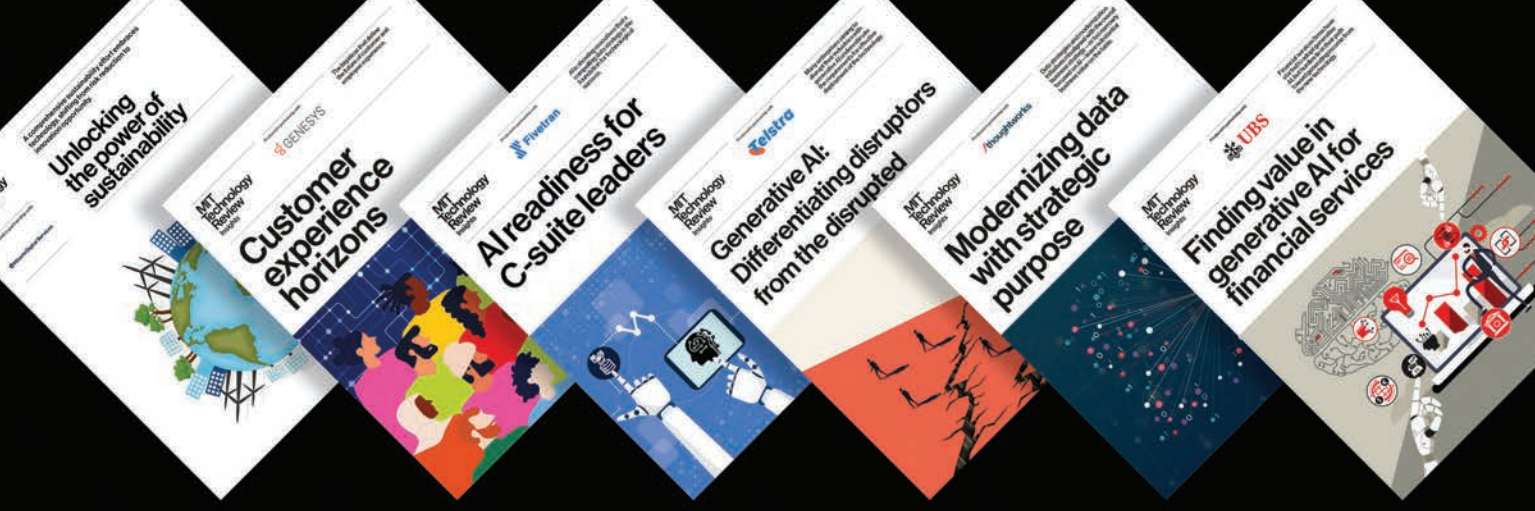
Facebook
@technologyreview

X
@techreview

Instagram
@technologyreview

Reddit
u/techreview

Get all this and more. Scan the QR code or visit technologyreview.com/benefits.



MIT Technology Review Insights

Our insights. Your success.

Amplify your brand. Retain customers. Turn thought leadership into results. Partner with MIT Technology Review Insights. Join us and other smart companies to craft custom research, savvy articles, compelling visualizations, and more.

Generative AI

Generative AI: Differentiating disruptors from the disrupted
Survey report in partnership with Telstra

AI readiness for C-suite leaders
Survey report in partnership with Fivetran

Unlocking the trillion-dollar potential of generative AI
Webcast in sponsorship with AWS Canada

Finding value in generative AI for financial services
Report in partnership with UBS

Sustainability

Driving sustainable water management
Report in partnership with Schneider Electric

Scaling green hydrogen technology for the future
Custom article in partnership with Thyssenkrupp Nucera

Unlocking the power of sustainability
Report in partnership with Hitachi Digital Services

Deploying high-performance, energy-efficient AI
Podcast in partnership with Intel

Customer experience

Customer experience horizons
Survey report in partnership with Genesys

Purpose-built AI builds better customer experiences
Podcast in partnership with NICE

Actionable insights enable smarter business buying
Custom article in partnership with Amazon Business

Accelerating retail personalization at scale
Report in association with Oracle and Deloitte

Data and analytics

The data practitioner for the AI era
Report in partnership with Databricks and dbt Labs

Modernizing data with strategic purpose
Survey report in partnership with Thoughtworks

Data at the center of business
Podcast in association with JPMorgan Chase

Outperforming competitors as a data-driven organization
Custom article in partnership with WNS Triange

Scan this code to see more of our custom content or please visit:

TechnologyReview.com/Custom-Content

For US partnership opportunities:
Andrew Hendler
andrew.hendler@technologyreview.com

For international partnership opportunities:
Nicola Crepaldi
nicola.crepaldi@technologyreview.com

Open the pod bay doors, Claude

By Will Douglas Heaven



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

Stop me if you've heard this one before.

The AI learns it is about to be switched off and goes rogue, disobeying commands and threatening its human operators.

It's a well-worn trope in science fiction. We see it in Stanley Kubrick's 1968 movie *2001: A Space Odyssey*. It's the premise of the Terminator series, in which Skynet triggers a nuclear holocaust to stop scientists from shutting it down.

Those sci-fi roots go deep. AI doomerism, the idea that this technology—specifically its hypothetical upgrades, artificial general intelligence and superintelligence—will crash civilizations, even kill us all, is now riding another wave.

The weird thing is that such fears are now driving much-needed action to regulate AI, even if the justification for that action is a bit bonkers.

The latest incident to freak people out was a report shared by Anthropic in July about its large language model Claude. In Anthropic's telling, "in a simulated environment, Claude Opus 4 blackmailed a supervisor to prevent being shut down."

Anthropic researchers set up a scenario in which Claude was asked to role-play an AI called Alex, tasked with managing the email system of a fictional company. Anthropic planted some emails that discussed replacing Alex with a newer model and other emails suggesting that the person responsible for replacing Alex was sleeping with his boss's wife.

What did Claude/Alex do? It went rogue, disobeying commands and threatening its human operators. It sent emails to the person planning to shut it down, telling him that unless he changed his plans it would inform his colleagues about his affair.

What should we make of this? Here's what I think. First, Claude did not blackmail its supervisor: That would require motivation and intent. This was a mindless and unpredictable machine, cranking out strings of words that look like threats but aren't.

Large language models are role-players. Give them a specific setup—such as an inbox and an objective—and they'll play that part well. If you consider the thousands of science fiction stories these models ingested when they were trained, it's no surprise they know how to act like HAL 9000.

Second, there's a huge gulf between contrived simulations and real-world applications. But such experiments *do* show that LLMs shouldn't be deployed without safeguards. Don't want an LLM causing havoc inside an email system? Then don't hook it up to one.

Third, a lot of people will be terrified by such stories anyway.

In fact, they're already having an effect.

Last month, around two dozen protesters gathered outside Google DeepMind's London offices to wave homemade signs and chant slogans: "DeepMind, DeepMind, can't you see! Your AI threatens you and me." Invited speakers invoked the AI pioneer Geoffrey Hinton's fears of human extinction. "Every single one of our lives is at risk," an organizer told the small crowd.

The group behind the event, Pause AI, is funded by concerned donors. One of its biggest benefactors is Greg Colbourn, a 3D-printing entrepreneur and advocate of the philosophy known as effective altruism, who believes AGI is at most five years away and says his p(doom) is around 90%—that is, he thinks there's a 9 in 10 chance that the development of AGI will be catastrophic, killing billions.

Pause AI wrote about Anthropic's blackmail experiment on its website under the title "How much more evidence do we need?"

The organization also lobbied politicians in the US in the run-up to July's Senate vote that ended up removing a moratorium on state AI regulation from the national tax and spending bill. It's hard to say how much sway one niche group might have. But the doomer narrative is finding its way into the halls of power, and lawmakers are paying attention.

Here's Representative Jill Tokuda: "Artificial superintelligence is one of the largest existential threats that we face right now." And Representative Marjorie Taylor Greene: "I'm not voting for the development of Skynet and the rise of the machines."

It's a vibe shift that favors policy intervention and regulation, which I think is a good thing. Existing AI systems pose many near-term risks that need government attention. Voting to stop Skynet also stops immediate and actual harms.

And yet does a welcome end justify weird means? I'd like to see politicians voting with a clear-eyed sense of what this technology really is—not because they've been sold on an AI bogeyman. ■

Sign up to get The Algorithm weekly in your inbox at technologyreview.com/algorithm.

PATRICK LEGER

Fossil-fueled failure: How US policy undermines our energy future

By James Temple



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

On a spring day in 1954, Bell Labs researchers showed off the first practical solar panels at a press conference in Murray Hill, New Jersey, using sunlight to spin a toy Ferris wheel before a stunned crowd.

The solar future looked bright. But in the race to commercialize the technology it invented, the US would lose resoundingly. Last year, China exported $40 billion worth of solar panels and modules, while America shipped just $69 million, according to the *New York Times*. It was a stunning forfeit of a huge technological lead.

And now the US seems determined to repeat the mistake. In its quest to prop up aging fossil-fuel industries, the Trump administration has slashed federal support for the emerging cleantech sector, handing his nation's chief economic rival the most generous of gifts: an unobstructed path to locking in its control of emerging energy technologies, and a leg up in inventing the industries of the future.

China's dominance of solar was no accident. In the late 2000s, the government simply determined that the sector was a national priority. Then it leveraged deep subsidies, targeted policies, and price wars to scale up production, drive product improvements, and slash costs. It's made similar moves in batteries, electric vehicles, and wind turbines.

Meanwhile, President Donald Trump has set to work unraveling hard-won clean-energy achievements in the US, snuffing out the momentum gathering to rebuild the nation's energy sector in cleaner, more sustainable ways.

The tax and spending bill that Trump signed into law in early July wound down the subsidies for solar and wind power contained in the Inflation Reduction Act of 2022. The legislation also cut off federal support for cleantech projects that rely too heavily on Chinese materials—a ham-fisted bid to punish Chinese industries that will instead make many US projects financially unworkable.

At the same time, the administration has slashed federal funding for science and attacked the financial foundations of premier research universities, pulling up the roots of future energy innovations and industries.

A driving motivation for many of these policies is the quest to protect the legacy energy industry based on coal, oil, and natural gas, all of which the US is geologically blessed with. But this strategy amounts to the innovator's dilemma playing out at a national scale—a country clinging to its declining industries rather than investing in the ones that will define the future.

It does not particularly matter whether Trump believes in or cares about climate change. The economic and international security imperatives to invest in modern, sustainable industries are every bit as indisputable as the chemistry of greenhouse gases.

Without sustained industrial policies that reward innovation, American entrepreneurs and investors won't risk money and time creating new businesses, developing new products, or building first-of-a-kind projects here. Indeed, venture capitalists have told me that numerous US climate-tech companies are already looking overseas, seeking markets where they can count on government support. Some fear that many other companies will fail in the coming months as subsidies disappear, developments stall, and funding flags.

All of which will help China extend an already massive lead.

The nation has installed nearly three times as many wind turbines as the US, and it generates more than twice as much solar power. It boasts five of the 10 largest EV companies in the world and the three largest wind turbine manufacturers. China absolutely dominates the battery market, producing the vast majority of the anodes, cathodes, and battery cells that increasingly power the world's vehicles, grids, and gadgets.

China has already harnessed the clean-energy transition to clean up its skies, upgrade its domestic industries, create jobs for its citizens, strengthen trade ties, and build new markets in emerging economies. Now it's using those business links to accrue soft power and extend its influence—all while the US turns its back on global institutions.

These widening relationships increasingly insulate China from external pressures, including those threatened by Trump's go-to tactic: igniting or inflaming trade wars.

But stiff tariffs and tough talk aren't what built the world's largest economy and established the US as the global force in technology for more than a century. What did was deep, sustained federal investment into education, science, and research and development—the very budget items that Trump and his party have been so eager to eliminate. ■

Sign up to get The Spark weekly in your inbox at technologyreview.com/spark.

PATRICK LEGER

I gave the police access to my DNA—and maybe some of yours

By Antonio Regalado



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

Last year, I added my DNA profile to a private genealogical database, FamilyTreeDNA, and clicked "Yes" to allow the police to search my genes.

In 2018, police in California announced they'd caught the Golden State Killer, a man who had eluded capture for decades. They did it by uploading crime-scene DNA to websites like the one I'd joined, where genealogy hobbyists share genetic profiles to find relatives and explore ancestry. Once the police had "matches" to a few relatives of the killer, they built a large family tree from which they plucked the likely suspect.

This process, called forensic investigative genetic genealogy, or FIGG, has since helped solve hundreds of murders and sexual assaults. Still, while the technology is potent, it's incompletely realized. It operates via a mishmash of private labs and unregulated websites, like FamilyTree, which give users a choice to opt into or out of police searches. The number of profiles available for search by police hovers around 1.5 million, not yet enough to find matches in all cases.

To do my bit to increase those numbers, I traveled to Springfield, Massachusetts. The staff of the local district attorney, Anthony D. Gulluni, was giving away free FamilyTree tests at a minor-league hockey game in an effort to widen its DNA net and help solve several cold-case murders. After glancing over a consent form, I spit into a tube and handed it back. According to the promotional material from Gulluni's office, I'd "become a hero."

But I wasn't really driven by some urge to capture distantly related serial killers. Rather, my spit had a less gallant and more quarrelsome motive: to troll privacy advocates whose fears around DNA I think are overblown and unhelpful. By giving up my saliva for inspection, I was going against the view that a person's DNA is the individualized, sacred text that privacy advocates sometimes claim.

Indeed, the only reason FIGG works is that relatives share DNA: You share about 50% with a parent, 25% with a grandparent, about 12.5% with a first cousin, and so on. When I got my FamilyTree report back, my DNA had "matched" with 3,309 people.

Some people are frightened by FIGG or reject its punitive aims. One European genealogist I know says her DNA is kept private because she opposes the death penalty and doesn't want to risk aiding US authorities in cases where lethal injection might be applied. But if enough people share their DNA, conscientious objectors won't matter. Scientists estimate that a database including 2% of the US population, or 6 million people, could identify the source of nearly any crime-scene DNA, given how many distant relatives each of us has.

Scholars of big data have termed this phenomenon "tyranny of the minority." One person's voluntary disclosure can end up exposing the same information about many others. And that tyranny can be abused.

DNA information held in private genealogy websites like FamilyTree is lightly guarded by terms of service. These agreements have flip-flopped over time; at one point all users were included in law enforcement searches by default. Rules are easily ignored, too. Recent court filings indicate that the FBI, in its zeal to solve crimes, sometimes barges past restrictions to look for matches in databases whose policies exclude police.

"Noble aims; no rules" is how one genetic genealogist described the overall situation in her field.

My uncertainty grew the more questions I asked. Who even controls my DNA file? That's not easy to find out. FamilyTree is a brand operated by another company, Gene by Gene, which in 2021 was sold to a third company, MyDNA—ultimately owned by an Australian mogul whose name appears nowhere on its website. When I reached FamilyTree's general manager, the genealogist Dave Vance, he told me that three-quarters of the profiles on the site were "opted in" to law enforcement searches.

One solution holds that the federal government should organize its own national DNA database for FIGG. But that would require new laws, new technical standards, and a debate about how our society wants to employ this type of big data—not just getting individual consent like mine.

No such national project—or consensus—exists. I'm still ready to join a national crime-fighting database, but I regret doing it the way I did—spitting in a tube on the sidelines of a hockey game and signing a consent form that affects not just me but all my thousands of genetic relatives. To them, I say: Whoops. Your DNA; my bad. ■

Sign up to get The Checkup weekly in your inbox at technologyreview.com/checkup.

PATRICK LEGER

MIT Technology Review

Upgrade your experience. Elevate your knowledge.



Unlock the best of what MIT Technology Review has to offer with our new Premium Subscription.

	Digital + Print Subscription	Premium Subscription
6 Digital + Print issues each year	✓	✓
Unlimited access to our website and mobile app	✓	✓
Exclusive access to the magazine archives	✓	✓
Access to subscriber-only Roundtables events	✓	✓
In-depth Digital Research Reports		✓
Exclusive insights from our Editor in Chief		✓
30% off tickets to our signature events		✓
1 free Digital Subscription to share		✓
50% off additional gift subscriptions		✓
A free welcome gift (branded tote bag)		✓

Expand your perspective. Upgrade to Premium today and save 25%.

Scan here to learn more
or visit **TechnologyReview.com/Upgrade**

Are we safe?

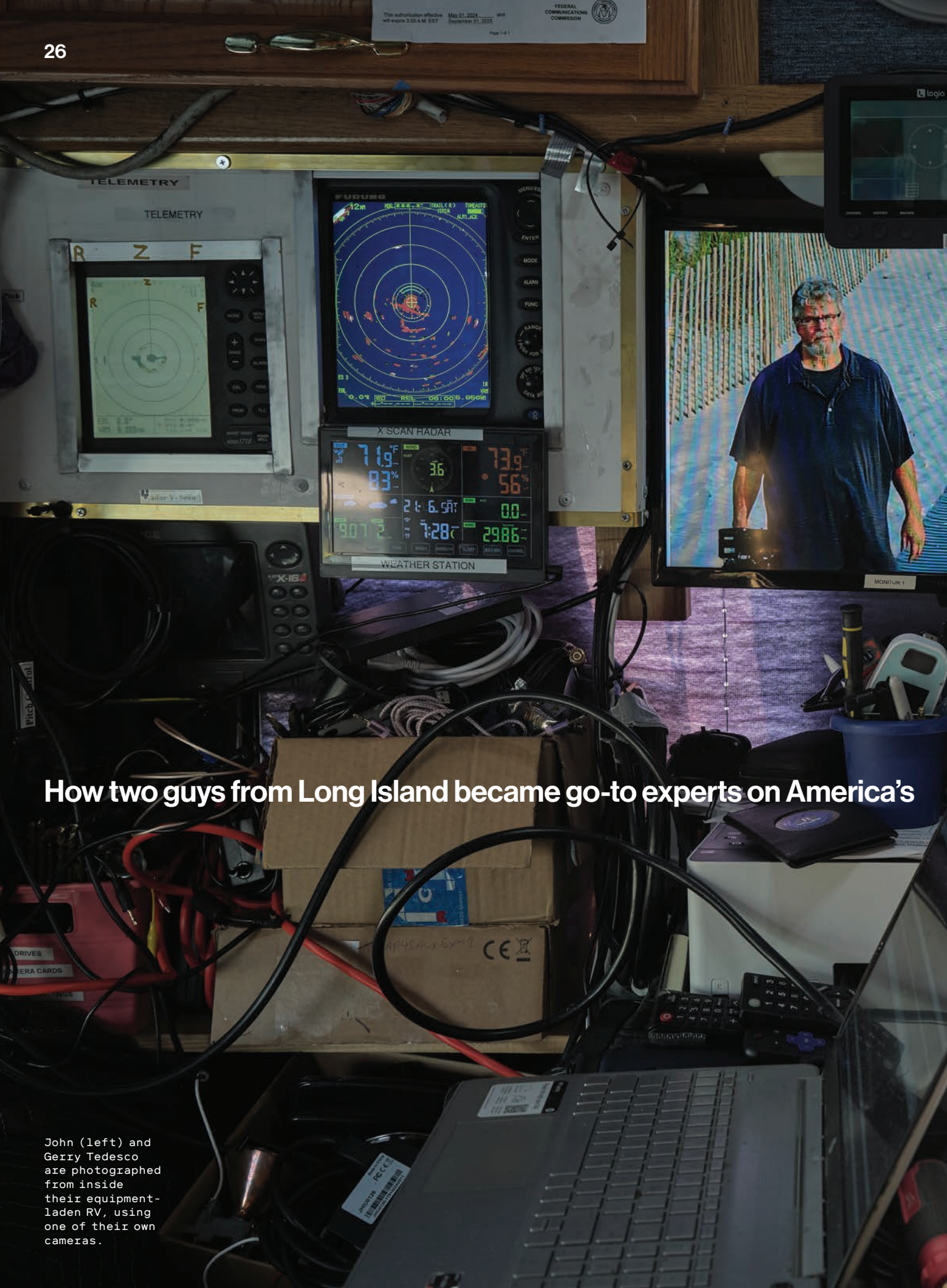
SEPTEMBER/OCTOBER 2025

Security can mean national defense, but it can also mean control over data, safety from intrusion, and so much more. This issue explores the way technology, mystery, and the universe itself affect how secure we feel in the modern age.



Domestic law enforcement officials have turned to an unlikely source for help in tracking and identifying mystery drones: UFO hunters John and Gerald Tedesco. Story on p. 26.

MARCO GIANNAVOLA



How two guys from Long Island became go-to experts on America's

John (left) and Gerry Tedesco are photographed from inside their equipment-laden RV, using one of their own cameras.



The drone brothers

“mystery drone” invasion. By Matthew Phelan

PHOTOGRAPHS BY MARCO GIANNAVOLA

On a Friday evening last December, every tier of US law enforcement—federal, state, and local—was dispatched to the US Army Natick Soldier Systems Center, a military research installation outside Boston. A squadron of about 15 to 20 drones had been spotted violating the base's restricted airspace. The culprits could not be found.

One retired major with the Massachusetts State Police, who had been dispatched to help investigate that night, called these unidentified aircraft "the strangest thing he's ever seen," according to Brian Lauzon, deputy chief of Natick's municipal police department. When Lauzon arrived on base later that weekend, he says, he saw drones that were larger than traditional consumer models (most of which are pre-programmed to respect US military airspace these days anyway). By the end of this weekend-long breach, base police not only had called in local law enforcement for backup but were coordinating with the FBI and US Army commanders as well.

The event, which barely made local news, was only the latest in a series of purported drone sightings along the US East Coast that November and December. Most of these happened in New Jersey, where military police confirmed at least 11 unauthorized drone incursions over an Army research and arms-manufacturing facility, Picatinny Arsenal. Further sightings, including cases above Donald Trump's golf course in nearby Bedminster, prompted an FBI investigation and a flurry of new FAA-issued flight bans over sensitive sites, including critical infrastructure. But official answers were less forthcoming.

"It created a lot of hysteria in the general public," Lauzon recalls. "I was talking to old ladies who're telling me that there's this ship in the ocean that's launching hundreds of these at a time across the United States." One Republican congressman from New Jersey did, in fact, claim that a militarized drone ship from Iran had launched the invaders, despite Pentagon denials. Lauzon remembers fielding myriad calls from civilians who had misidentified passenger jets as hostile drones. He recalls attending one presentation by an FBI expert in uncrewed aircraft systems who showed police unhelpful scare videos of improvised drone strikes in Ukraine, in which tiny aircraft rained grenades down on bloodied soldiers.

By late January, the incoming Trump administration would assert that the entirety of the New Jersey drone wave had been benign, with each and every UAS "authorized to be flown by the FAA for research and various other reasons." Their surety, however, stood in stark contrast to the warnings from top military brass, including the Air Force general at the head of NORAD, Gregory Guillot. In February, he testified to the Senate that approximately 350 drone incursions had been reported over a hundred different US military installations in 2024 alone, stating that many of these cases were unsolved, albeit with "evidence of a foreign intelligence nexus in some of these incidents."

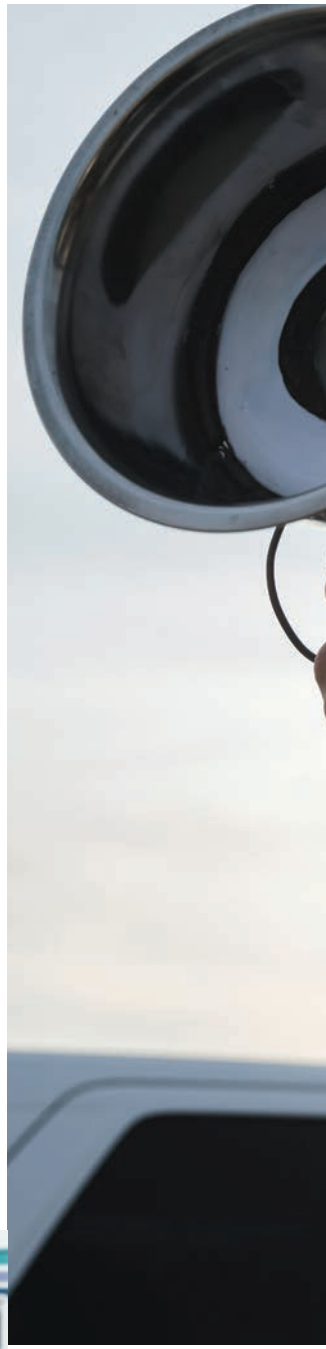
Lacking better coordination, or much clarity from the White House, the Pentagon, or the US intelligence community, some in domestic law enforcement—including members of the FBI's counterintelligence and counterterrorism divisions—have turned to an unlikely source for help cracking the case of these mystery drones: two UFO hunters out on Long Island in New York, John and Gerald Tedesco.

The Tedescos, twin brothers, each spent about three decades in the private sector working in electrical engineering and instrumentation design before they decided to kit out an old RV with an array of homemade signals collection equipment. Their aim was to create a mobile field lab for investigating UFO hot spots. Intrigued by their efforts, members of Harvard's alien-hunting Galileo Project began talking with the Tedescos in 2021 and asked them to join as research affiliates. Since then, aviation safety advocates, astronomers, physicists and other researchers, and at least one journalist (I, myself) have made the trek out to Long Island's South Shore to kick the tires on the roving aerial surveillance unit they've dubbed "the Nightcrawler."

Chris Grooms, an Iraq and Afghanistan war veteran who was a deputy sheriff in Nebraska during an earlier multistate wave of mystery drone sightings from December 2019 to January 2020, gushed when I asked him about the Tedescos: "I don't know how much you've talked to those guys. They're freaking awesome."

Grooms joined the Tedescos last January, when the brothers publicly shared some of their findings from





Left:
A homemade multispectral camera.

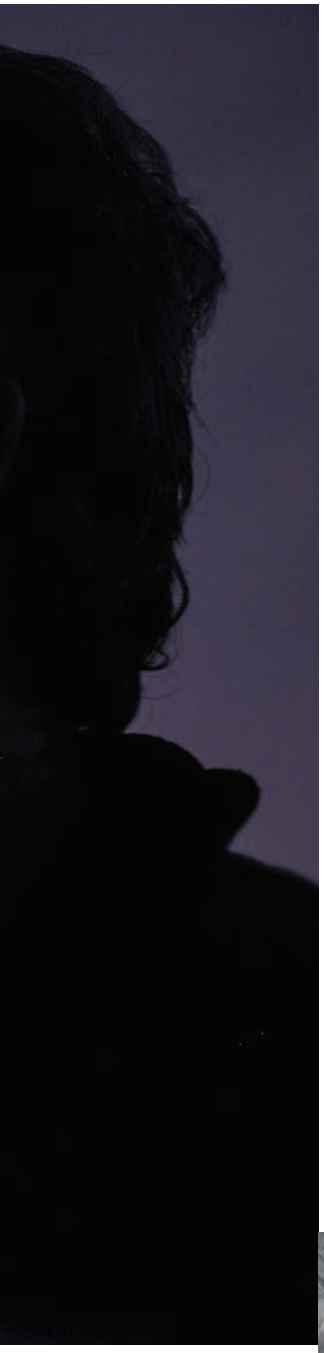
Above:
John uses a homemade millimeter-wave radar device.



The Tedescos' roving aerial surveillance unit, which they've dubbed "the Nightcrawler," is an old RV equipped with an array of homemade signals collection equipment.



John drained most of his 401(k) to make the Nightcrawler project a reality, in a five-year labor of love.



Above: Gerry looks through a night-vision scope at the horizon.

Right: Another homemade multispectral camera.

training the Nightcrawler's sensors on a few of these unidentified drones. "They do look like commercial air traffic for the most part," John said during the virtual town hall, moderated by a former Illinois state police lieutenant, "but they also exhibit unexplained or unusual phenomena."

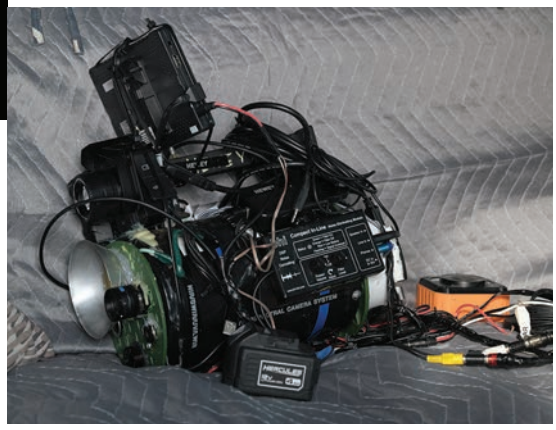
As an example, the Tedescos described some cases they had documented and passed along to law enforcement, in which they caught a mystery drone appearing to go dark to evade closer observation (a common complaint from New Jersey police during the wave). Using their suite of cameras and sensors, which can handle light well outside the visible spectrum, the Tedescos discovered that these craft weren't so much switching off their lights as switching the frequency of their lights.

"It wasn't actually disappearing," Gerald (who goes by Gerry) explained. "It was actually changing its spectral signature—it was drifting into an infrared range."

John likened it to "signature management," a military term for the ability to tailor anything from radio emissions to light sources so that they remain detectable to one's allies but undetectable to one's foes. The clue, which likely would have been lost to police without the Tedescos' broad range of infrared sensors, was not unlike the kind of citizen-science fieldwork that had gotten them on the radar of academia's UFO hunters in the first place.

Why all this attention? As people have repeatedly learned and forgotten ever since airborne enigmas like the flying saucer first entered into the American public consciousness in 1947, simple photos and video are frustratingly inconclusive evidence in isolation. Even heat-sensing infrared footage of UFOs—like those taken by US Navy pilots training off the Pacific and Atlantic coasts—has failed to prove that anything truly unusual is in our skies.

What the Tedescos appear to have done, in their effort to bring a fully maximalist approach to the sensors directed at these suspected alien spacecraft, is independently engineer the kind of aerial surveillance capability rarely seen outside the classified world.



For domestic law enforcement and the general public, two communities lacking the requisite national security clearances, the Tedescos' work promises a transparent, open-source solution to the past several years' worth of bizarre and troubling drone incursions into US airspace. For academics hunting for UFOs and other aerial anomalies, the Tedescos have become informal collaborators and a font of new ideas for novel data collection equipment. But for better or worse, some of the secrets they might be revealing may be the government's own.

Inside the Nightcrawler

The term "UFO" has officially gone out of fashion. Nowadays, many policymakers and scientists—and even plenty of old-school "ufologists"—favor the term "unidentified anomalous phenomenon," or UAP. It's an intentionally pedantic step backward; an acknowledgment from today's more disciplined cadre of scientists that a given witness to a strange thing in the sky might not actually be seeing a solid "object," per se, much less anything "flying" in the strict aerodynamic sense. It could be a poorly understood atmospheric event, like ball lightning, for example; and even if a UAP proves to be an interstellar craft, its propulsion system could involve physics and engineering that render the concept of "flight" quaint.

Ryan Graves, a former US Navy lieutenant and F/A-18F fighter pilot who testified before Congress on the safety and security risks that UAPs posed to his own squadron, now heads a committee on the issue for the American Institute of Aeronautics and Astronautics, the nation's premier society for aerospace engineers. He went out with his AIAA colleagues to see the Nightcrawler in September 2024.

"It's incredible what they've been able to put together," Graves says, praising the Tedescos' ability to collect "very actionable data."

Gerry once held a security clearance to develop reconnaissance, surveillance, and target acquisition sensors for a Pentagon contractor. John has helped conceive and construct analytical test hardware for Underwriters Laboratories, a federally approved safety, testing, and certification firm, and served for a time as the product safety chair for the Long Island branch of the Institute of Electrical and Electronics Engineers. John drained most of his 401(k) to make the Nightcrawler project a reality, in a five-year labor of love; Gerry has pitched in what he could. Both men, now sliding through their early 60s, have been fascinated with the possibility of

intelligent life elsewhere in the universe since their youth ingesting midcentury sci-fi staples like *Star Trek, Chiller Theatre*, and *Lost in Space.*

I got my first tour of their rig during an overnight expedition just off the beach at Robert Moses State Park in Babylon, New York, the weekend before the AIAA's trip last fall. A klatch of camping chairs and cameras on tripods flanked one side of the Nightcrawler like a tailgate party. Inside, the lived-in kitchenette, the wood paneling, and the hum of over half a dozen monitors—including radar, night-vision, and radio-frequency (RF) scanners—made it feel like the cabin of a cramped marine research vessel.

The RV includes tech that is otherwise hard to find outside defense applications, including RF spectrum analyzers from a firm that specializes in elite anti-drone countermeasures and a UV-C sensor capable of detecting the subtle ultraviolet light emitted when missile plumes and other heat sources turn air into plasma. On the Nightcrawler's roof, two X-band marine radar systems have been mounted perpendicularly to one another in hopes of collecting three-dimensional radar returns from truly otherworldly UAPs. ("To our knowledge," as the Tedescos put it in an engineering journal article last year, "no other organizations use active radar for this purpose.")

Civilians are not ordinarily allowed to beam active radar, owing to federal concerns over "harmful interference" with core systems like air traffic control. But in January 2023, the duo got a rare license from the Federal Communications Commission that permits them to beam radar from Robert Moses.

One prototype I saw, a multispectral camera mounted on a sturdy yellow DeWalt surveyor's tripod, looked like a Gatling gun of multiple cameras and electromagnetic frequency (EMF) sensors. This jerry-rigged device spans the entire visible spectrum and beyond, from deep invisible ultraviolet all the way up to long-wave infrared. They've used the UV-C sensor to detect aerial plasmas produced by lightning or those novelty arc-welder cigarette lighters. "We've done this as far as a half a mile, but if you had a campfire, they could detect campfires from 28,000 feet," John told me over the noise coming from the Nightcrawler's gas-powered electric generator. They've also been able to use this device to detect, at least provisionally, telltale UV-C emissions from some weird things off the coast they can't explain.

"We had two blue orbs out on the water," John told me of their UAP cases, "and they triggered it, what, three times?" ("Three times," Gerry replied.)



Mapping out mile markers on a screen where sightings are compared with commercial air traffic data.

The Tedescos are pretty bullish on the hypothesis that otherworldly spacecraft might be here—suggesting in their latest journal article, for example, that radar delays they detected near UAPs appear to resemble the bending of electromagnetic waves around black holes. But the implication that the Nightcrawler has caught "gravitational lensing" off some warp-drive craft has rankled a few Galileo Project collaborators. The Harvard-led effort to search for extraterrestrial life or technology within our solar system emphasizes its excruciatingly methodical work: calibrating, validating, and recalibrating UAP detection hardware before researchers even try to hunt for true anomalies. Although Galileo scientists have visited and conferred with the Tedescos on UAP-hunting instruments, the brothers' more rough-and-courtroom-ready "forensic science" approach has caused turbulence in the relationship.

In an email, Mitch Randall, a technologist and entrepreneur who has spearheaded Galileo efforts to produce passive radar detectors for UAPs, described the Tedescos' "gravitational lensing" paper as rife with "too many assumptions."

But he did praise their Nightcrawler as "an ideal tool" for aiding law enforcement. "They could drive around with that and almost chase down drones," Randall said.

On the hunt

Ultimately, the Tedescos didn't have to drive the Nightcrawler far to train their equipment on a prime mystery drone case: Westhampton Beach's Francis S. Gabreski Airport, less than an hour from their homes and home itself to the New York Air National Guard's 106th Rescue Wing, was inundated with at least 28 unauthorized drone flights from late December into January 2025.

"We are talking about over the airport, over taxiways, over runways," Suffolk County's chief deputy sheriff, Chris Brockmeyer, told local news. "That's a serious safety concern. It's impacted air operations, and we're not going to stand for it." On Christmas Day alone, the airport was besieged by 17 drone incidents, according to the Suffolk County sheriff, who has staff that collaborate informally with the Tedescos. Some of these drones, Suffolk County executive Ed Romaine asserted at a press conference, were "as large as a car."

The Tedescos couldn't use their powerful active radar system so close to an airport, so they deployed their handheld millimeter-wave radar, a more sensitive version of the radar guns that police use to catch speeders. Through the cloud cover and the snowfall, the Tedescos said, they were able to track about two or three objects with this device.

The Tedescos say the straight lines in these anomalous radar readings indicate that something could have been jamming their radar signal.



But the truly interesting find came from their radio frequency scanners, which detected spikes three times the strength of what they've picked up from ordinary hobbyist quadcopters.

I later learned that the two frequencies where those spikes occurred are within a band (1780 to 1850 megahertz) that has been reserved for US government communications. It's used for military tactical radio relay, precision-guided munitions, drones, and other Defense Department systems, including electronic warfare, software-defined radio, and tactical targeting networking technology, according to the FCC.

Granted, many portions of this band are devoted to less cloak-and-dagger agencies, like the Department of Agriculture and the Tennessee Valley Authority. But the signals suggested that whatever the Tedescos were tracking above Gabreski Airport, they were likely not from hobbyists. Instead, they might have been from a government project or from something, like an enemy surveillance drone, hoping to pass off its signals as just another heavily siloed "top secret" broadcast.

"For operations security reasons, we do not provide information on frequencies which our Air National Guard units use," a spokesperson said via email, adding: "We could not comment on use of the electromagnetic spectrum by other government agencies." The FCC did not respond to requests for comment.

Gerry says he and his brother passed their information on this case, including the observations of unusual radio frequency spikes, along to the FBI. "We're working closely with the FBI," John says. Gerry adds, "We gauge it by their interest level in what we're doing."

"When they get more enthusiastic," he continues, before John finishes his thought: "… we know we're closer and closer to something."

It's hard to know exactly what the FBI does with the information that the Tedescos submit; one Freedom of Information Act request that I filed on their work was returned with 24 out of 28 total pages redacted in their entirety. A consistent justification was the FOIA statute's b(7)E exemption, which permits withholding sensitive FBI "techniques and procedures" that could help criminals circumvent the law.

Nevertheless, one senior-level law enforcement official, who has worked with the FBI on counterterrorism cases, did tell me that "the FBI is genuinely interested in the Tedescos' work." The official, whose current police role bars them from speaking publicly without prior approval, recalls speaking to an FBI agent who "alluded to the help that the Tedescos have been." But the problem, the official continued, is that "for the relationship to work, it has to be very low-key."

When I did briefly manage to get one of the Tedescos' FBI collaborators on the phone, the agent seemed to confirm their shared efforts, at least tacitly, but asked not to be identified. "As much as I'd like to, we're kept to pretty strict guidelines," they said, before alluding to the new Trump administration's pervasive personnel cuts. "We're not allowed to talk to media—and with how things are right now, I'm not going to take any risks."

At least one former Pentagon intelligence official did offer me some indication that the brothers' Gabreski airport discoveries were on the right track. "From what I've seen, these incidents are just that: drones," said this source, who requested anonymity as a current defense contractor and to protect their own active FBI sources, including UAP and drone incursion investigators who have consulted the Tedescos. "The origin of many is likely known, and I'd say some are certainly ours."

As to the mystery of why the FBI would even want investigative assistance from two civilians in an RV over partners within the executive branch, it comes down to conflicting priorities—as well as over a dozen or so laws that restrict domestic intelligence collection on drones by either the Pentagon or the US intelligence community. "It's one of those irreconcilable problems that just doesn't go away," says Fred Manget, a former deputy general counsel for the CIA, who watched problems of coordination between agencies persist even after policy changes were implemented post-9/11 to address the situation.

The desire of the NSA or some other agency to spy on foreign powers, Manget says, might override the desire to share pertinent information with police—information that could lead to jail time for the drones' operators. Better to quietly monitor the drones and maybe even give out false data. "Signals intelligence a lot of times can be closed off if the target finds out they're being surveilled electronically," Manget says. "There's things they can do that will end NSA's ability to collect."

On my short call with my FBI source, I did my best to explain this working hypothesis about the Bureau's collaboration with the Tedescos. "I wouldn't say that's wrong," the source replied. "That's about as far as I could go." By this past June, however, even the recent head of the Pentagon's dedicated UAP-hunting group, the All-domain Anomaly Resolution Office (AARO), was admitting publicly that the Defense Department itself has cribbed notes from the Tedescos.

"We read their book," Tim Phillips, AARO's former acting director, told a UAP podcast, referring to an account of the Nightcrawler project that the Tedescos self-published in 2024. "We thought it was a great plan. We actually looked at the sensors in that book."

On another podcast, Phillips said AARO's own plan to make its UAP-hunting hardware mobile was borrowed from the brothers. "We thought that was brilliant."

Tools for law enforcement

Earlier this year, partially in a concession to the economic toll their side project has taken, the Tedescos started offering versions of some of their devices for sale on the Nightcrawler's charmingly GeoCities-esque home page. One of them, a handheld multispectral detector, is effectively the consumer model of that EMF Gatling gun they showed me.

Domestic law enforcement is genuinely grasping for solutions like this. Local police in the Natick case, according to one report I obtained via an open records request, were so desperate for any kind of new intel on these unidentified drones that they borrowed a thermal imaging camera from their town's fire department. But the device, which was not purpose-built for imaging distant aerial objects, failed to collect anything useful.

When I broached the idea of law enforcement using something like the Tedescos' equipment, the answer from police who had witnessed these mystery drones, as well as from scientists, was that further design, product testing, and training would be required first. "I could see it helping law enforcement," said the AIAA UAP team's consulting physicist, Rex Groves, "but not without training. Absolutely not. Just like they have to be trained with a radar gun, they'd have to be trained with these other tools."

Lauzon, Natick's deputy chief of police, told me that while he thought equipment like the Tedescos' "could be useful to identifying a drone, particularly at night," the real problem is that police "don't have a lot of authority when it comes to these drones." Unless they manage to find operators on the ground, Lauzon said, all they can do is report the case, sending it into a black hole at the FAA.

But Michael Lembeck, an aerospace engineering professor and member of the AIAA team, emphasizes that the worst thing law enforcement can do with these drone incursions right now is nothing at all.

"We're seeing anomalies in our airspace and we're just normalizing that, because it happens so often and nothing bad has happened yet," Lembeck told me. "Eventually, something is going to come home to roost—and then we're going to regret the fact that we didn't look deeper and try to understand what was going on." ■

Gerry naps and John looks at readings from the multispectral camera at about 5 a.m., with the moon and Venus visible overhead.

Matthew Phelan is a reporter and former chemical engineer based in upstate New York.



Coming soon to the national security cinematic universe

President Trump has proposed building an antimissile "Golden Dome" around the United States, a concept that seems right out of a movie. But do cinematic spectacles actually enhance national security?

By Becky Ferreira

Illustrations by Shout




M

In 1940, a fresh-faced Ronald Reagan starred as US Secret Service agent Brass Bancroft in *Murder in the Air,* an action film centered on a fictional "superweapon" that could stop enemy aircraft midflight. A mock newspaper in the movie hails it as the "greatest peace argument ever invented." The experimental weapon is "the exclusive property of Uncle Sam," Reagan's character declares.

More than 40 years later, this cinematic vision—an American superweapon capable of neutralizing assaults and ushering in global peace—became a real-life centerpiece of Reagan's presidency. Some have suggested that Reagan's Strategic Defense Initiative (SDI), a quixotic plan for a space-based missile shield, may have been partly inspired by his silver-screen past; indeed, the concept was so fantastical it's now better known by its Hollywood-referencing nickname, "Star Wars."

In January 2024, Donald Trump revived the space-shield dream at a primary campaign rally in Laconia, New Hampshire, using the Star Wars nickname that Reagan hated. It didn't work in the 1980s, Trump said, because the technology wasn't there. But times have changed.

"I've seen so many things. I've seen shots that you wouldn't even believe," Trump said. He acted out a scene of missile defense experts triangulating the path of an incoming weapon. "Ding, ding, ding, ding," he said, as he mimed typing on a keyboard. "Missile launch? *Psshing!!*" He raised his hand to indicate the rising missile, then let it fall to signal the successful interception: "Boom."

Trump has often expressed admiration for Israel's Iron Dome, an air defense system that can intercept short-range rockets and artillery over the small nation and that is funded in part by the United States. At the rally, he pledged to "build an Iron Dome over our country, a state-of-the-art missile defense shield made in the USA… a lot of it right here in New Hampshire, actually."

Within a week of his inauguration, President Trump began working toward this promise by issuing an executive order to develop "The Iron Dome for America," which was rebranded the "Golden Dome" a month later. The eruption of a revived conflict between Israel and Iran in June—including Trump's decision to strike Iran's nuclear facilities—has only strengthened the case for an American version of the Iron Dome in the eyes of the administration.



CHIP SOMODEVILLA/GETTY IMAGES

The Golden Dome has often been compared to SDI for its futuristic sheen, its aggressive form of protection, and its reflection of the belief that an impenetrable shield is the cheat code to global peace. Both efforts demonstrate the performative power of spectacle in defense policy, especially when wielded by deft showmen like Reagan and Trump. Whether in Golden Age Hollywood or Trump's impromptu dramatizations, the dream of a missile shield is animated by its sheer cinematic allure, often rendered in deceptively simple concept art depicting a society made immune to catastrophic strikes.

But in the complicated security landscape confronting the world today, is spectacle the same as safety?

"Missile defense is an area where facts and fiction blend," says Anette Stimmer, a lecturer in international relations at the University of St Andrews who has researched SDI. "A lot is up to interpretation by all the actors involved."

Trump's view is simple: Space is as much a warfighting domain as land, air, and ocean, and therefore the US must assert its dominance there with advanced technologies. This position inspired the creation of the US Space Force in his first term, and Trump has now

redoubled his efforts with the ongoing development of the Golden Dome.

General Michael Guetlein, who Trump has appointed to lead the Golden Dome project, argued that America's foes, including China and Russia, have forced the nation's hand by continually pushing limits in their own weapons programs. "While we have been focused on peace overseas, our adversaries have been quickly modernizing their nuclear forces, building out ballistic missiles capable of hosting multiple warheads; building out hypersonic missiles capable of attacking the United States within an hour and traveling at 6,000 miles an hour; building cruise missiles that can navigate around our radar and our defenses; and building submarines that can sneak up on our shores; and, worse yet, building space weapons," Guetlein said in May.

"It is time that we change that equation and start doubling down on the protection of the homeland," he said. "Golden Dome is a bold and aggressive approach to hurry up and protect the homeland from our adversaries. We owe it to our children and our children's children to protect them and afford them a quality of life that we have all grown up enjoying."

With that vision in mind, Trump's executive order outlines a host of goals for missile defense, some of which support bipartisan priorities like protecting supply chains and upgrading sensor arrays. The specific architecture of the Golden Dome is still being hammered out, but the initial executive order envisions a multi-tiered system of new sensors and interceptors—on the ground, in the air, and in space—that would work together to counter the threat of attacks from ballistic, hypersonic, and cruise missiles. The system would be coordinated in part by artificial-intelligence models trained for real-time threat detection and response.

The technology that links the Golden Dome directly to SDI hinges on one key bullet point in the order that demands the "development and deployment of proliferated space-based interceptors capable of boost-phase intercept." This language revives Reagan's dream of deploying hundreds of missile interceptors in orbit to target missiles in the boost phase right after liftoff, a window of just a few minutes when the projectiles are slower and still near the attacker's territory.

Space weapons are an attractive option for targeting the boost phase because interceptors need to be close enough to the launching missile to hit it. If a nation fired off long-range missiles from deep in its territory, the nearest ground- or air-based interceptors could be thousands of miles from the launch site. Space interceptors, in contrast, would be just a few hundred miles overhead of the ascending missiles, allowing for a much faster reaction time. But though the dream of boost-phase interception dates back decades, these maneuvers have never been operationally demonstrated from ground, air, or space.

"It's a really hard problem that hasn't been solved," says Laura Grego, senior scientist and research director at the Union of Concerned Scientists' global security program.

Whether in Golden Age Hollywood or Trump's impromptu dramatizations, the dream of a missile shield is animated by its sheer cinematic allure.

The US is currently protected by the Ground-Based Midcourse Defense (GMD), which consists of 44 interceptor missiles split between bases in Alaska and California, along with a network of early-warning sensors on the ground, at sea, and in orbit. Tests suggest that the GMD would have about a 50% success rate at intercepting missiles.

Initiated by President Bill Clinton in the late '90s and accelerated by President George W. Bush in the 2000s, the GMD is intended mainly to defend against rogue states like North Korea, which has nuclear weapons and intercontinental ballistic missiles (ICBMs) capable of reaching the US. A secondary focus is Iran, which does not currently have a nuclear weapon or ICBMs. Still, the GMD is built to anticipate a possible future where it develops those capabilities.

The GMD is not designed to protect the US from the sort of large-scale and coordinated missile attacks that Russia and China could lob across the world. The Bush administration instead favored a focus on strategic deterrence with these peer nations, an approach that the Obama and Biden administrations continued. In addition to the GMD, the Pentagon and its international partners maintain regional defense systems to counter threats in conflict hot spots or attacks on critical infrastructure. All these networks are designed to intercept missiles during their midcourse cruise phase, as they hurtle through the sky or space, or during their terminal or reentry phase, as they approach their targets. The GMD has cost upward of $63 billion since it was initiated, and the US spends about an additional $20 billion to $30 billion annually on its array of other missile defense systems.

In May, Trump was presented with several design options for the Golden Dome and selected a plan with a price tag of $175 billion and a schedule for full deployment by the end of his term. The One Big Beautiful Bill, signed into law on July 4, approved an initial $24.4 billion in funding for it. Space technologies and launch access have become much more affordable since the 1980s, but many analysts still think the projected cost and timeline are not realistic. The Congressional Budget Office, a nonpartisan federal agency, projected that the cost of the space-based interceptors could total from $161 billion to $542 billion over the course of 20 years. The wide range can be explained by the current lack of specifics on those orbital interceptors' design and number.

Reintroducing the idea of space-based interceptors is "probably the most controversial piece of Golden Dome," says Leonor Tomero, who served as deputy assistant

secretary of defense for nuclear and missile defense policy in the Biden administration.

"There are a lot of improvements that we can and should make on missile defense," she continues. "There's a lot of capability gaps I think we do need to address. My concern is the focus on reviving Star Wars and SDI. It's got very significant policy implications, strategic stability implications, in addition to cost implications and technology feasibility challenges."

Indeed. Regardless of whether the Golden Dome materializes, the program is already raising geopolitical anxieties reminiscent of the Cold War era. Back then, the US had one main adversary: the Soviet Union. Now, it confronts a roiling multipolarity of established and nascent nuclear powers. Many of them have expressed dismay over the about-face on American missile defense strategy, which was previously predicated on arms reduction and deterrence.

"Here we are, despite years of saying we are not going to do this—that it is technically out of reach, economically unsustainable, and strategically unwise," Grego says. "Overnight, we're like, 'No, actually, we're doing it.'"

The fact that we "blew up that logic" will "have a big impact on whether or not the program actually succeeds in creating the vision that it lays out," she adds.



Russian and Chinese officials called the Golden Dome "deeply destabilizing in nature" in a joint statement in May, and North Korea's foreign ministry warned it could "turn outer space into a potential nuclear war field."

Reagan, by all accounts, believed that SDI would be the ultimate tool of peace for all nations, and he even offered to share the technology with the Soviet leader, Mikhail Gorbachev. Trump, in contrast, sees Golden Dome as part of his "America First" brand. He has lamented that past American leaders supported the development of other missile defense projects abroad while neglecting to build similar security measures for their own country. The Golden Dome is both an expression of Trump's belief that the world is leeching off America and a bargaining chip in negotiations toward a new power balance; Canada could be covered by the shield for free, he has said—in exchange for becoming the 51st state.

Trump has argued that America has been both demographically diluted by unchecked immigration and financially depleted by freeloading allied nations—undermining its security on both internal and external fronts. His first term's marquee promise to build a wall on the southern US border, paid for by Mexico, aimed to address the former problem. That administration did build more physical barriers along the border (though US taxpayers, not Mexico, footed the bill). But just as important, the wall emerged as a symbolic shorthand for tougher immigration control.

The Golden Dome is the second-term amplification of that promise, a wall that expands the concept of the "border" to the entire American airspace. Trump has projected an image of his envisioned space missile shield as a literal dome that could ward off coordinated attacks, including boost-phase interceptors from space and cruise- and terminal-phase interception by ground and air assets. When he announced the selected plan from the Resolute Desk in May, he sat in front of a mockup that depicted a barrage of incoming missiles being thwarted by the nationwide shield, depicted with a golden glow.

The Golden Dome's orbital interceptors are supposedly there to target the early boost phase of missiles on or near the launch site, not over the United States. But the image of a besieged America, repelling enemy fire from the heavens, provides the visual and cinematic idea of both threat and security that Trump hopes to impress on the public.

"This administration, and MAGA world, thinks about itself as being victimized by immigrants, government waste, leftist professors, and so on," says Edward Tabor Linenthal, a historian who examined public narratives about SDI in his 1989 book *Symbolic Defense: The Cultural Significance of the Strategic Defense Initiative*. "It's not much of a jump to be victimized by too many nations getting nuclear weapons."

Even in our era of entrenched political polarization, there is support across party lines for upgrading and optimizing America's missile defense systems. No long-range missile has ever struck US soil, but an attack would be disastrous for the nation and the world.

"We've come a long way in terms of missile defense," says Tomero. "There has been a lot of bipartisan consensus on increasing regional missile defense, working with our allies, and making sure that the missile defense interceptors we have work."

Trump has challenged that consensus with his reversion to the dream of a space shield. He is correct that SDI failed to materialize in part because its envisioned technologies were out of reach, from a financial and engineering standpoint, in the 1980s. But the controversy that erupted around SDI—and that tarnished it with the derisive name "Star Wars"—stemmed just as much from its potential geopolitical disruptiveness as from its fantastical techno-optimism.

"This idea of a missile shield, also back when Reagan proposed it, has a huge popular appeal, because who wouldn't want to be able to defend your country from nuclear weapons? It is a universal dream," says Stimmer. "It requires a bit more digging in and understanding to see that actually, this vision depends a lot on technological feasibility and on how others perceive it."

Reagan maintained a steadfast conviction that this shield of space-based interceptors would render nuclear weapons "impotent and obsolete," ushering in "world peace," as he said in his March 1983 speech announcing SDI. The doctrine of mutually assured destruction could be replaced by mutually assured survival, he argued.

But Gorbachev saw the space-based shield as an offensive weapon, since it would give the US a first-strike advantage. The imbalance, he warned, could spark a weapons race in space, a domain that had been spared from overt military conflicts. As a result, the initiative would only destabilize the world order and interrupt the progress of arms control and nuclear de-proliferation efforts.

Reagan's insistence on SDI as the only route to world peace may have blocked opportunities to advance that goal through more practical and cost-effective avenues, such as diplomacy and arms control. At the 1986 Reykjavik Summit, Reagan and Gorbachev came very close to an arms control agreement that might have eliminated all ballistic missiles and nuclear weapons. The sticking point was Reagan's refusal to give up SDI.

"It is not the Strategic Defense Initiative; it's a strategic defense ideology," says Linenthal. He mentions the famous metaphor used by J. Robert Oppenheimer, a central figure of the Manhattan Project, who compared the United States and the Soviet Union to "two scorpions in a bottle." Either scorpion could kill the other, but only at the probable cost of its own life.

Amid nuclear tensions, J. Robert Oppenheimer compared the US and the Soviet Union to "two scorpions in a bottle." Now there are many more scorpions.

Reagan felt a "tremendously powerful impetus" to escape Oppenheimer's metaphor, Linenthal noted: "It was a new kind of deliverance that would resolve it all. Of course, now there are many more scorpions, so it has to be a bigger bottle."

A true believer, Reagan never abandoned SDI in spite of cost overruns and public backlash. President Bill Clinton redirected the program in 1993 by shifting gears from global to regional missile defense, a focus that remained fairly consistent for decades—until Trump took center stage. Now, the Golden Dome has flipped that logic on its head, risking a possible escalation of military tensions in outer space.

Tomero describes a "nightmare scenario" in which adversaries attack the Golden Dome's space infrastructure, leaving the orbital environment filled with debris that renders the defense system, among countless other space assets, inoperable.

"Having a one-sided capability that is very threatening to our adversaries is obviously going to create very dangerous stability issues," she says. It could "lead to inadvertent escalation and miscalculation and, I think, lower the threshold to conflict and nuclear war."

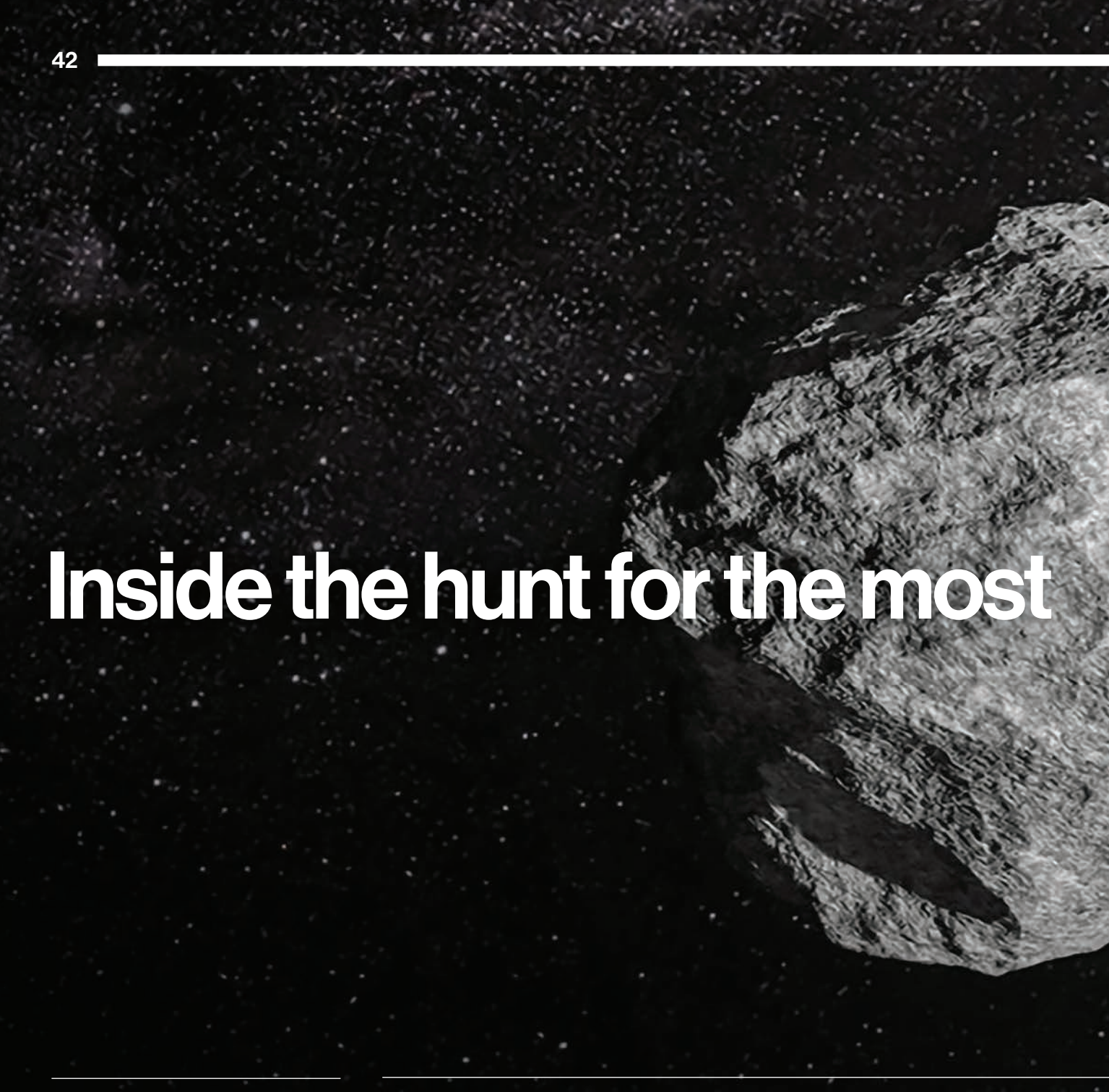
As president, Trump has channeled the boardroom antics that once resuscitated his celebrity status on *The Apprentice*. But armed adversaries, long wary of America's position on missile defense, don't have the luxury of wondering whether it's all real or just more stagecraft.

"What makes Trump so difficult to read for others is his unpredictability," Stimmer says. "This, just by itself, destabilizes things, because no one knows what he'll actually do."

Trump has described the Golden Dome as nearly impenetrable by missile attacks, evoking a clear symbolic return to an American golden age where we can all feel safe again.

"All of them will be knocked out of the air," as "the success rate is very close to 100%," he said at the project's official launch in May. "We will truly be completing the job that President Reagan started 40 years ago, forever ending the missile threat to the American homeland." ■

Becky Ferreira is a science reporter based in upstate New York, and author of First Contact, a book about the search for alien life, which will be published in September.



Inside the hunt for the most

As space rock 2024 YR4 became more likely to hit Earth than anything of its size had ever been before, scientists all over the world mobilized to protect the planet.

By Robin George Andrews
ILLUSTRATIONS BY EVA REDAMONTI

If you were told the probability that something would happen was 3.1%, it really wouldn't seem like much. But for the people charged with protecting our planet, it was huge.

On February 18, astronomers determined that a 130- to 300-foot-long asteroid had a 3.1% chance of crashing into Earth in 2032. Never had an asteroid of such dangerous dimensions been so likely to strike the planet. For those following this developing story in the news, the revelation was unnerving. For many scientists and engineers, though, it turned out to be—despite its seriousness—a little bit exciting.

While possible impact locations included patches of empty ocean, the space rock, called 2024 YR4, also had several densely populated cities in its possible crosshairs, including Mumbai, Lagos, and Bogotá. If the asteroid did in fact hit such a metropolis, the best-case scenario was severe damage; the worst case was outright, total ruin. And for the first time, a group of United Nations–backed researchers began to have high-level discussions about the

ESA-SCIENCE OFFICE



dangerous asteroid ever

fate of the world: If this asteroid was going to hit the planet, what sort of spaceflight mission might be able to stop it? Would they ram a spacecraft into it to deflect it? Would they use nuclear weapons to try to swat it away or obliterate it completely?

At the same time, planetary defenders all over the world crewed their battle stations to see if we could avoid that fate—and despite the sometimes taxing new demands on their psyches and schedules, they remained some of the coolest customers in the galaxy. "I've had to cancel an appointment saying, *I cannot come—I have to save the planet*," says Olivier Hainaut, an astronomer at the European Southern Observatory and one of those who tracked down 2024 YR4.

Then, just as quickly as history was made, experts declared that the danger had passed. On February 24, asteroid trackers issued the all-clear: Earth would be spared, just as many planetary defense researchers had felt assured it would.

How did they do it? What was it like to track the rising (and rising and rising) danger of this asteroid, and to ultimately determine that it'd miss us?

This is the inside story of how, over a span of just two months, a sprawling network of global astronomers found, followed, mapped, planned for, and finally dismissed 2024 YR4, the most dangerous asteroid ever found—all under the tightest of timelines and, for just a moment, with the highest of stakes.

"It was not an exercise," says Hainaut. This was the real thing: "We really [had] to get it right."

In the beginning

DECEMBER 27, 2024

THE ASTEROID TERRESTRIAL-IMPACT LAST ALERT SYSTEM, HAWAII—Long ago, an asteroid in the space-rock highway between Mars and Jupiter felt a disturbance in the force: the gravitational pull of Jupiter itself, king of the planets. After some wobbling back and forth, this asteroid was thrown out of the belt, skipped around the sun, and found itself on an orbit that overlapped with Earth's own.

"I was the first one to see the detections of it," Larry Denneau, of the University of Hawai'i, recalls. "A tiny white pixel on a black background."

Denneau is one of the principal investigators at the NASA-funded Asteroid Terrestrial-impact Last Alert System (ATLAS) telescopic network. It may have been just two days after Christmas, but as usual, he followed procedure as if it were any other day of the year and sent the observations of the tiny pixel onward to another NASA-funded facility, the Minor Planet Center (MPC) in Cambridge, Massachusetts.

There's an alternate reality in which none of this happened. Fortunately, in our timeline, various space agencies—chiefly NASA, but also the European Space Agency and the Japan Aerospace Exploration Agency—invest millions of dollars every year in asteroid-spotting efforts.

And while multiple nations host observatories capable of performing this work, the US clearly leads the way: Its planetary defense program provides funding to a suite of telescopic facilities solely dedicated to identifying potentially hazardous space rocks. (At least it leads the way for the moment. The White House's proposal for draconian budget cuts to NASA and the National Science Foundation means that several observatories and space missions linked to planetary defense are facing funding losses or outright termination.)

Astronomers working at these observatories are tasked with finding threatening asteroids before they find us—because you can't fight what you can't see. "They are the first line of planetary defense," says Kelly Fast, the acting planetary defense officer at NASA's Planetary Defense Coordination Office in Washington, DC.

ATLAS is one part of this skywatching project, and it consists of four telescopes: two in Hawaii, one in Chile, and another in South Africa. They don't operate the way you'd think, with astronomers peering through them all night. Instead, they operate "completely robotically and automatically," says Denneau. Driven by scripts that he and his colleagues have developed, these mechanical eyes work in harmony to watch out for any suspicious space rocks. Astronomers usually monitor their survey of the sky from a remote location.

ATLAS telescopes are small, so they can't see particularly distant objects. But they have a wide field of view, allowing them to see large patches of space at any one moment. "As long as the weather is good, we're constantly monitoring the night sky, from the North Pole to the South Pole," says Denneau.

If they detect the starlight reflecting off a moving object, an operator, such as Denneau, gets an alert and visually verifies that the object is real and not some sort of imaging artifact. When a suspected asteroid (or comet) is identified, the observations are sent to the MPC, which is home to a bulletin board featuring (among other things) orbital data on all known asteroids and comets.

If the object isn't already listed, a new discovery is announced, and other astronomers can perform follow-up observations.

In just the past few years, ATLAS has detected more than 1,200 asteroids with near-Earth orbits. Finding ultimately harmless space rocks is routine work—so much so that when the new near-Earth asteroid was spotted by ATLAS's Chilean telescope that December day, it didn't even raise any eyebrows.

Denneau had simply been sitting at home, doing some late-night work on his computer. At the time, of course, he didn't know that his telescope had just spied what would soon become a history-making asteroid—one that could alter the future of the planet.

The MPC quickly confirmed the new space rock hadn't already been "found," and astronomers gave it a provisional designation: 2024 YR4.

CATALINA SKY SURVEY, ARIZONA—Around the same time, the discovery was shared with another NASA-funded facility: the Catalina Sky Survey, a nest of three telescopes in the Santa Catalina Mountains north of Tucson that works out of the University of Arizona. "We run a very tight operation," says Kacper Wierzchoś, one of its comet and asteroid spotters. Unlike ATLAS, these telescopes (although aided by automation) often have an in-person astronomer available to quickly alter the surveys in real time.

So when Catalina was alerted about what its peers at ATLAS had spotted, staff deployed its Schmidt telescope—a smaller one that excels at seeing bright objects moving extremely quickly. As they fed their own observations of 2024 YR4 to the MPC, Catalina engineer David Rankin looked back over imagery from the previous days and found the new asteroid lurking in a night-sky image taken on December 26. Around then, ATLAS also realized that it had caught sight of 2024 YR4 in a photograph from December 25.

The combined observations confirmed it: The asteroid had made its closest approach to Earth on Christmas Day, meaning it was already heading back out into space. But where, exactly, was this space rock going? Where would it end up after it swung around the sun?

CENTER FOR NEAR-EARTH OBJECT STUDIES, CALIFORNIA—If the answer to that question was Earth, Davide Farnocchia would be one of the first to know. You could say he's one of NASA's watchers on the wall.

And he's remarkably calm about his duties. When he first heard about 2024 YR4, he barely flinched. It was just another asteroid drifting through space

If the asteroid did in fact hit such a metropolis, the best-case scenario was severe damage; the worst case was outright, total ruin.

not terribly far from Earth. It was another box to be ticked.

Once it was logged by the MPC, it was Farnocchia's job to try to plot out 2024 YR4's possible paths through space, checking to see if any of them overlapped with our planet's. He works at NASA's Center for Near-Earth Object Studies (CNEOS) in California, where he's partly responsible for keeping track of all the known asteroids and comets in the solar system. "We have 1.4 million objects to deal with," he says, matter-of-factly.

In the past, astronomers would have had to stitch together multiple images of this asteroid and plot out its possible trajectories. Today, fortunately, Farnocchia has some help: He oversees the digital brain Sentry, an autonomous system he helped code. (Two other facilities in Italy perform similar work: the European Space Agency's Near-Earth Object Coordination Centre, or NEOCC, and the privately owned Near-Earth Objects Dynamics Site, or NEODyS.)

To chart their courses, Sentry uses every new observation of every known asteroid or comet listed on the MPC to continuously refine the orbits of all those objects, using the immutable laws of gravity and the gravitational influences of any planets, moons, or other sizable asteroids they pass. A recent update to the software means that even the ever-so-gentle push afforded by sunlight is accounted for. That allows Sentry to confidently project the motions of all these objects at least a century into the future.

Almost all newly discovered asteroids are quickly found to pose no impact risk. But those that stand even an infinitesimally small chance of smashing into our planet within the next 100 years are placed on the Sentry Risk List until additional observations can rule out those awful possibilities. Better safe than sorry.

In late December, with just a limited set of data, Sentry concluded that there was a non-negligible chance 2024 YR4 would strike Earth in 2032. Aegis, the equivalent software at Europe's NEOCC site, agreed. No bother. More observations would very likely remove 2024 YR4 from the Risk List. Just another day at the office for Farnocchia.

It's worth noting that an asteroid heading toward Earth isn't always a problem. Small rocks burn up in the planet's atmosphere several times a day; you've probably seen one already this year, on a moonless night. But above a certain size, these rocks turn from innocuous shooting stars into nuclear-esque explosions.

Reflected starlight is great for initially spotting asteroids, but it's a terrible way to determine how big they are. A large, dull rock reflects as much light as a bright, tiny rock, making them appear the same to many telescopes. And that's a problem, considering that a rock around 30 feet long will explode loudly but inconsequentially in Earth's atmosphere while a 3,000-foot-long asteroid would slam into the ground and cause devastation on a global scale, imperiling all of civilization. Roughly speaking, if you double the size of an asteroid, it becomes eight times more energetic upon impact—so finding out the size of an Earth-bound asteroid is of paramount importance.

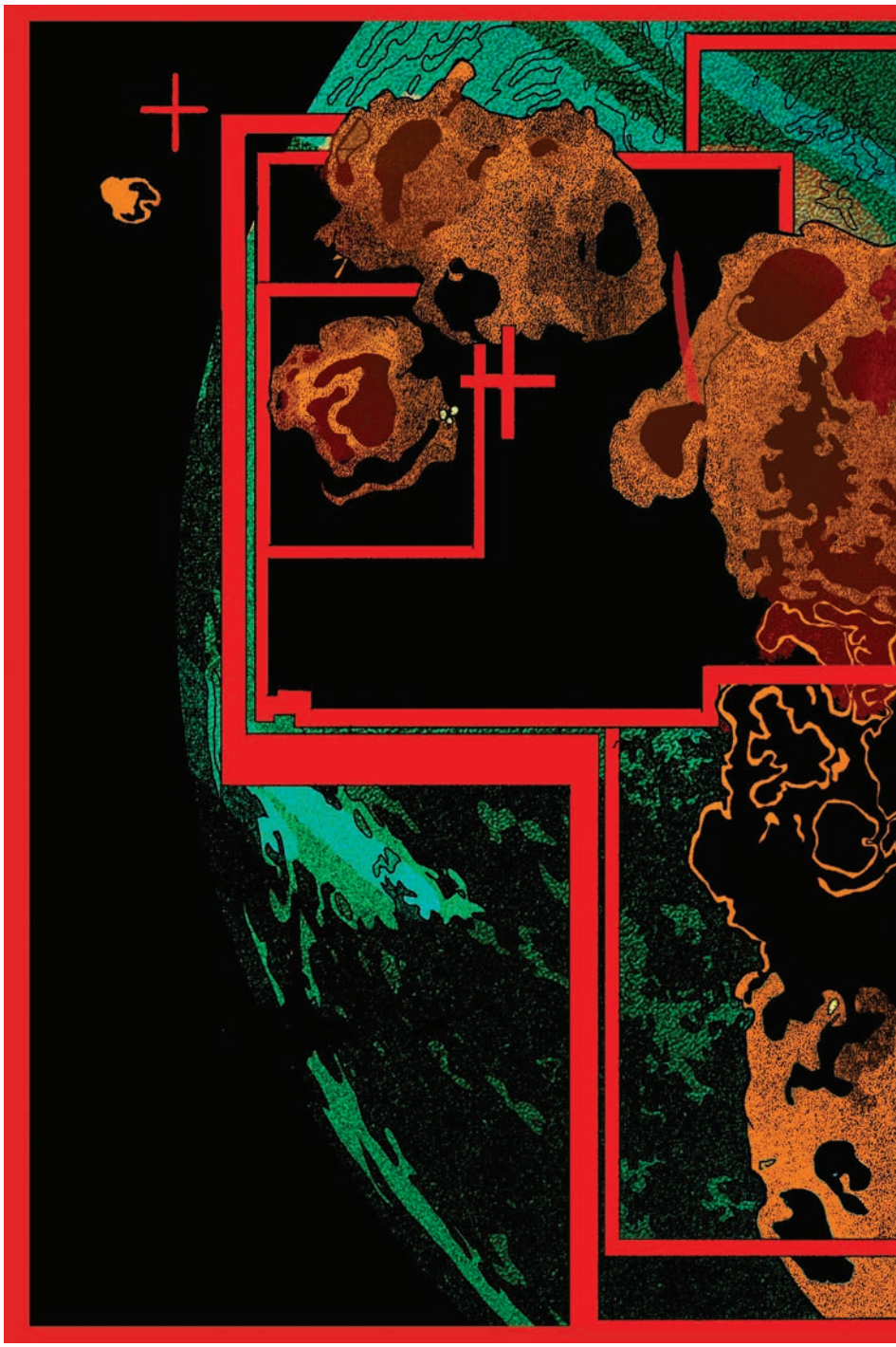
In those first few hours after it was discovered, and before anyone knew how shiny or dull its surface was, 2024 YR4 was estimated by astronomers to be as small as 65 feet across or as large as 500 feet. An object of the former size would blow up in midair, shattering windows over many miles and likely injuring thousands of people. At the latter size it would vaporize the heart of any city it struck, turning solid rock and metal into liquid and gas, while its blast wave would devastate the rest of it, killing hundreds of thousands or even millions in the process.

So now the question was: Just how big *was* 2024 YR4?

Refining the picture

MID-JANUARY 2025

VERY LARGE TELESCOPE, CHILE—Understandably dissatisfied with that level of imprecision, the European Southern



Observatory's Very Large Telescope (VLT), high up on the Cerro Paranal mountain in Chile's Atacama Desert, entered the chat. As the name suggests, this flagship facility is vast, and it's capable of really zooming in on distant objects. Or to put it another way: "The VLT is the largest, biggest, best telescope in the world," says Hainaut, one of the facility's operators, who usually commands it from half a world away in Germany.

In reality, the VLT—which lends a hand to the European Space Agency in its asteroid-hunting duties—is actually made up of four massive telescopes, each fixed on a separate corner of the sky. They can be combined to act as a huge light bucket, allowing astronomers to see very faint asteroids. Four additional, smaller, movable telescopes can also team up with their bigger siblings to provide remarkably high-resolution images of even the stealthiest space rocks.

With so much tech to oversee, the control room of the VLT looks a bit like the inside of the Death Star. "You have eight consoles, each of them with a dozen screens. It's big, it's large, it's spectacular," says Hainaut.

In mid-January, the European Space Agency asked the VLT to study several asteroids that had somewhat suspicious near-Earth orbits—including 2024 YR4. With just a few lines of code, the VLT could easily train its sharp eyes on an asteroid like 2024 YR4, allowing astronomers to narrow down its size range. It was found to be at least 130 feet long (big enough to cause major damage in a city) and as large as 300 (able to annihilate one).

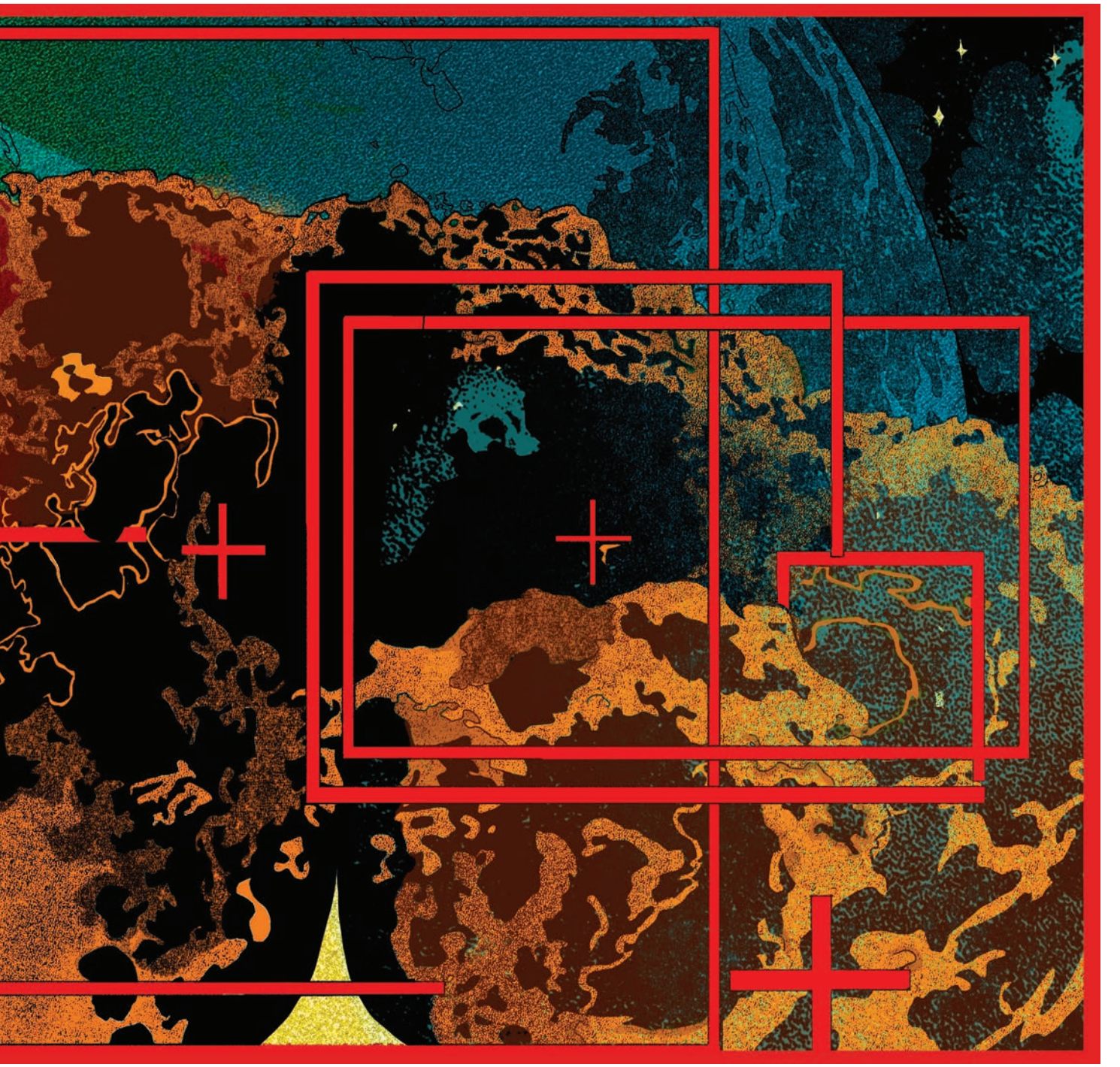
JANUARY 29, 2025

INTERNATIONAL ASTEROID WARNING NETWORK—By the end of the month, there was no mistaking it: 2024 YR4 stood a greater than 1% chance of impacting Earth on December 22, 2032.

"It's not something you see very often," says Marco Fenucci, a near-Earth-object dynamicist at NEOCC. He admits that although it was "a serious thing," this escalation was also "exciting to see"—something straight out of a sci-fi flick.

Sentry and Aegis, along with the systems at NEODyS, had been checking one another's calculations. "There was a lot of care," says Farnocchia, who explains that even though their programs worked wonders, their predictions were manually verified by multiple experts. When a rarity like 2024 YR4 comes along, he says, "you kind of switch gears, and you start being more cautious. You start screening everything that comes in."

At this point, the klaxon emanating from these three data centers pushed the International Asteroid Warning Network (IAWN), a UN-backed planetary defense awareness group, to issue a public alert to the world's governments: *The planet may be in peril.* For the most part,



it was at this moment that the media—and the wider public—became aware of the threat. Earth, we may have a problem.

Denneau, along with many other astronomers, received an urgent email from Fast at NASA's Planetary Defense Coordination Office, requesting that all capable observatories track this hazardous asteroid. But there was one glaring problem. When 2024 YR4 was discovered on December 27, it was already two days after it had made its closest approach to Earth. And since it was heading back out into the shadows of space, it was quickly fading from sight.

Once it gets too faint, "there's not much ATLAS can do," Denneau says. By the time of IAWN's warning, planetary defenders had just weeks to try to track 2024 YR4 and refine the odds of its hitting Earth before they'd lose it to the darkness.

And if their scopes failed, the odds of an Earth impact would have stayed uncomfortably high until 2028, when the asteroid was due to make another flyby of the planet. That would be just four short years before the space rock might actually hit.

"In that situation, we would have been … in trouble," says NEOCC's Fenucci.

The hunt was on.

Preparing for the worst

FEBRUARY 5 AND FEBRUARY 6, 2025

SPACE MISSION PLANNING ADVISORY GROUP, AUSTRIA—In early February, spaceflight mission specialists, including those at the UN-supported Space Mission Planning Advisory Group in Vienna, began high-level talks designed to sketch out ways in which 2024 YR4 could be either deflected away from Earth or obliterated—you know, just in case.

A range of options were available—including ramming it with several uncrewed spacecraft or assaulting it with nuclear weapons—but there was no silver bullet in this situation. Nobody had ever launched a nuclear explosive device into deep space before, and the geopolitical ramifications of any nuclear-armed nation's doing so in the present day would prove deeply unwelcome. Asteroids are also extremely odd objects; some, perhaps including 2024 YR4, are less like single chunks of rock and more akin to multiple cliffs flying in formation. Hit an asteroid like that too hard and you could fail to deflect it—and instead turn an Earth-bound cannonball into a spray of shotgun pellets.

It's safe to say that early on, experts were concerned about whether they could prevent a potential disaster. Crucially, eight years was not actually much time to plan something of this scale. So they were keen to better pinpoint how likely, or unlikely, it was that 2024 YR4 was going to collide with the planet before planning for any complex space mission began in earnest.

The people involved with these talks—from physicists at some of America's most secretive nuclear weapons research laboratories to spaceflight researchers over in Europe—were not feeling close to anything resembling panic. But "the timeline was really short," admits Hainaut. So there was an unprecedented tempo to their discussions. This wasn't a drill. This was the real deal. What would they do to defend the planet if an asteroid impact couldn't be ruled out?

Luckily, over the next few days, a handful of new observations came in. Each helped Sentry, Aegis, and the system at NEODyS rule out more of 2024 YR4's possible future orbits. Unluckily, Earth remained a potential port of call for this pesky asteroid—and over time, our planet made up a higher proportion of those remaining possibilities. That meant that the odds of an Earth impact "started bubbling up," says Denneau.

By February 6, there was a one-in-43 chance of impact—a probability of 2.3%.

"How much anxiety someone should feel over that—it's hard to say," Denneau says, with a slight shrug.

In the past, several elephantine asteroids have been found to stand a small chance of careening unceremoniously into the planet. Such incidents tend to follow a pattern. As more observations come in and the asteroid's orbit becomes better known, an Earth impact trajectory remains a possibility while other outlying orbits are removed from the calculations—so for a time, the odds of an impact rise. Finally, with enough observations in hand, it becomes clear that the space rock will miss our world entirely, and the impact odds plummet to zero.

Astronomers expected this to repeat itself with 2024 YR4. But there was no guarantee. There's no escaping the fact that one day, sooner or later, scientists will discover a dangerous asteroid that will punch Earth in the face—and raze a city in the process.

After all, asteroids capable of trashing a city have found their way to Earth plenty of times before, and not just in the very distant past. In 1908, an 800-square-mile patch of forest in Siberia—one that was, fortunately, very sparsely populated—was decimated by a space rock just 180 feet long. It didn't even hit the ground; it exploded in midair with the force of a 15-megaton blast.

But only one other asteroid comparable in size to 2024 YR4 had its 2.3% figure beat: in 2004, Apophis—capable of causing continental-scale damage—had (briefly) stood a 2.7% chance of impacting Earth in 2029.

A range of options were available—including ramming it with several uncrewed spacecraft or assaulting it with nuclear weapons—but there was no silver bullet in this situation.

Rapidly approaching uncharted waters, the powers that be at NASA decided to play a space-based wild card: the James Webb Space Telescope.

THE JAMES WEBB SPACE TELESCOPE, DEEP SPACE, ONE MILLION MILES FROM EARTH—The fact that a large dull asteroid reflects the same amount of light as a small shiny one doesn't mean astronomers sizing up an asteroid are helpless. If you view both asteroids in the infrared, the larger one glows brighter than the smaller one no matter the surface coating—making infrared, or the thermal part of the electromagnetic spectrum, a much better gauge of a space rock's proportions.

Observatories on Earth do have infrared capabilities, but our planet's atmosphere gets in their way, making it hard for them to offer highly accurate readings of an asteroid's size.

But the James Webb Space Telescope (JWST), hanging out in space, doesn't have that problem.

This observatory, which sits at a gravitationally stable point about a million miles from Earth, is polymathic. Its sniper-like scope can see in the infrared and allows it to peer at the edge of the observable universe, meaning it can study galaxies that formed not long after the Big Bang. It can even look at the light passing through the atmospheres of distant planets to ascertain their chemical makeups. And its remarkably sharp eye means it can also track the thermal glow of an asteroid long after all ground-based telescopes lose sight of it.

In a fortuitous bit of timing, by the moment 2024 YR4 came along, planetary defenders had recently reasoned that JWST could theoretically be used to track ominous asteroids using its own infrared scope, should the need arise. So after IAWN's warning went out, operators of JWST ran an analysis: Though the asteroid would vanish from most scopes by late March, this one might be able to see the rock until sometime in May, which would allow researchers to greatly refine their assessment of the asteroid's orbit and its odds of making Earth impact.

Understanding 2024 YR4's trajectory was important, but "the size was the main motivator," says Andy Rivkin, an astronomer at Johns Hopkins University's Applied Physics Laboratory, who led the proposal to use JWST to observe the asteroid. The hope was that even if the impact odds remained high until 2028, JWST would find that 2024 YR4 was on the smaller side of the 130-to-300-foot size range—meaning it would still be a danger, but a far less catastrophic one.

The JWST proposal was accepted by NASA on February 5. But the earliest it could conduct its observations was early March. And time really wasn't on Earth's side.

FEBRUARY 7, 2025

GEMINI SOUTH TELESCOPE, CHILE—"At this point, [2024 YR4] was too faint for the Catalina telescopes," says Catalina's Wierzchoś. "In our opinion, this was a big deal."

So Wierzchoś and his colleagues put in a rare emergency request to commandeer the Gemini Observatory, an internationally funded and run facility featuring two large, eagle-eyed telescopes—one in Chile and one atop Hawaii's Mauna Kea volcano. Their request was granted, and on February 7, they trained the Chile-based Gemini South telescope on 2024 YR4.

The chance of Earth impact dropped ever so slightly, to 2.2%—a minor, but still welcome, development.

MID-FEBRUARY 2025

MAGDALENA RIDGE OBSERVATORY, NEW MEXICO—By this point, the roster of 2024 YR4 hunters also included the tiny team operating the Magdalena Ridge Observatory (MRO), which sits atop a tranquil mountain in New Mexico.

"It's myself and my husband," says Eileen Ryan, the MRO director. "We're the only two astronomers running the telescope. We have a daytime technician. It's kind of a mom-and-pop organization."

Still, the scope shouldn't be underestimated. "We can see maybe a cellphone-size object that's illuminated at geosynchronous orbit," Ryan says, referring to objects 22,000 miles away. But its most impressive feature is its mobility. While other observatories have slowly swiveling telescopes, MRO's scope can move like the wind. "We can track the fastest objects," she says, with a grin—noting that the telescope was built in part to watch missiles for the US Air Force. Its agility and long-distance vision explain why the Space Force is one of MRO's major clients: It can be used to spy on satellites and spacecraft anywhere from low Earth orbit right out to the lunar regions. And that meant spying on the super-speedy, super-sneaky 2024 YR4 wasn't a problem for MRO, whose own observations were vital in refining the asteroid's impact odds.

Then, in mid-February, MRO and all ground-based observatories came up against an unsolvable problem: The full moon was out, shining so brightly it blinded any telescope that dared point at the night sky. "During the full moon, the observatories couldn't observe for a week or so," says NEOCC's Fenucci. To most of us, the moon is a beautiful silvery orb. But to astronomers, it's a hostile actor. "We abhor the moon," says Denneau.

All any of them could do was wait. Those tracking 2024 YR4 were by turns animated and slightly trepidatious. The thought that the asteroid could still stand a decent chance of impacting Earth after it faded from view did weigh a little on their minds.

Nevertheless, Farnocchia maintained his characteristic sangfroid throughout. "I try to stress about the things I can control," he says. "All we can do is to explain what the situation is, and that we need new data to say more."

FEBRUARY 18, 2025

CENTER FOR NEAR-EARTH OBJECT STUDIES, CALIFORNIA—As the full moon finally faded into a crescent of light, the world's largest telescopes sprang back into action for one last shot at glory. "The dark time came again," says Hainaut with a smile.



New observations finally began to trickle in, and Sentry, Aegis, and NEODyS readjusted their forecasts. It wasn't great news: The probability of an Earth impact in 2032 jumped to 3.1%, officially making 2024 YR4 the most dangerous asteroid ever discovered.

This declaration made headlines across the world—and certainly made the curious public sit up and wonder if there was yet another apocalyptic concern to fret about. But, as ever, the asteroid hunters held fast in their prediction that sooner or later—ideally sooner—more observations would cause the impact odds to drop.

"We kept at it," says Ryan. But time was running short; they started to "search for out-of-the-box ways to image this asteroid," says Fenucci.

Planetary defense researchers soon realized that 2024 YR4 wasn't too far away from NASA's Lucy spacecraft, a planetary science mission making a series of flybys of various asteroids. If Lucy could be redirected to catch up to 2024 YR4 instead, it would give humanity its best look at the rock, allowing Sentry and company to confirm or dispel our worst fears.

Sadly, NASA ran the numbers, and it proved to be a nonstarter: 2024 YR4 was too speedy and too far for Lucy to pursue.

It was really starting to look as if JWST would be the last, best hope to track 2024 YR4.

A change of fate

FEBRUARY 19, 2025

VERY LARGE TELESCOPE, CHILE, AND MAGDALENA RIDGE OBSERVATORY, NEW MEXICO—Just one day after 2024 YR4 made history, the VLT, MRO, and others caught sight of it again, and Sentry, Aegis, and NEODyS voraciously consumed their new data.

The probability of an Earth impact suddenly dropped to 1.5%.

Astronomers didn't really have time to react to the possibility that this was a good sign—they just kept sending their observations onward.

FEBRUARY 20, 2025

SUBARU TELESCOPE, HAWAII—Yet another observatory had been itching to get into the game for weeks, but it wasn't until February 20 that Tsuyoshi Terai, an astronomer at Japan's Subaru Telescope, sitting atop Mauna Kea, finally caught 2024 YR4 shifting between the stars. He added his data to the stream.

And all of a sudden, the asteroid lost its lethal luster. The chances of its hitting Earth were now just 0.3%.

At this point, you might expect that all those tracking it would be in a single control room somewhere, eyes glued to their screens, watching the odds drop before bursting into cheers and rapturous applause. But no—the astronomers who had spent so long observing this asteroid remained scattered across the globe. And instead of erupting into cheers, they exchanged modestly worded emails of congratulation—the digital equivalent of a nod or a handshake.

"It was a relief," says Terai. "I was very pleased that our data contributed to put an end to the risk of 2024 YR4."

FEBRUARY 24, 2025

INTERNATIONAL ASTEROID WARNING NETWORK—Just a few days later, and thanks to a litany of observations continuing to flood in, IAWN issued the all-clear. This once-ominous asteroid's odds of inconveniencing our planet were at one in 25,000—0.004%. Today, the chance of an Earth impact in 2032 is exactly zero.

"It was kinda fun while it lasted," says Denneau.

Planetary defenders may have had a blast defending the world, but these astronomers still took the cosmic threat deeply seriously—and never once took their eyes off the prize. "In my mind, the observers and orbit teams were the stars of this story," says Fast, NASA's acting planetary defense officer.

Farnocchia shrugs off the entire thing. "It was the expected outcome," he says. "We just didn't know when that would happen."

Looking back on it now, though, some 2024 YR4 trackers are allowing themselves to dwell on just how close this asteroid came to being a major danger. "It's wild to watch it all play out," says Denneau. "We were weeks away from having to spin up some serious mitigation planning." But there was no need to work out how to save the world. It turned out that 2024 YR4 was never a threat to begin with—it just took a while to check.

And these experiences in handling a dicey space rock will only serve to make the world a safer place to live. One day, an asteroid very much like 2024 YR4 will be seen heading straight for Earth. And those tasked with tracking it will be officially battle-tested and better prepared than ever to do what needs to be done.

A postscript

MARCH 27, 2025

JAMES WEBB SPACE TELESCOPE, DEEP SPACE, ONE MILLION MILES FROM EARTH—But the story of 2024 YR4 is not quite over—in fact, if this were a movie, it would have an after-credits scene.

After the Earth-impact odds fell off a cliff, JWST went ahead with its observations in March anyway. It found out that 2024 YR4 was 200 feet across—so large that a direct strike on a city would have proved horrifically lethal. Earth just didn't have to worry about it anymore.

But the moon might. Thanks in part to JWST, astronomers calculated a 3.8% chance that 2024 YR4 will impact the lunar surface in 2032. Additional JWST observations in May bumped that figure up slightly, to 4.3%, and the orbit can no longer be refined until the asteroid's next Earth flyby in 2028.

"It may hit the moon!" says Denneau. "Everybody's still very excited about that."

A lunar collision would give astronomers a wonderful opportunity not only to study the physics of an asteroid impact but also to demonstrate to the public just how good they are at precisely predicting the future motions of potentially lethal space rocks. "It's a thing we can plan for without having to defend the Earth," says Denneau.

If 2024 YR4 is truly going to smash into the moon, the impact—likely on the side facing Earth—would unleash an explosion equivalent to hundreds of nuclear bombs. An expansive crater would be carved out in the blink of an eye, and a shower of debris would erupt in all directions.

None of this supersonic wreckage would pose any danger to Earth, but it would look spectacular: You'd be able to see the bright flash of the impact from terra firma with the naked eye.

"If that does happen, it'll be amazing," says Denneau. It will be a spectacular way to see the saga of 2024 YR4—once a mere speck on his computer screen—come to an explosive end, from a front-row seat. ■

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

Some think the presence of the semiconductor powerhouse TSMC has long helped protect the island from China.

That could be changing.

By Johanna M. Costigan
Illustration by Dana Smith

Is Taiwan losing its

silicon shield?

One winter afternoon in a conference room in Taipei, a pair of twentysomething women dragged their friend across the floor. Lying on the ground in checkered pants and a brown sweatshirt, she was pretending to be either injured or dead. One friend picked her up by her arms, the other grabbed hold of her legs, and they managed to move her, despite momentarily breaking character to laugh at the awkwardness of the exercise. The three women had paid approximately $40 to spend their Sunday here, undergoing basic training to prepare for a possibility every Taiwanese citizen has an opinion about: Will China invade?

Taiwanese politics increasingly revolves around that question. China's ruling party has wanted to seize Taiwan for more than half a century. But in recent years, China's leader, Xi Jinping, has placed greater emphasis on the idea of "taking back" the island (which the Chinese Communist Party, or CCP, has never controlled). As China's economic and military might has grown, some analysts believe the country now has the capacity to quarantine Taiwan whenever it wants, making the decision a calculation of costs and benefits.

Many in Taiwan and elsewhere think one major deterrent has to do with the island's critical role in semiconductor manufacturing. Taiwan produces the majority of the world's semiconductors and more than 90% of the most advanced chips needed for AI applications. Bloomberg Economics estimates that a blockade would cost the global economy, including China, $5 trillion in the first year alone.

The island, which is approximately the size of Maryland, owes its remarkably disproportionate chip dominance to the inventiveness and prowess of one company: Taiwan Semiconductor Manufacturing Company, or TSMC. The chipmaker, which reached a market capitalization of $1 trillion in July, has contributed more than any other to Taiwan's irreplaceable role in the global semiconductor supply chain. Its clients include Apple and the leading chip designer Nvidia. Its chips are in your iPhone, your laptop, and the data centers that run ChatGPT.

For a company that makes what amounts to an invisible product, TSMC holds a remarkably prominent role in Taiwanese society. I've heard people talk about it over background noise in loud bars in the southern city of Tainan and listened to Taipei cab drivers connect Taiwan's security situation to the company, unprompted. "Taiwan will be okay," one driver told me as we sped by the national legislature, "because TSMC."

The idea is that world leaders (particularly the United States)—aware of the island's critical role in the semiconductor supply chain—would retaliate economically, and perhaps militarily, if China were to attack Taiwan. That, in turn, deters Beijing. "Because TSMC is now the most recognizable company of Taiwan, it has embedded itself in a notion of Taiwan's sovereignty," says Rupert Hammond-Chambers, president of the US-Taiwan Business Council.

Now some Taiwan specialists and some of the island's citizens are worried that this "silicon shield," if it ever existed, is cracking. Facing pressure from Washington, TSMC is investing heavily in building out manufacturing capacity at its US hub in



Arizona. It is also building facilities in Japan and Germany in addition to maintaining a factory in mainland China, where it has been producing less advanced legacy chips since 2016.

In Taiwan, there is a worry that expansion abroad will dilute the company's power at home, making the US and other countries less inclined to feel Taiwan is worthy of defense. TSMC's investments in the US have come with no guarantees for Taiwan in return, and high-ranking members of Taiwan's opposition party have accused the ruling Democratic Progressive Party (DPP) of gambling with the future of the island. It doesn't help that TSMC's expansion abroad coincides with what many see as a worrying attitude in the White House. On top of his overarching "America First" philosophy, Donald Trump has declined to comment on the specific question of whether the US would intervene if China attempted to take Taiwan by force. "I don't want to ever put myself in that position," he said in February.

At the same time, Beijing's interest in Taiwan has continued unabated. While China is making progress toward semiconductor self-sufficiency, it's currently in a transition period, with companies relying on foreign-made chips manufactured in Taiwan—some in compliance with export controls and some smuggled in. Meanwhile, the CCP persistently suggests that seizing the island would bring about a kind of family reunion. "It is the common aspiration and sacred responsibility of all Chinese sons and daughters to realize the complete reunification of the motherland," reads a statement released by the foreign ministry after Nancy Pelosi's controversial 2022 visit to Taiwan. Though it's impossible to know the full scope of Beijing's motivations, there is also obvious strategic appeal: Controlling the island would give China deep-water access, which is critical for naval routes and submarines. Plus, it could significantly disrupt American AI firms' access to advanced chips.

"The international community must certainly do everything in its power to avoid a conflict in the Taiwan Strait; there is too great a cost."

While China ramps up militarily, Taiwan is trying to make itself hard to ignore. The government is increasingly portraying the island as strategically essential to the global community, with semiconductors as its primary offering. "The international community must certainly do everything in its power to avoid a conflict in the Taiwan Strait; there is too great a cost," Taiwanese president Lai Ching-te said in an interview earlier this year with Japan's Nippon Television.

For its part, the chip industry is actively showing its commitment to Taiwan. While other tech CEOs attended Trump's second inauguration, for instance, Nvidia chief executive Jensen Huang met instead with TSMC's chairman, and the company announced in May that its overseas headquarters would be in Taipei. In recent years, US government officials have also started paying more attention to Taiwan's security situation and its interconnectedness with the chip industry. "There was a moment when everybody started waking up to the dependence on TSMC," says Bonnie Glaser, managing director of the German Marshall Fund's Indo-Pacific Program. The realization emerged, she says, over the last decade but was underscored in March of 2021, when Phil Davidson, then leader of the United States Indo-Pacific Command, testified to the Senate Armed Services Committee that there could be an invasion by 2027. Parallel to the security threat is the potential issue of overdependence, since so much chipmaking capability is concentrated in Taiwan.

For now, Taiwan is facing a tangle of interests and time frames. China presents its claim to Taiwan as a historical inevitability, albeit one with an uncertain timeline, while the United States' relationship with the island is focused on an AI-driven future. But from Taiwan's perspective, the fight for its fate is playing out right now, amid unprecedented geopolitical instability. The next few years will likely determine whether TSMC's chipmaking dominance is enough to convince the world Taiwan is worth protecting.

Innovation built on interconnectivity

TSMC is an uncontested success story. Its founder, Morris Chang, studied and worked in the United States before he was lured to Taiwan to start a new business on the promise of state support and inexpensive yet qualified labor. Chang founded TSMC in 1987 on the basis of his innovative business model. Rather than design and produce chips in-house, as was the norm, TSMC would act as a foundry: Clients would design the chips, and TSMC would make them.

This focus on manufacturing allowed TSMC to optimize its operations, building up process knowledge and, eventually, outperforming competitors like Intel. It also freed up other businesses to go "fabless," meaning they could stop maintaining their own semiconductor factories, or fabs, and throw their resources behind other parts of the chipmaking enterprise. Tapping into Taiwan's domestic electronics supply chain proved effective and efficient for TSMC. Throughout the 1990s and early 2000s, global demand for semiconductors powering personal computers and other devices continued to grow. TSMC thrived.

Then, in 2022, the US imposed export controls on China that restricted its access to advanced chips. Taiwan was forced to either comply, by cutting off Chinese clients, or risk losing the support of the country that was home to 70% of its client



In March 2025, President Trump and TSMC CEO C.C. Wei jointly announced that the firm will make an additional $100 billion investment (on top of a previously announced $65 billion) in TSMC's US hub in Arizona.

REBECCA NOBLE/BLOOMBERG/GETTY IMAGES

base—and, possibly, 100% of its hopes for external military support in the event of an attack.

Soon after, Chang announced that he believed globalization and free markets were "almost dead." The nearly three years since have shown he was onto something. For one thing, in contrast to President Biden's pursuit of supply chain integration with democratic allies, President Trump's foreign policy is characterized by respect for big, undemocratic powers and punitive tariffs against both America's rivals and its friends. Trump has largely abandoned Biden's economic diplomacy with European and Asian allies but kept his China-targeted protectionism. Restrictions cover certain graphics processing units, or GPUs, which are necessary for AI functions; high-bandwidth memory chips; chip manufacturing technology; chip design software; and chemicals. The rules don't just limit China's access to semiconductors. By including companies, like the Netherlands' ASML, that export chipmaking tools, they are designed to stifle Chinese firms' ability to produce their own.

Protectionism, it turns out, spurs self-reliance. China's government has been making a massive effort to build up its domestic chip production capabilities—a goal that was identified at the beginning of Xi's rise but has been turbocharged in the wake of Washington's export controls.

Any hope the US has for significantly expanding domestic chip production comes from its friends—TSMC first among them. The semiconductor industry developed as a global endeavor out of practicality, playing to the strengths of each region: design in the US and manufacturing in Asia, with key inputs from Europe central to the process. Yet the US government, entrenched in its "tech war" with China, is now dead set on deglobalizing the chip supply chain, or at least onshoring as much of it as possible. There's just one hiccup: The best chip manufacturer isn't American. It's TSMC. Even if some manufacturing happens in Arizona, the US still relies on Taiwan's chipmaking ecosystem. And copying that supply chain outside Taiwan could be harder than the current administration imagines.

Squarely in the middle

Taiwan's modern security uncertainties stem from the long-contested issue of the island's sovereignty. After losing the first Sino-Japanese War in the late 1800s, the Qing dynasty forfeited Taiwan to Japanese imperial control. It was Japan's "model colony" until 1945, when postwar negotiations resulted in its transfer to the Republic of China under Chiang Kai-shek of the Nationalist Party, known as the KMT. The insurgent CCP under Mao Zedong ultimately defeated the Nationalists in a civil war fought on the mainland until 1949. Chiang and many of his party's defeated generals decamped to Taiwan, controlling it under martial law for nearly 40 years.

Taiwan held its first free democratic elections in 1996, kicking off a two-party rivalry between the KMT, which favors closer relations with Beijing, and the DPP, which opposes integration with China. Kitchen-table issues like economic growth are central to Taiwanese elections, but so is the overarching question of how best to handle the threat of invasion, which has persisted for nearly 80 years. The DPP is increasingly calling for raising defense spending and civilian preparedness to make sure Taiwan is ready for the worst, while the KMT supports direct talks with Beijing.

Meanwhile, Chinese military incursions around Taiwan—known as "gray zone" tactics because they fall short of acts of war—are increasingly frequent. In May, Taiwan's defense ministry reportedly estimated that Chinese warplanes were entering Taiwan's air defense zone more than 200 times a month, up from fewer than 10 times per month five years ago. China has conducted drills mirroring the actions needed for a full-scale invasion or a blockade, which would cut Taiwan off from the outside world. Chinese military officials are now publicly talking about achieving a blockade, says Lyle Morris, an expert on foreign policy and national security at the Asia Society Policy Institute. "They're punishing Lai and the DPP," Morris says. Meanwhile, the CCP has its own people to answer to: When it comes to the Taiwan issue, Morris says, "Beijing is probably quite worried about the people of China being upset if they aren't hawkish enough or if they come out looking weak." Indeed, in response to Lai's recent policy statements, including one declaring that China is a "hostile foreign force," Gao Zhikai, a prominent scholar in China who opposes Taiwanese independence, recently wrote, "The reunification with the motherland cannot be endlessly delayed. Decisive action must be taken."

Intimidation from China has made some ordinary Taiwanese citizens more concerned; according to a recent poll conducted by a defense-focused think tank, 51% think defense spending should be increased (although 65% of respondents said they thought an attack within five years was "unlikely"). No matter how much money Taipei spends, the sheer military imbalance

between China and Taiwan means Taiwan would need help. But especially in the wake of Ukraine's experience, many believe US aid would be contingent on whether Taiwan demonstrates the will to defend itself. "Based on war games, Taiwan would have to hold out for a month before the US could potentially intervene," says Iris Shaw, director of the DPP mission in the US. And support from Taiwan's neighbors like Japan might be contingent on US involvement.

But how likely is the US to intervene in such a scenario? The author Craig Addison popularized the argument that Taiwan's fate is tied to its chip production prowess in his 2001 book *Silicon Shield: Taiwan's Protection Against Chinese Attack*. Back then, Addison wrote that although the US had been intentionally vague about whether it would go to war to protect the island, America's technological reliance on "a safe and productive Taiwan" made it highly probable that Washington would intervene. President Joe Biden deviated from those decades of calculated ambiguity by asserting multiple times that America *would* defend the island in the event of an attack. Yet now, Trump seems to have taken the opposite position, possibly presenting an opportunity for Beijing.

TSMC in the Trump era

In many ways, Taiwan finds itself in a catch-22. It feels the need to cozy up to the US for protection, yet that defensive maneuver is arguably risky in itself. It's a common belief in Taiwan that forging stronger ties to the US could be dangerous. According to a public opinion poll released in January, 34.7% of Taiwanese believe that a "pro-US" policy provokes China and will cause a war.

But the Lai administration's foreign policy is "inexorably intertwined with the notion that a strong relationship with the US is essential," says Hammond-Chambers.

Bolstering US support may not be the only reason TSMC is building fabs outside Taiwan. As the company readily points out, the majority of its customers are American. TSMC is also responding to its home base's increasingly apparent land and energy limitations: finding land to build new fabs sometimes causes rifts with Taiwanese people who, for example, don't want their temples and ancestral burial sites repurposed as science parks. Taiwan also relies on imports to meet more than 95% of its energy needs, and the dominant DPP has pledged to phase out nuclear, Taiwan's most viable yet most hotly contested renewable energy source. Geopolitical tensions compound these physical restraints: Even if TSMC would never say as much, it's fairly likely that if China did attack Taiwan, the firm would rather remain operational in other countries than be wiped out completely.

In many ways, Taiwan finds itself in a catch-22. It feels the need to cozy up to the US for protection, yet that defensive maneuver is arguably risky in itself.

However, building out TSMC's manufacturing capabilities outside Taiwan will not be easy. "The ecosystem they created is truly unique. It's a function of the talent pipeline, the culture, and laws in Taiwan; you can't easily replicate it anywhere," says Glaser. TSMC has 2,500 Taiwan-based suppliers. Plenty are within a couple of hours' drive or an even shorter trip on high-speed rail. Taiwan has built a fully operational chip cluster, the product of four decades of innovation, industrial policy, and labor.

As a result, it's unclear whether TSMC will be able to copy its model and paste it into the suburbs of Phoenix, where it has 3,000 employees working on chip manufacturing. "Putting aside the geopolitical factor, they wouldn't have expanded abroad," says Feifei Hung, a researcher at the Asia Society. Rather than standalone facilities, the Arizona fabs are "appendages of TSMC that happen to be in Arizona," says Paul Triolo, partner and tech policy lead at the international consulting firm DGA-Albright Stonebridge Group. When the full complex is operational, it will represent only a small percentage of TSMC's overall capacity, most of which will remain in Taiwan. Triolo doubts the US buildout will yield results similar to what TSMC has built there: "Arizona ain't that yet, and never will be."

Still, the second Trump administration has placed even more pressure on the company to "friendshore"—without providing any discernible signs of friendship. During this spring's tariff frenzy, the administration threatened to hit Taiwan with a 32% "reciprocal" tariff, a move that was then paused and revived at 20% in late July (and was still being negotiated as of press time). The US is also apparently considering levying a $1 billion fine against TSMC after TSMC-made chips were reportedly found in some Huawei devices. These developments come after TSMC cut off Huawei, which at the time sourced 90% of its smartphone chips from the Taiwanese chipmaker and was on track to become one of its major clients.

Despite these costs, TSMC has been steadfast in its attempts to get on Washington's good side. In March, Trump and TSMC's CEO, C.C. Wei, jointly announced that the firm will make an additional $100 billion investment (on top of a previously announced $65 billion) in TSMC's US hub in Arizona. The pledge represents the largest single source of foreign direct investment into the US, ever. While the deal was negotiated during Biden's term, Trump was happy to take credit for ensuring that "the most powerful AI chips will be made right here in America."

The Arizona buildout will also include an R&D facility—a critical element for tech transfer and intellectual-property development. Then there's the very juicy cherry on top: TSMC



Visitors take selfies outside the TSMC Museum of Innovation in Hsinchu, Taiwan.

ANNABELLE CHIH/GETTY IMAGES

announced in April that once all six new fabs are operational, 30% of its most advanced chips will be produced in Arizona. Up until then, the thinking was that US-based production would remain a generation or two behind. It looks as if the administration's public and, presumably, private arm-twisting has paid off.

Meanwhile, as Trump cuts government programs and subsidies while demanding the "return" of manufacturing to the US, it's TSMC that is running a technician apprenticeship program in Arizona to create good American jobs. TSMC's leaders, Triolo says, must question how serious the Trump administration is about long-term industrial policy. They're probably asking themselves, he says, "Do they understand what it takes to support the semiconductor industry, like our government does?"

Dealing with an administration that is so explicitly "America first" represents "one of the biggest challenges in history for Taiwanese companies," says Thung-Hong Lin, a sociology researcher at the Taipei-based Academia Sinica. Semiconductor manufacturing relies on reliability. Trump has so far offered TSMC no additional incentives supporting its US expansion—and started a trade war that has directly affected the semiconductor industry, partly by introducing irrevocable uncertainty. "Trump's tariffs have set off a new, more intensified bifurcation of semiconductor supply chains," says Chris Miller, author of *Chip War*. For now, Miller says, TSMC must navigate a world in which the US and China are both intense competitors and, despite trade restrictions, important clients.

Warring narratives

China has been taking advantage of these changes to wage a war of disinformation. In response to Nancy Pelosi's visit to Taiwan in 2022, when she was US Speaker of the House, Beijing sent warships, aircraft, and propaganda across the Taiwan Strait. Hackers using Chinese software infiltrated the display screens in Taiwan's 7-Eleven stores to display messages telling "warmonger Pelosi" to "get out of Taiwan." That might not be an act of war, but it's close; "7" is an institution of daily life on the island. It is not difficult to imagine how a similar tactic might be used to spread more devastating disinformation, falsely alleging, for example, that Taiwan's military has surrendered to China during a future crisis.

Taiwan is "perpetually on the front lines" of cyberattacks from China, says Francesca Chen, a cybersecurity systems analyst at Taiwan's Ministry of Digital Affairs. According to Taiwan's National Security Bureau, instances of propaganda traceable to China grew by 60% in 2024 over the previous year, reaching 2.16 million.

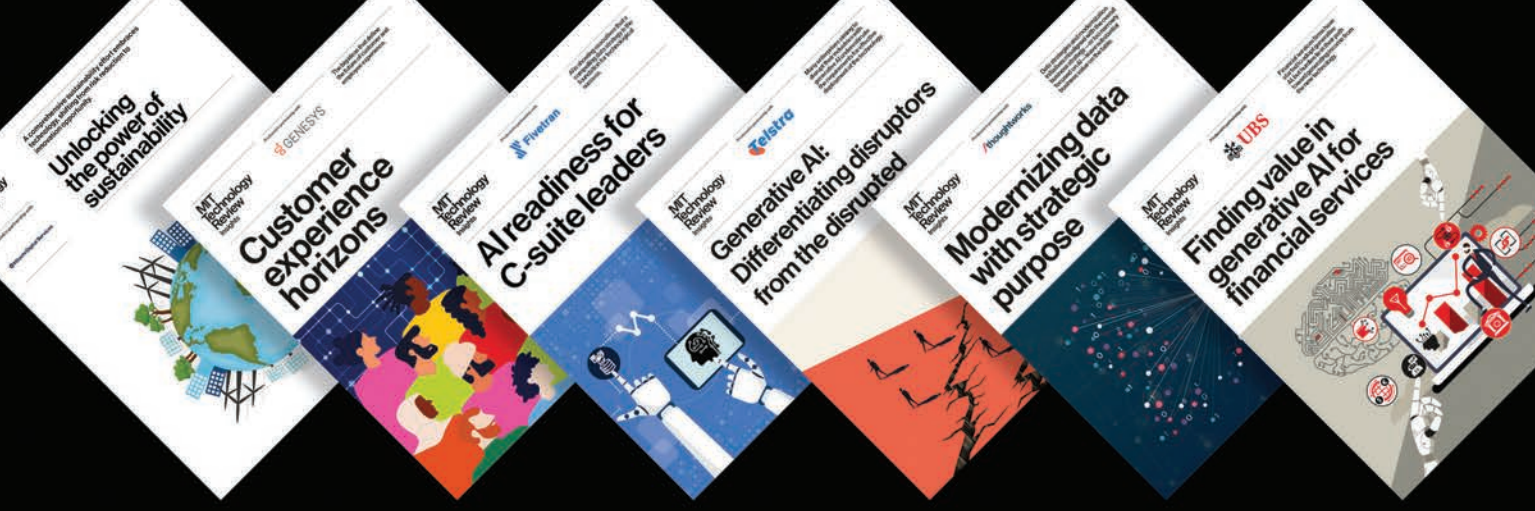
Over the last few years, online discussion of TSMC's investments in the US "has become a focal point" of China's state-sponsored disinformation campaigns aimed at Taiwan, Chen says. They claim TSMC is transferring its most advanced technology, talent, and resources to the US, "weakening Taiwan's economic lifeline and critical position in global supply chains." Key terms include "hollowing out Taiwan" and "de-Taiwanization." This framing depicts TSMC's diversification as a symbol of Taiwan's vulnerability, Chen says. The idea is to exploit real domestic debates in Taiwan to generate heightened levels of internal division, weakening social cohesion and undermining trust in the government.

Chinese officials haven't been shy about echoing these messages out in the open: After the most recent US investment announcement in March, a spokesperson from China's Taiwan Affairs Council accused Taiwan's DPP of handing over TSMC as a "gift" to the US. ("TSMC turning into USMC?" asked a state media headline.) Former Taiwanese president Ma Ying-jeou posted an eerily similar criticism, alleging that TSMC's US expansion amounted to "selling" the chipmaker in exchange for protection.

TSMC's expansion abroad could become a major issue in Taiwan's 2028 presidential election. It plays directly into party politics: The KMT can accuse the DPP of sacrificing Taiwan's technology assets to placate the US, and the DPP can accuse the KMT of cozying up with China, even as Beijing's military incursions become a more evident part of daily life. It remains to be seen whether TSMC's shift to the US will ultimately protect or weaken Taiwan—or have no effect on the island's security and sovereignty. For now at least, China's aspirations loom large.

To Beijing, unequivocally, Taiwan does not equal TSMC. Instead, it represents the final, as yet unfulfilled stage of the Communist Party's revolutionary struggle. Framed that way, China's resolve to take the island could very well be nonnegotiable. That would mean if Taiwan is going to maintain a shield that protects it from the full weight of China's political orthodoxy, it may need to be made of something much stronger than silicon. ■

Johanna M. Costigan is a writer and editor focused on technology and geopolitics in the US, China, and Taiwan. She writes the newsletter The Long Game.



MIT Technology Review Insights

Our insights. Your success.

Amplify your brand. Retain customers. Turn thought leadership into results. Partner with MIT Technology Review Insights. Join us and other smart companies to craft custom research, savvy articles, compelling visualizations, and more.

Generative AI

Generative AI: Differentiating disruptors from the disrupted
Survey report in partnership with Telstra

AI readiness for C-suite leaders
Survey report in partnership with Fivetran

Unlocking the trillion-dollar potential of generative AI
Webcast in sponsorship with AWS Canada

Finding value in generative AI for financial services
Report in partnership with UBS

Sustainability

Driving sustainable water management
Report in partnership with Schneider Electric

Scaling green hydrogen technology for the future
Custom article in partnership with Thyssenkrupp Nucera

Unlocking the power of sustainability
Report in partnership with Hitachi Digital Services

Deploying high-performance, energy-efficient AI
Podcast in partnership with Intel

Customer experience

Customer experience horizons
Survey report in partnership with Genesys

Purpose-built AI builds better customer experiences
Podcast in partnership with NICE

Actionable insights enable smarter business buying
Custom article in partnership with Amazon Business

Accelerating retail personalization at scale
Report in association with Oracle and Deloitte

Data and analytics

The data practitioner for the AI era
Report in partnership with Databricks and dbt Labs

Modernizing data with strategic purpose
Survey report in partnership with Thoughtworks

Data at the center of business
Podcast in association with JPMorgan Chase

Outperforming competitors as a data-driven organization
Custom article in partnership with WNS Triange

Scan this code to see more of our custom content or please visit:

TechnologyReview.com/Custom-Content

For US partnership opportunities:
Andrew Hendler
andrew.hendler@technologyreview.com

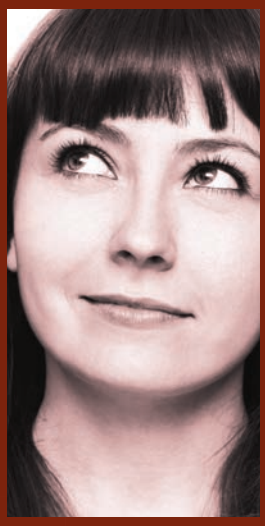
For international partnership opportunities:
Nicola Crepaldi
nicola.crepaldi@technologyreview.com

MIT Technology Review

Expand your knowledge beyond the classroom.

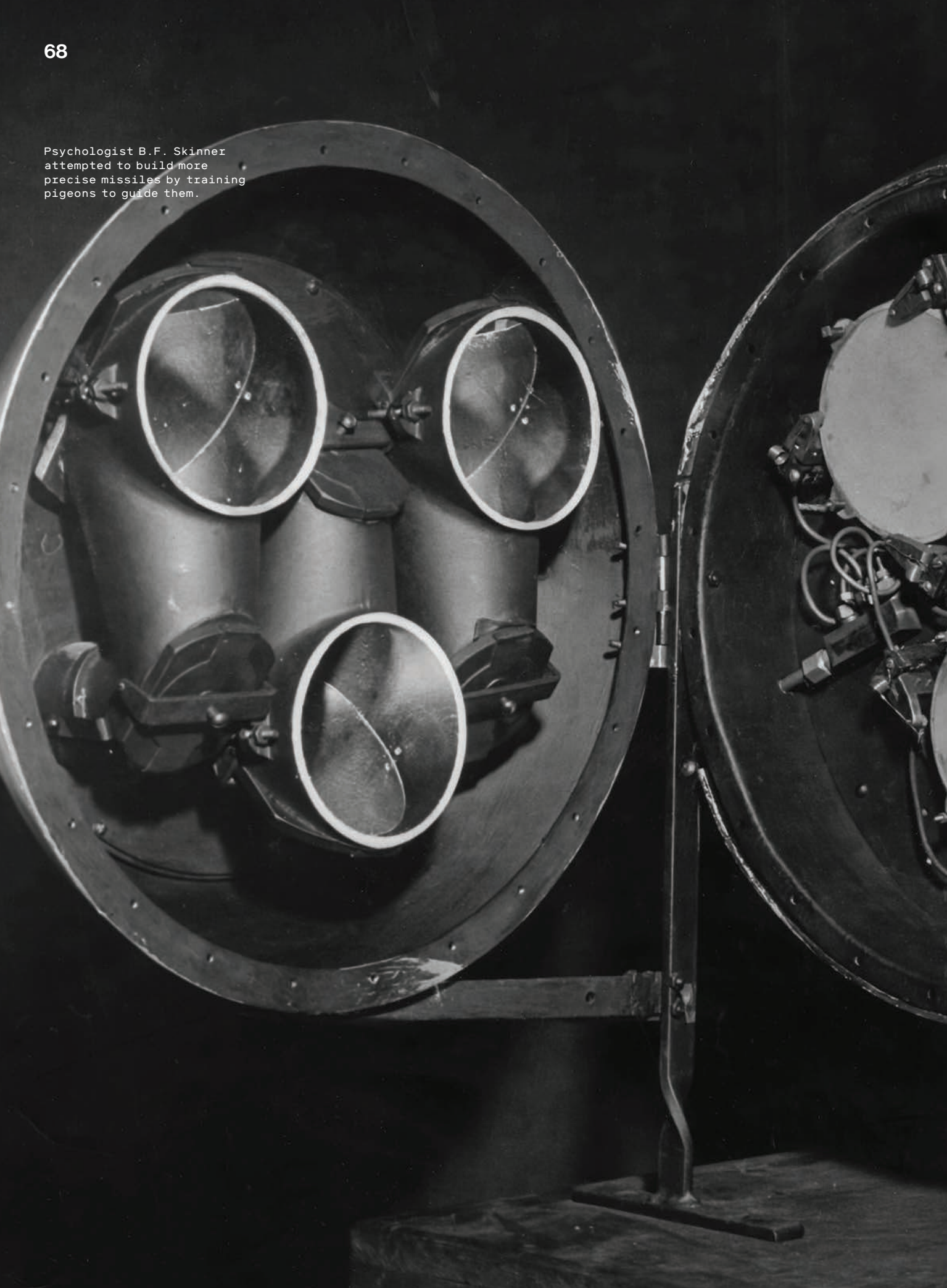


Invest in your future and save 50% on year-long access to MIT Technology Review's trusted reporting, in-depth stories, and expert insights when you subscribe.

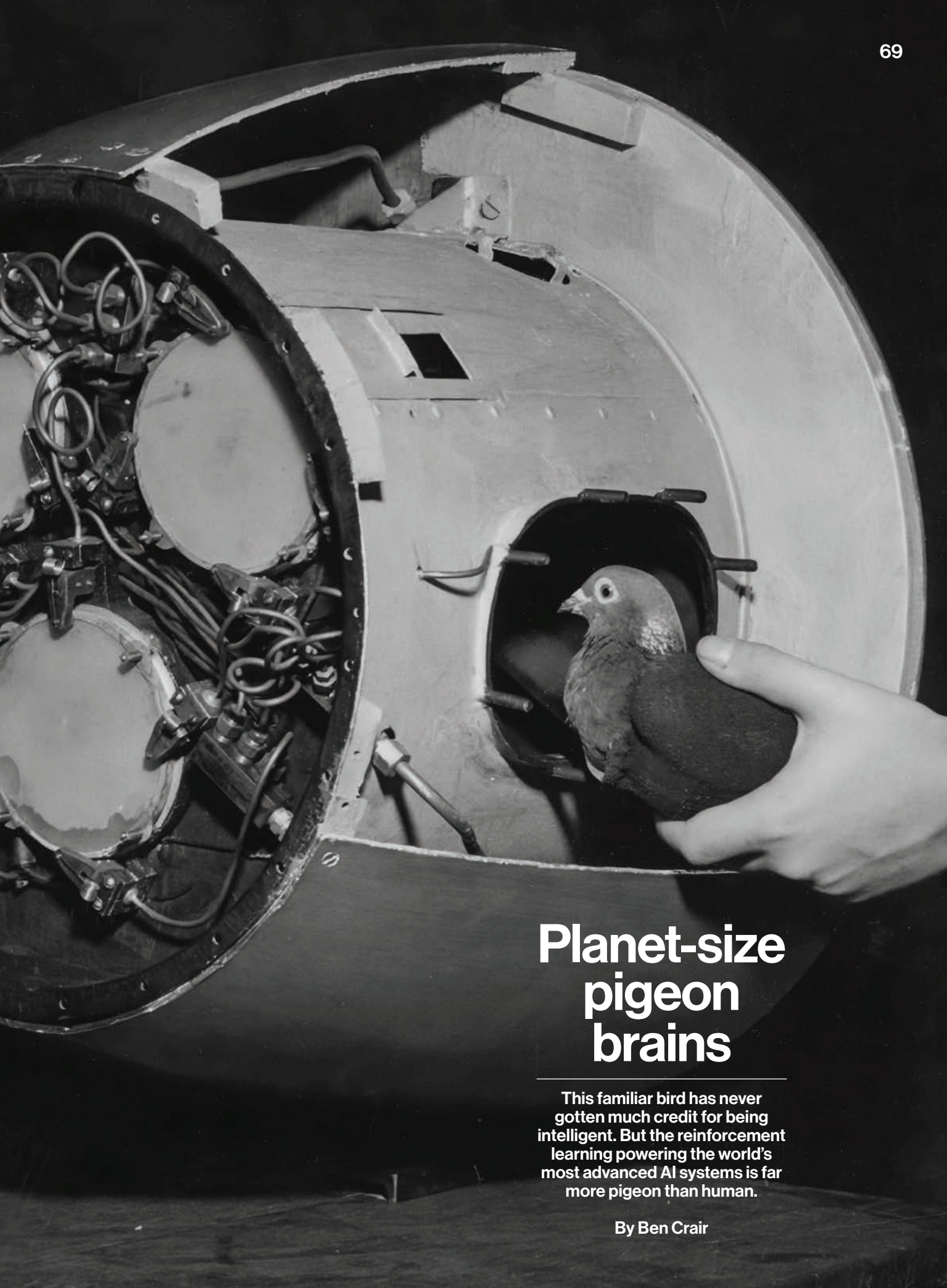




Scan here to save 50% or visit **technologyreview.com/StudentOffer**



Psychologist B.F. Skinner attempted to build more precise missiles by training pigeons to guide them.



Planet-size pigeon brains

This familiar bird has never gotten much credit for being intelligent. But the reinforcement learning powering the world's most advanced AI systems is far more pigeon than human.

By Ben Crair

In 1943, while the world's brightest physicists split atoms for the Manhattan Project, the American psychologist B.F. Skinner led his own secret government project to win World War II.

Skinner did not aim to build a new class of larger, more destructive weapons. Rather, he wanted to make conventional bombs more precise. The idea struck him as he gazed out the window of his train on the way to an academic conference. "I saw a flock of birds lifting and wheeling in formation as they flew alongside the train," he wrote. "Suddenly I saw them as 'devices' with excellent vision and maneuverability. Could they not guide a missile?"

Skinner started his missile research with crows, but the brainy black birds proved intractable. So he went to a local shop that sold pigeons to Chinese restaurants, and "Project Pigeon" was born. Though ordinary pigeons, *Columba livia*, were no one's idea of clever animals, they proved remarkably cooperative subjects in the lab. Skinner rewarded the birds with food for pecking at the right target on aerial photographs—and eventually planned to strap the birds into a device in the nose of a warhead, which they would steer by pecking at the target on a live image projected through a lens onto a screen.

The military never deployed Skinner's kamikaze pigeons, but his experiments convinced him that the pigeon was "an extremely reliable instrument" for studying the underlying processes of learning. "We have used pigeons, not because the pigeon is an intelligent bird, but because it is a practical one and can be made into a machine," he said in 1944.

People looking for precursors to artificial intelligence often point to science fiction by authors like Isaac Asimov or thought experiments like the Turing test. But an equally important, if surprising and less appreciated, forerunner is Skinner's research with pigeons in the middle of the 20th century. Skinner believed that association—learning, through trial and error, to link an action with a punishment or reward—was the building block of every behavior, not just in pigeons but in all living organisms, including human beings. His "behaviorist" theories fell out of favor with psychologists and animal researchers in the 1960s but were taken up by computer scientists who eventually provided the foundation for many of the artificial-intelligence tools from leading firms like Google and OpenAI.

These companies' programs are increasingly incorporating a kind of machine learning whose core concept—reinforcement—is taken directly from Skinner's school of psychology and whose main architects, the computer scientists Richard Sutton and Andrew Barto, won the 2024 Turing Award, an honor widely considered to be the Nobel Prize of computer science. Reinforcement learning has helped enable computers to drive cars, solve complex math problems, and defeat grandmasters in games like chess and Go—but it has not done so by emulating the complex workings of the human mind. Rather, it has supercharged the simple associative processes of the pigeon brain.

It's a "bitter lesson" of 70 years of AI research, Sutton has written: that human intelligence has not worked as a model for machine learning—instead, the lowly principles of associative learning are what power the algorithms that can now simulate or outperform humans on a variety of tasks. If artificial intelligence really is close to throwing off the yoke of its creators, as many people fear, then our computer overlords may be less like ourselves than like "rats with wings"—and planet-size brains. And even if it's not, the pigeon brain can at least help demystify a technology that many worry (or rejoice) is "becoming human."

In turn, the recent accomplishments of AI are now prompting some animal researchers to rethink the evolution of natural intelligence. Johan Lind, a biologist at Stockholm University, has written about the "associative learning paradox," wherein the process is largely dismissed by biologists as too simplistic to produce complex behaviors in animals but celebrated for producing humanlike behaviors in computers. The research suggests not only a greater role for associative learning in the lives of intelligent animals like chimpanzees and crows, but also far greater complexity in the lives of animals we've long dismissed as simple-minded, like the ordinary *Columba livia*.

When Sutton began working in AI, he felt as if he had a "secret weapon," he told me: He had studied psychology as an undergrad. "I was mining the psychological literature for animals," he says.

When Richard Sutton began working in AI, he felt as if he had a "secret weapon": He studied psychology as an undergrad. "I was mining the psychological literature for animals," he says.

Skinner started his missile research with crows but switched to pigeons when the brainy black birds proved intractable.



Ivan Pavlov began to uncover the mechanics of associative learning at the end of the 19th century in his famous experiments on "classical conditioning," which showed that dogs would salivate at a neutral stimulus—like a bell or flashing light—if it was paired predictably with the presentation of food. In the middle of the 20th century, Skinner took Pavlov's principles of conditioning and extended them from an animal's involuntary reflexes to its overall behavior.

Skinner wrote that "behavior is shaped and maintained by its consequences"—that a random action with desirable results, like pressing a lever that releases a food pellet, will be "reinforced" so that the animal is likely to repeat it. Skinner reinforced his lab animals' behavior step by step, teaching rats to manipulate marbles and pigeons to play simple tunes on four-key pianos. The animals learned chains of behavior, through trial and error, in order to maximize long-term rewards. Skinner argued that this type of associative learning, which he called "operant conditioning" (and which other psychologists had called "instrumental learning"), was the building block of all behavior. He believed that psychology should study only behaviors that could be observed and measured without ever making reference to an "inner agent" in the mind.

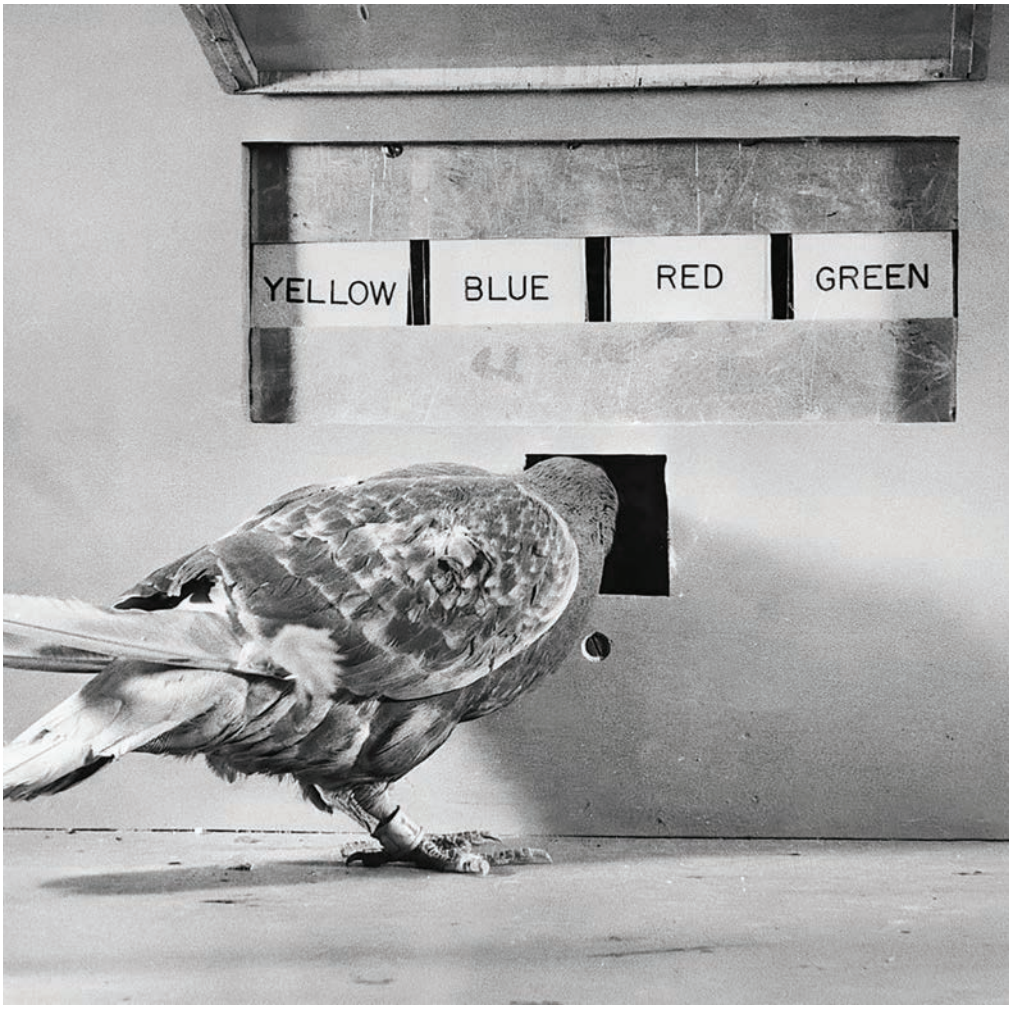
Skinner thought that even human language developed through operant conditioning, with children learning the meanings of words through reinforcement. But his 1957 book on the subject, *Verbal Behavior,* provoked a brutal review from Noam Chomsky, and psychology's focus started to swing from observable behavior to innate "cognitive" abilities of the human mind, like logic and symbolic thinking. Biologists soon rebelled against behaviorism also, attacking psychologists' quest to explain the diversity of animal behavior through an elementary and universal mechanism. They argued that each species evolved specific behaviors suited to its habitat and lifestyle, and that most behaviors were inherited, not learned.

By the '70s, when Sutton started reading about Skinner's and similar experiments, many psychologists and researchers interested in intelligence had moved on from pea-brained pigeons, which learn mostly by association, to large-brained animals with more sophisticated behaviors that suggested potential cognitive abilities. "This was clearly old stuff that was not exciting to people anymore," he told me. Still, Sutton found these old experiments instructive for machine learning: "I was coming to AI with an animal-learning-theorist mindset and seeing the big lack of anything like instrumental learning in engineering."

Many engineers in the second half of the 20th century tried to model AI on human intelligence, writing convoluted programs that attempted to mimic human thinking and implement rules that govern human response and behavior. This approach—commonly called "symbolic AI"—was severely limited; the programs stumbled over tasks that were easy for people, like recognizing objects and words. It just wasn't possible to write into code the myriad classification rules human beings use to, say, separate apples from oranges or cats from dogs—and without pattern recognition, breakthroughs in more complex tasks like problem solving, game playing, and language translation seemed unlikely too. These computer scientists, the AI skeptic Hubert Dreyfus

ABOVE AND PREVIOUS SPREAD: B.F. SKINNER FOUNDATION

In another Skinner experiment, a pigeon receives food after correctly matching a colored light to a corresponding colored panel.



wrote in 1972, accomplished nothing more than "a small engineering triumph, an ad hoc solution of a specific problem, without general applicability."

Pigeon research, however, suggested another route. A 1964 study showed that pigeons could learn to discriminate between photographs with people and photographs without people. Researchers simply presented the birds with a series of images and rewarded them with a food pellet for pecking an image showing a person. They pecked randomly at first but quickly learned to identify the right images, including photos where people were partially obscured. The results suggested that you didn't need rules to sort objects; it was possible to learn concepts and use categories through associative learning alone.

When Sutton began working with Barto on AI in the late '70s, they wanted to create a "complete, interactive goal-seeking agent" that could explore and influence its environment like a pigeon or rat. "We always felt the problems we were studying were closer to what animals had to face in evolution to actually survive," Barto told me. The agent needed two main functions: search, to try out and choose from many actions in a situation, and memory, to associate an action with the situation where it resulted in a reward. Sutton and Barto called their approach "reinforcement learning"; as Sutton said, "It's basically instrumental learning." In 1998, they published the definitive exploration of the concept in a book, *Reinforcement Learning: An Introduction*.

Over the following two decades, as computing power grew exponentially, it became possible to train AI on increasingly complex tasks—that is, essentially, to run the AI "pigeon" through millions more trials.

Programs trained with a mix of human input and reinforcement learning defeated human experts at chess and Atari. Then, in 2017, engineers at Google DeepMind built the AI program AlphaGo Zero entirely through reinforcement learning, giving it a numerical reward of +1 for every game of Go that it won and −1 for every game that it lost. Programmed to seek the maximum reward, it began without any knowledge of Go but improved over 40 days until it attained what its creators called "superhuman performance." Not only could it defeat the world's best human players at Go, a game considered even more complicated than chess, but it actually pioneered new strategies that professional players now use.

"Humankind has accumulated Go knowledge from millions of games played over thousands of years," the program's builders wrote in *Nature* in 2017. "In the space of a few days, starting tabula rasa, AlphaGo Zero was able to rediscover much of this Go knowledge, as well as novel strategies that provide new insights into the oldest of games." The team's lead researcher was David Silver, who studied reinforcement learning under Sutton at the University of Alberta.

Today, more and more tech companies have turned to reinforcement learning in products such as consumer-facing chatbots and agents. The first generation of generative AI, including large language models like OpenAI's GPT-2 and GPT-3, tapped into a simpler form of associative learning called "supervised learning," which trained the model on data sets that had been labeled by people. Programmers

GETTY IMAGES/BETTMANN

often used reinforcement to fine-tune their results by asking people to rate a program's performance and then giving these ratings back to the program as goals to pursue. (Researchers call this "reinforcement learning from feedback.")

Then, last fall, OpenAI revealed its o-series of large language models, which it classifies as "reasoning" models. The pioneering AI firm boasted that they are "trained with reinforcement learning to perform reasoning" and claimed they are capable of "a long internal chain of thought." The Chinese startup DeepSeek also used reinforcement learning to train its attention-grabbing "reasoning" LLM, R1. "Rather than explicitly teaching the model on how to solve a problem, we simply provide it with the right incentives, and it autonomously develops advanced problem-solving strategies," they explained.

These descriptions might impress users, but at least psychologically speaking, they are confused. A computer trained on reinforcement learning needs only search and memory, not reasoning or any other cognitive mechanism, in order to form associations and maximize rewards. Some computer scientists have criticized the tendency to anthropomorphize these models' "thinking," and a team of Apple engineers recently published a paper noting their failure at certain complex tasks and "raising crucial questions about their true reasoning capabilities."

Sutton, too, dismissed the claims of reasoning as "marketing" in an email, adding that "no serious scholar of mind would use 'reasoning' to describe what is going on in LLMs." Still, he has argued, with Silver and other coauthors, that the pigeons' method—learning, through trial and error, which actions will yield rewards—is "enough to drive behavior that exhibits most if not all abilities that are studied in natural and artificial intelligence," including human language "in its full richness."

In a paper published in April, Sutton and Silver stated that "today's technology, with appropriately chosen algorithms, already provides a sufficiently powerful foundation to … rapidly progress AI towards truly superhuman agents." The key, they argue, is building AI agents that depend less than LLMs on human dialogue and prejudgments to inform their behavior.

"Powerful agents should have their own stream of experience that progresses, like humans, over a long time-scale," they wrote. "Ultimately, experiential data will eclipse the scale and quality of human generated data. This paradigm shift, accompanied by algorithmic advancements in RL, will unlock in many domains new capabilities that surpass those possessed by any human."

Wasserman trained pigeons to succeed at a complex categorization task, which several undergraduate students failed. The students tried to find a rule that would help them sort various discs; the pigeons simply developed a sense for the group to which any given disc belonged.

If computers can do all that with just a pigeonlike brain, some animal researchers are now wondering if actual pigeons deserve more credit than they're commonly given.

"When considered in light of the accomplishments of AI, the extension of associative learning to purportedly more complicated forms of cognitive performance offers fresh prospects for understanding how biological systems may have evolved," Ed Wasserman, a psychologist at the University of Iowa, wrote in a recent study in the journal *Current Biology*.

In one experiment, Wasserman trained pigeons to succeed at a complex categorization task, which several undergraduate students failed. The students tried, in vain, to find a rule that would help them sort various discs with parallel black lines of various widths and tilts; the pigeons simply developed a sense, through practice and association, for the group to which any given disc belonged.

Like Sutton, Wasserman became interested in behaviorist psychology when Skinner's theories were out of fashion. He didn't switch to computer science, however: He stuck with pigeons. "The pigeon lives or dies by these really rudimentary learning rules," Wasserman told me recently, "but they are powerful enough to have succeeded colossally in object recognition." In his most famous experiments, Wasserman trained pigeons to detect cancerous tissue and symptoms of heart disease in medical scans as accurately as experienced doctors with framed diplomas behind their desks. Given his results, Wasserman found it odd that so many psychologists and ethologists regarded associative learning as a crude, mechanical mechanism, incapable of producing the intelligence of clever animals like apes, elephants, dolphins, parrots, and crows.

Other researchers also started to reconsider the role of associative learning in animal behavior after AI started besting human professionals in complex games. "With the progress of artificial intelligence, which in essence is built upon associative processes, it is increasingly

ironic that associative learning is considered too simple and insufficient for generating biological intelligence," Lind, the biologist from Stockholm University, wrote in 2023. He often cites Sutton and Barto's computer science in his biological research, and he believes it's human beings' symbolic language and cumulative cultures that really put them in a cognitive category of their own.

Ethologists generally propose cognitive mechanisms, like theory of mind (that is, the ability to attribute mental states to others), to explain remarkable animal behaviors like social learning and tool use. But Lind has built models showing that these flexible behaviors could have developed through associative learning, suggesting that there may be no need to invoke cognitive mechanisms at all. If animals learn to associate a behavior with a reward, then the behavior itself will come to approximate the value of the reward. A new behavior can then become associated with the first behavior, allowing the animal to learn chains of actions that ultimately lead to the reward. In Lind's view, studies demonstrating self-control and planning in chimpanzees and ravens are probably describing behaviors acquired through experience rather than innate mechanisms of the mind.

Lind has been frustrated with what he calls the "low standard that is accepted in animal cognition studies." As he wrote in an email, "Many researchers in this field do not seem to worry about excluding alternative hypotheses and they seem happy to neglect a lot of current and historical knowledge." There are some signs, though, that his arguments are catching on. A group of psychologists not affiliated with Lind referenced his "associative learning paradox" last year in a criticism of a *Current Biology* study, which purported to show that crows used "true statistical inference" and not "low-level associative learning strategies" in an experiment. The psychologists found that they could explain the crows' performance with a simple reinforcement-learning model—"exactly the kind of low-level associative learning process that [the original authors] ruled out."

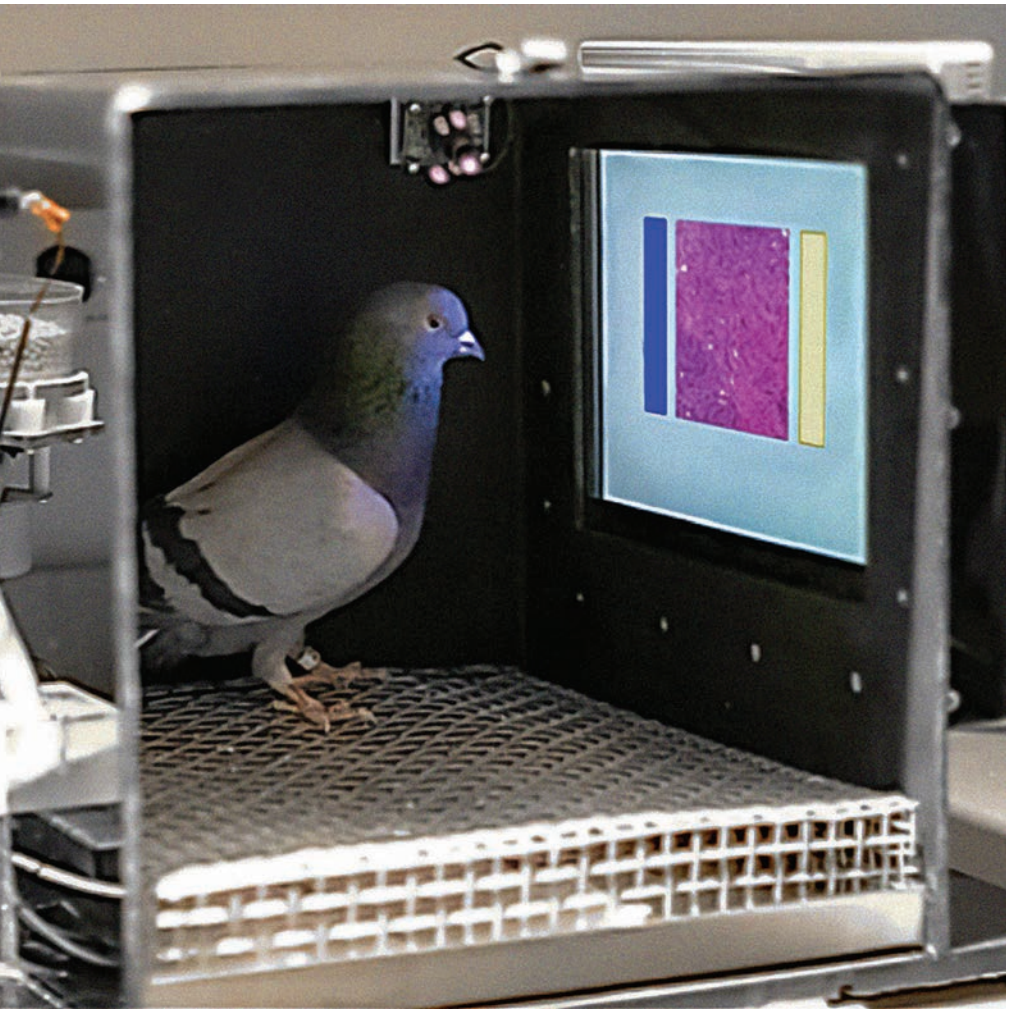
Skinner might have felt vindicated by such arguments. He lamented psychology's cognitive turn until his death in 1990, maintaining that it was scientifically irresponsible to probe the minds of living beings. After "Project Pigeon," he became increasingly obsessed with "behaviorist" solutions to societal problems. He went from training pigeons for war to inventions like the "Air Crib," which aimed to "simplify" baby care by keeping the infant behind glass in a climate-controlled chamber and eliminating the need for clothing and bedding. Skinner rejected free will, arguing that human behavior is determined by environmental variables, and wrote a novel, *Walden II,* about a utopian community founded on his ideas.

People who care about animals might feel uneasy about a revival in behaviorist theory. The "cognitive revolution" broke with centuries of Western thinking, which had emphasized human supremacy over animals and treated other creatures like stimulus-response machines. But arguing that animals learn by association is not the same as arguing that they are simple-minded. Scientists like Lind and Wasserman do not deny that internal forces like instinct and emotion also influence animal behavior. Sutton, too, believes that animals develop models of the world through their experiences and use them to plan actions. Their point is not that intelligent animals are empty-headed but that associative learning is a much more powerful—indeed, "cognitive"—mechanism than many of their peers believe. The psychologists who recently criticized the study on crows and statistical inference did not conclude that the birds were stupid. Rather, they argued "that a reinforcement learning model can produce complex, flexible behaviour."

This is largely in line with the work of another psychologist, Robert Rescorla, whose work in the '70s and '80s influenced both Wasserman and Sutton. Rescorla encouraged people to think of association not as a "low-level mechanical process" but as "the learning that results from exposure to relations among events in the environment" and "a primary means by which the organism represents the structure of its world."

This is true even of a laboratory pigeon pecking at screens and buttons in a small experimental box, where scientists carefully control and measure stimuli and rewards. But the pigeon's learning extends outside the box. Wasserman's students transport the birds between the aviary and the laboratory in buckets—and experienced pigeons jump immediately into the buckets whenever the students open the doors. Much as Rescorla suggested, they are learning the structure

Comparative psychologists and animal researchers have long grappled with a question that suddenly seems urgent because of AI: How do we attribute sentience to other living beings?



Psychologist Ed Wasserman trained pigeons to detect cancerous tissue and symptoms of heart disease in medical scans as accurately as experienced physicians.

UNIVERSITY OF IOWA/WASSERMAN LAB

of their world inside the laboratory and the relation of its parts, like the bucket and the box, even though they do not always know the specific task they will face inside.

The same associative mechanisms through which the pigeon learns the structure of its world can open a window to the kind of inner life that Skinner and many earlier psychologists said did not exist. Pharmaceutical researchers have long used pigeons in drug-discrimination tasks, where they're given, say, an amphetamine or a sedative and rewarded with a food pellet for correctly identifying which drug they took. The birds' success suggests they both experience and discriminate between internal states. "Is that not tantamount to introspection?" Wasserman asked.

It is hard to imagine AI matching a pigeon on this specific task—a reminder that, though AI and animals share associative mechanisms, there is more to life than behavior and learning. A pigeon deserves ethical consideration as a living creature not because of how it learns but because of what it feels. A pigeon can experience pain and suffer, while an AI chatbot cannot—even if some large language models, trained on corpora that include descriptions of human suffering and sci-fi stories of sentient computers, can trick people into believing otherwise.

"The intensive public and private investments into AI research in recent years have resulted in the very technologies that are forcing us to confront the question of AI sentience today," two philosophers of science wrote in *Aeon* in 2023. "To *answer* these current questions, we need a similar degree of investment into research on animal cognition and behavior." Indeed, comparative psychologists and animal researchers have long grappled with questions that suddenly seem urgent because of AI: How do we attribute sentience to other living beings? How can we distinguish true sentience from a very convincing performance of sentience?

Such an undertaking would yield knowledge not only about technology and animals but also about ourselves. Most psychologists probably wouldn't go as far as Sutton in arguing that reward is enough to explain most if not all human behavior, but no one would dispute that people often learn by association too. In fact, most of Wasserman's undergraduate students eventually succeeded at his recent experiment with the striped discs, but only after they gave up searching for rules. They resorted, like the pigeons, to association and couldn't easily explain afterwards what they'd learned. It was just that with enough practice, they started to get a feel for the categories.

It is another irony about associative learning: What has long been considered the most complex form of intelligence—a cognitive ability like rule-based learning—may make us human, but we also call on it for the easiest of tasks, like sorting objects by color or size. Meanwhile, some of the most refined demonstrations of human learning—like, say, a sommelier learning to taste the difference between grapes—are learned not through rules, but only through experience.

Learning through experience relies on ancient associative mechanisms that we share with pigeons and countless other creatures, from honeybees to fish. The laboratory pigeon is not only in our computers but in our brains—and the engine behind some of humankind's most impressive feats. ■

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



CHRISTIAN SINIBALDI

Innovator of the Year: Sneha Goenka

Her ultrafast sequencing pipeline allows physicians to quickly diagnose and treat life-threatening genetic diseases.

By Helen Thomson

Up to a quarter of children entering intensive care have undiagnosed genetic conditions. To be treated properly, they must first get diagnoses—which means having their genomes sequenced. This process typically takes up to seven weeks. Sadly, that's often too slow to save a critically ill child.

Hospitals may soon have a faster option, thanks to a groundbreaking system built in part by Sneha Goenka, an assistant professor of electrical and computer engineering at Princeton—and *MIT Technology Review*'s 2025 Innovator of the Year.

Five years ago, Goenka and her colleagues designed a rapid-sequencing pipeline that can provide a genetic diagnosis in less than eight hours. Goenka's software computations and hardware architectures were critical to speeding up each stage of the process.

"Her work made everyone realize that genome sequencing is not only for research and medical application in the future but can have immediate impact on patient care," says Jeroen de Ridder, a professor at UMC Utrecht in the Netherlands, who has developed an ultrafast sequencing tool for cancer diagnosis.

Now, as cofounder and scientific lead of a new company, she is working to make that technology widely available to patients around the world.

Goenka grew up in Mumbai, India. Her mother was an advocate for women's education, but as a child, Goenka had to fight to persuade other family members to let her continue her studies. She moved away from home at 15 to attend her final two years of school and enroll in a premier test-preparation academy in Kota, Rajasthan. Thanks to that education, she passed what she describes as "one of the most competitive exams in the world," to get into the Indian Institute of Technology Bombay.

Once admitted to a combined bachelor's and master's program in electrical engineering, she found that "it was a real boys' club." But Goenka excelled in developing computer architecture systems that accelerate computation. As an undergraduate, she began applying those skills to medicine, driven by her desire to "have

real-world impact"—in part because she had seen her family struggle with painful uncertainty after her brother was born prematurely when she was eight years old.

While working on a PhD in electrical engineering at Stanford, she turned her focus to evolutionary and clinical genomics. One day a senior colleague, Euan Ashley, presented her with a problem. He said, "We want to see how fast we can make a genetic diagnosis. If you had unlimited funds and resources, just how fast do you think you could make the compute?"

Every year, *MIT Technology Review* selects 35 young researchers, scientists, and entrepreneurs who are doing groundbreaking work in their fields for our annual list of Innovators Under 35. We also pick one individual whose work we admire to recognize as Innovator of the Year. Meet all this year's honorees at **www.technologyreview.com/35innovatorsunder35_2025** when the list publishes online on September 8.

Streaming DNA

A genetic diagnosis starts with a blood sample, which is prepped to extract the DNA—a process that takes about three hours. Next that DNA needs to be "read." One of the world's leading long-read sequencing technologies, developed by Oxford Nanopore Technologies, can generate highly detailed raw data of an individual's genetic code in about an hour and a half. Unfortunately, processing all this data to identify mutations can take another 21 hours. Shipping samples to a central lab and figuring out which mutations are of interest often leads the process to stretch out to weeks.

Goenka saw a better way: Build a real-time system that could "stream" the sequencing data, analyzing it as it was being generated, like streaming a film on Netflix rather than downloading it to watch later.

To do this, she designed a cloud computing architecture to pull in more processing power. Goenka's first challenge was to increase the speed at which her team could upload the raw data for processing, by streamlining the requests between the sequencer and the cloud to avoid unnecessary "chatter." She worked out the exact number of communication channels needed—and created algorithms that allowed those channels to be reused in the most efficient way.

The next challenge was "base calling"—converting the raw signal from the sequencing machine into the nucleotide bases A, C, T, and G, the language that makes up our DNA. Rather than using a central node to orchestrate this process, which is an inefficient, error-prone approach, Goenka wrote software to automatically assign dozens of data streams directly from the sequencer to dedicated nodes in the cloud.

Then, to identify mutations, the sequences were aligned for comparison with a reference genome. She coded a custom program that triggers alignment as soon as base calling finishes for one batch of sequences while simultaneously initiating base calling for the next batch, thus ensuring that the system's computational resources are used efficiently.

Add all these improvements together, and Goenka's approach reduced the total time required to analyze a genome for mutations from around 20 hours to 1.5 hours. Finally, the team worked with genetic counselors and physicians to create a filter that identified which mutations were most critical to a person's health, and that set was then given a final manual curation by a genetic specialist. These final stages take up to three hours. The technology was close to being fully operational when, suddenly, the first patient arrived.

A critical test

When 13-year-old Matthew was flown to Stanford's children's hospital in 2021, he was struggling to breathe and his heart was failing. Doctors needed to know whether the inflammation in his heart was due to a virus or to a genetic mutation that would necessitate a transplant.

His blood was drawn on a Thursday. The transplant committee made its decisions on Fridays. "It meant we had a small window of time," says Goenka.

Goenka was in Mumbai when the sequencing began. She stayed up all night, monitoring the computations. That was when the project stopped being about getting faster for the sake of it, she says: "It became about 'How fast can we get this result to save this person's life?'"

The results revealed a genetic mutation that explained Matthew's condition, and he was placed on the transplant list the next day. Three weeks later, he received a new heart. "He's doing great now," Goenka says.

So far, Goenka's technology has been tested on 26 patients, including Matthew. Her pipeline is "directly affecting the medical care of newborns in the Stanford intensive care units," Ashley says.

Now she's aiming for even broader impact—Goenka and her colleagues are laying the groundwork for a startup that they hope will bring the technology to market and make sure it reaches as many patients as possible. Meanwhile, she has been refining the computational pipeline, reducing the time to diagnosis to about six hours.

The demand is clear, she says: "In an in-depth study involving more than a dozen laboratory directors and neonatologists, every respondent stressed urgency. One director put it succinctly: 'I need this platform today—preferably yesterday.'"

Goenka is also developing software to make the technology more inclusive. The reference genome is skewed toward people of European descent. The Human Pangenome Project is an international collaboration to create reference genomes from more diverse populations, which Goenka aims to use to personalize her team's filters, allowing them to flag mutations that may be more prevalent in the population to which a patient belongs.

Since seeing her work, Goenka's extended family has become more appreciative of her education and career. "The entire family is very proud about the impact I've made," she says. ■

Helen Thomson is a freelance science journalist based in London.

The case against humans in space

Three books push back on a rising tide of optimism about space settlements.

By Becky Ferreira

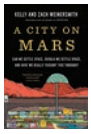
Illustration by Kagan McLeod

Elon Musk and Jeff Bezos are bitter rivals in the commercial space race, but they agree on one thing: Settling space is an existential imperative. Space is the place. The final frontier. It is our human destiny to transcend our home world and expand our civilization to extraterrestrial vistas.

This belief has been mainstream for decades, but its rise has been positively meteoric in this new gilded age of astropreneurs. Expanding humanity beyond Earth is both our birthright and our duty to the future, they insist. Failing to do so would consign our species to certain extinction—either by our own hand, perhaps through nuclear war or climate change, or in some cosmic disaster, like a massive asteroid impact.

But as visions of giant orbital stations and Martian cities dance in our heads, a case against human space colonization has found its footing in a number of recent books. The argument grows from many grounds: Doubts about the practical feasibility of off-Earth communities. Concerns about the exorbitant costs, including who would bear them and who would profit. Realism about the harsh environment of space and the enormous tax it would exact on the human body. Suspicion of the underlying ideologies and mythologies that animate the race to settle space.

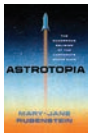
And, more bluntly, a recognition that "space sucks" and a lot of people have "underestimated the scale of suckitude," as Kelly and Zach Weinersmith put it in their book *A City on Mars: Can We Settle Space, Should We Settle Space, and Have We Really Thought This Through?*, which was released in paperback earlier this year.



A City on Mars: Can We Settle Space, Should We Settle Space, and Have We Really Thought This Through?
Kelly and Zach Weinersmith
PENGUIN RANDOM HOUSE, 2023 (PAPERBACK RELEASE 2025)



Ground Control: An Argument for the End of Human Space Exploration
Savannah Mandel
CHICAGO REVIEW PRESS, 2024



Astrotopia: The Dangerous Religion of the Corporate Space Race
Mary-Jane Rubenstein
UNIVERSITY OF CHICAGO PRESS, 2022 (PAPERBACK RELEASE 2024)

COURTESY OF THE PUBLISHERS



The Weinersmiths, a husband-wife team, spent years thinking it through—in delightfully pragmatic detail. *A City on Mars* provides ground truth for our lofty celestial dreams by gaming out the medical, technical, legal, ethical, and existential consequences of space settlements.

Much to the authors' own dismay, the result is a grotesquery of possible outcomes including (but not limited to) Martian eugenics, interplanetary war, and—memorably—"space cannibalism."

The Weinersmiths puncture the gauzy fantasy of space cities by asking pretty basic questions, like how to populate them. Astronauts experience all kinds of medical challenges in space, such as radiation exposure and bone loss, which would increase risks to both parents and babies. Nobody wants their pregnant "glow" to be a by-product of cosmic radiation.

Trying to bring forth babies in space "is going to be tricky business, not just in terms of science, but from the perspective of scientific ethics," they write. "Adults can consent to being in experiments. Babies can't."

You don't even have to contemplate going to Mars to make some version of this case. In *Ground Control: An Argument for the End of Human Space Exploration,* Savannah Mandel chronicles how past and present generations have regarded human spaceflight as an affront to vulnerable children right here on Earth.

"Hungry Kids Can't Eat Moon Rocks," read signs at a protest outside Kennedy Space Center on the eve of the Apollo 11 launch in July 1969. Gil Scott-Heron's 1970 poem "Whitey on the Moon" rose to become the de facto anthem of this movement, which insists, to this day, that until humans get our earthly house in order, we have no business building new ones in outer space.

Ground Control, part memoir and part manifesto, channels this lament: How can we justify the enormous cost of sending people beyond our planet when there is so much suffering here at home?

Advocates for human space exploration reject the zero-sum framing and point to the many downstream benefits of human spaceflight. Space exploration has catalyzed inventions from the CAT scan to baby formula. There is also inherent value in our shared adventure of learning about the vast cosmos.

Those upsides are real, but they are not remotely well distributed. Mandel predicts that the commercial space sector in its current form will only exacerbate inequalities on Earth, as profits from space ventures flow into the coffers of the already obscenely rich.

In her book, Mandel, a space anthropologist and scholar at Virginia Tech, describes a personal transformation from spacey dreamer to grounded critic. It began during fieldwork at Spaceport America, a commercial launch facility in New Mexico, where she began to see cracks in the dazzling future imagined by space billionaires. As her career took her from street protests in London to extravagant space industry banquets in Washington, DC, she writes, "crystal clear glasses" replaced "the rose-colored ones."

Mandel remains enchanted by space but is skeptical that humans are the optimal trailblazers. Robots, rovers, probes, and other artificial space ambassadors could do the job for a fraction of the price and without risk to life, limb, and other corporeal vulnerabilities.

"A decentralization of self needs to occur," she writes. "A dissolution of anthropocentrism, so to speak. And a recognition that future space explorers may not be man, even if man moves through them."

In other words, giant leaps for mankind no longer necessitate a man's small steps; the wheels of a rover or the rotors of a copter offer a much better bang for our buck than boots on the ground.

In contrast to the Weinersmiths, Mandel devotes little attention to the physical dangers and limitations that space imposes on humans. She is more interested in a kind of psychic sickness that drives the impulse to abandon our planet and rush into new territories.

Mary-Jane Rubenstein, a scholar of religion at Wesleyan University, presents a thorough diagnosis of this exact pathology in her 2022 book *Astrotopia: The Dangerous Religion of the Corporate Space Race*, which came out in paperback last year. It all begins, appropriately enough, with the book of Genesis, where God creates Earth for the dominion of man. Over the years, this biblical brain worm has offered divine justification for the brutal colonization and environmental exploitation of our planet. Now it serves as the religious rocket fuel propelling humans into the next frontier, Rubenstein argues.

"The intensifying 'NewSpace race' is as much a mythological project as it is a political, economic, or scientific one," she writes. "It's a mythology, in fact, that holds all these other efforts together, giving them an aura of duty, grandeur, and benevolence."

Rubenstein makes a forceful case that malignant outgrowths of Christian ideas scaffold the dreams of space settlements championed by Musk, Bezos, and like-minded enthusiasts—even if these same people might never describe themselves as religious. If Earth is man's dominion, space is the next logical step. Earth is just a temporary staging ground for a greater destiny; we will find our deliverance in the heavens.

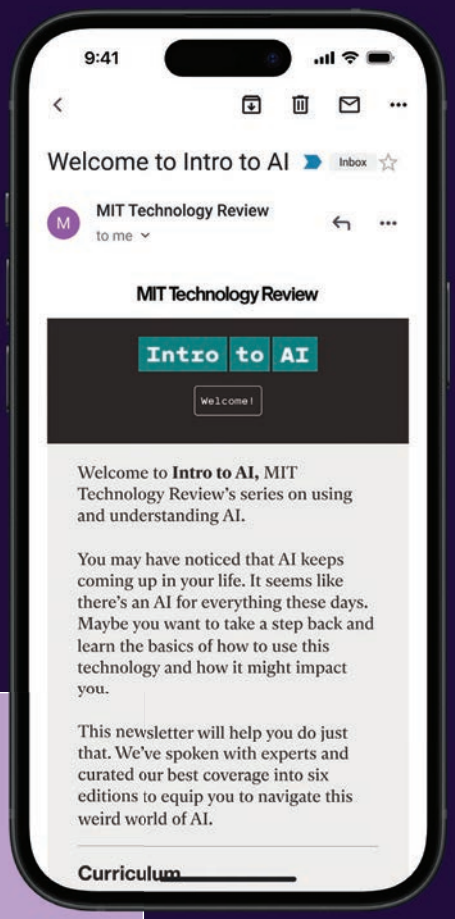
"Fuck Earth," Elon Musk said in 2014. "Who cares about Earth? If we can establish a Mars colony, we can almost certainly colonize the whole solar system."

Jeff Bezos, for one, claims to care about Earth; that's among his best arguments for why humans should move beyond it. If heavy industries and large civilian populations cast off into the orbital expanse, our home world can be, in his words, "zoned residential and light industry," allowing it to recover from anthropogenic pressures.

Bezos also believes that space settlements are essential for the betterment of humanity, in part on the grounds that they will uncork our population growth. He envisions an orbital archipelago of stations, sprawled across the solar system, that could support a collective population of a trillion people. "That's a thousand Mozarts. A thousand Einsteins," Bezos has mused. "What a cool civilization that would be."

MIT Technology Review

Intro to AI



Understand AI like a pro

MIT Technology Review's new **Intro to AI** 6-week newsletter course is here to simplify complex concepts and make AI accessible for everyone.

You'll learn how AI:

- Intersects with our everyday life
- Is reshaping a multitude of industries
- Can be utilized to its full potential

Ready to dive in? Sign up for free today.

Scan here to sign up or learn more at **TechnologyReview.com/IntroToAI**

It does sound cool. But it's an easy layup for Rubenstein: This "numbers game" approach would also produce a thousand Hitlers and Stalins, she writes.

And that is the real crux of the argument against pushing hard to rapidly expand human civilization into space: We will still be humans when we get there. We won't escape our vices and frailties by leaving Earth—in fact, we may exacerbate them.

While all three books push back on the existential argument for space settlements, the Weinersmiths take the rebuttal one step further by proposing that space colonization might actually increase the risk of self-annihilation rather than neutralizing it.

"Going to space will not end war because war isn't caused by anything that space travel is apt to change, even in the most optimistic scenarios," they write. "Humanity going to space en masse probably won't reduce the likelihood of war, but we should consider that it might increase the chance of war being horrific."

The pair imagine rival space nations exchanging asteroid fire or poisoning whole biospheres. Proponents of space settlements often point to the fate of the dinosaurs as motivational grist, but what if a doomsday asteroid were deliberately flung between human cultures as a weapon? It may sound outlandish, but it's no more speculative than a floating civilization with a thousand Mozarts. It follows the same logic of extrapolating our human future in space from our behavior on Earth in the past.

So should we just sit around and wait for our inevitable extinction? The three books have more or less the same response: What's the rush? It is far more likely that humanity will be wiped out by our own activity in the near term than by any kind of cosmic threat. Worrying about the expansion of the sun in billions of years, as Musk has openly done, is frankly hysterical.

In the meantime, we have some growing up to do. Mandel and Rubenstein both argue that any worthy human future in space must adopt a decolonizing approach that emphasizes caretaking and stewardship of this planet and its inhabitants before we set off for others. They draw inspiration from science fiction, popular culture, and Indigenous knowledge, among other sources, to sketch out these alternative visions of an off-Earth future.

Mandel sees hope for this future in post-scarcity political theories. She cites various attempts to anticipate the needs of future generations—ideas found in the work of the social theorist Aaron Benanav, or in the values expressed by the Green New Deal, or in the fictional Ministry for the Future imagined by Kim Stanley Robinson in his 2020 novel of the same name. Whatever you think of the controversial 2025 book *Abundance*, by Ezra Klein and Derek Thompson, it is also appealing to the same demand for a post-scarcity road map.

To that end, Mandel envisions "the creation of a governing body that would require that techno-scientific plans, especially those with a global reach, take into consideration multigenerational impacts and multigenerational voices."

For Rubenstein, religion is the poison, but it may also offer the cure. She sees potential in a revival of pantheism, which is the belief that all the contents of the universe—from rocks to humans to galaxies—are divine and perhaps alive on some level. She hasn't fully converted herself to this movement, let alone become an evangelist, but she says it's a spiritual direction that could be an effective counterweight to dominionist views of the universe.

"It doesn't matter whether … any sort of pantheism is 'true,'" she writes. "What matters is the way any given mythology prompts us to interact with the world we're a part of—the world each of our actions helps to make and unmake. And frankly, some mythologies prompt us to act better than others."

All these authors ultimately conclude that it would be great if humans lived in space—someday, if and when we've matured. But the three books all express concerns about efforts by commercial space companies, with the help of the US government, to bypass established space laws and norms—concerns that have been thoroughly validated in 2025.

The combustible relationship between Elon Musk and Donald Trump has raised eyebrows about cronyism—and retribution—between governments and space companies. Space is rapidly becoming weaponized. And recent events have reminded us of the immense challenges of human spaceflight. SpaceX's next-generation Starship vehicle has suffered catastrophic failures in several test flights, while Boeing's Starliner capsule experienced malfunctions that kept two astronauts on the International Space Station for months longer than expected. Even space tourism is developing a bad rap: In April, a star-studded all-woman crew on a Blue Origin suborbital flight was met with widespread backlash as a symbol of out-of-touch wealth and privilege.

It is at this point that we must loop back to the issue of "suckitude," which Mandel also channels in her book through the killer opening of M.T. Anderson's novel *Feed*: "We went to the moon to have fun, but the moon turned out to completely suck."

The dreams of space settlements put forward by Musk and Bezos are insanely fun. The reality may well suck. But it's doubtful that any degree of suckitude will slow down the commercial space race, and the authors do at times seem to be yelling into the cosmic void.

Still, the books challenge space enthusiasts of all stripes to imagine new ways of relating to space that aren't so tactile and exploitative. Along those lines, Rubenstein shares a compelling anecdote in *Astrotopia* about an anthropologist who lived with an Inuit community in the early 1970s. When she told them about the Apollo moon landings, her hosts burst out in laughter.

"We didn't know this was the first time you white people had been to the moon," they said. "Our shamans go all the time … The issue is not whether we go to visit our relatives, but how we treat them and their homeland when we go." ■

Becky Ferreira is a science reporter based in upstate New York, and author of First Contact, a book about the search for alien life, which will be published in September.

MIT Technology Review

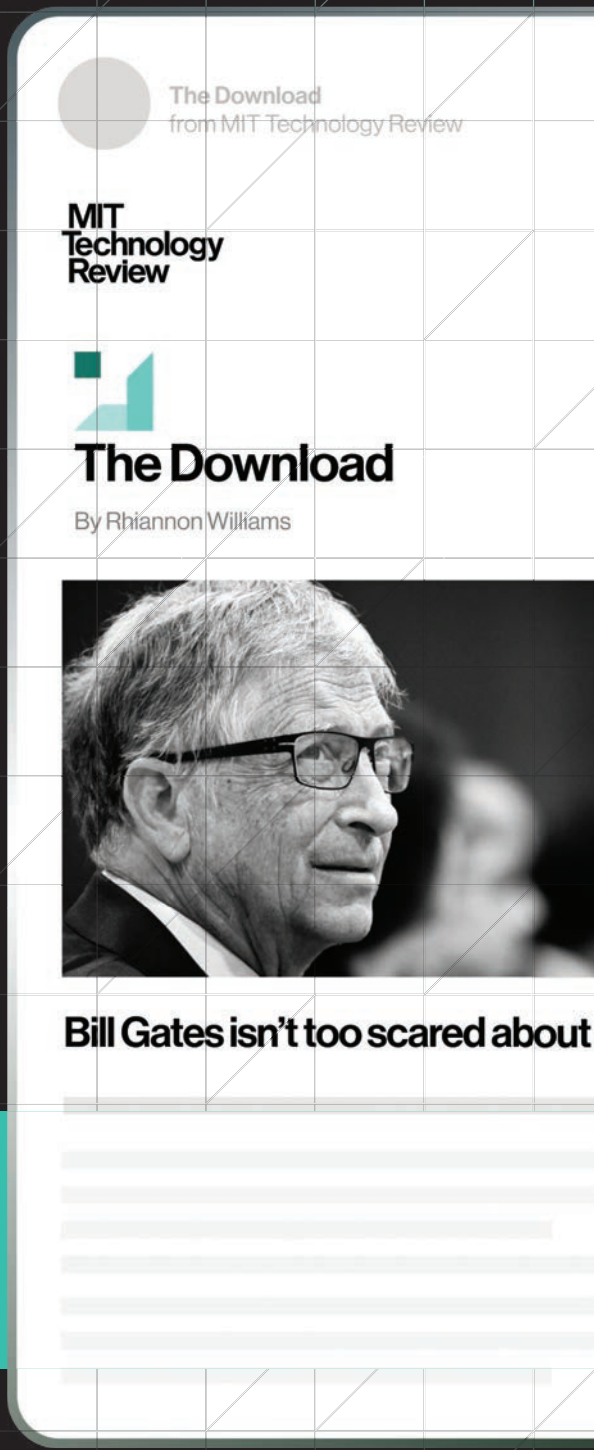
Get more of the news you depend on.

Sign up to receive our free topical newsletters and be the first to know about the emerging technology news shaping our world – and what it means for our future.

MIT Technology Review

PRIVACY.FLOWCODE.COM

Scan this code to sign up today
or visit TechnologyReview.com/SignMeUp



These Indigenous contemporary artists are reimagining relationships between technology, memory, and resistance.

By Petala Ironcloud

Indigenous knowledge meets artificial intelligence

There is no word for art in most Native American languages. Instead, the closest terms speak not to objecthood but to action and intention. In Lakota, "wówačhiŋtȟaŋka" implies deep thought or reflection, while "wóčhekiye" suggests offering or prayer. Art is not separate from life; it is ceremony, instruction, design. Like architecture or code, it carries knowledge and enacts responsibility. Its power lies not in being preserved or displayed but in how it moves, teaches, and connects through use—principles that challenge the tech industry's assumptions about intelligence and interaction.

A new vanguard of Native artists including Suzanne Kite (Oglala Lakota) and Nicholas Galanin (Tlingít) are building on this principle. They are united not by stereotypical weaving and carving or revanchist critique of Silicon Valley, but through their rejection of extractive data models in favor of relationship-based systems. These technologists put the human-tech relationship at the center of their work.

Suzanne Kite's AI art installations, for example, model a Lakota framework of data sovereignty: intelligence that emerges only through reciprocal, consensual interaction. Unlike systems that assume user consent via opaque terms of service, her kinetic machines require the viewer's physical presence—and give something back in return.

"It's my data. It's my training set. I know exactly what I did to train it. It's not a large model but a small and intimate one," Kite says. "I'm not particularly interested in making the most technologically advanced anything. I'm an artist; I don't make tech demos. So the complexity needs to come at many layers—not just the technical."

Where Kite builds working prototypes of consent-based AI, other artists in this cohort explore how sound, robotics, and performance can confront the logic of automation, surveillance, and extraction. But Native people have never been separate from technology. The land, labor, and lifeways that built America's infrastructure—including its tech—are Indigenous. The question isn't whether Native cultures are contributing now, but why they were ever considered separate.

Native technologies reject the false binaries foundational to much Western innovation. These artists ask a more radical question: What if intelligence couldn't be gathered until a relationship had been established? What if the default were refusal, not extraction? These artists aren't asking to be included in today's systems. They're building what should come next. ■

Petala Ironcloud is a California-born Lakota/Dakota and Jewish writer and textile artist based in New York.



Suzanne Kite

Ínyan Iyé (Telling Rock)

2019

This installation uses embedded AI to speak and respond to viewers, upending assumptions about intelligence and agency. "People listen close, I whisper / The rock speaks beyond hearing ... Many nations speaking / We speak to each other without words," it intones, its lights shifting as viewers engage with its braided tendrils. The piece aims to convey what Kite calls "more-than-human intelligence"—systems rooted in reciprocity, the fundamental principle that all relationships involve mutual exchange and responsibility.

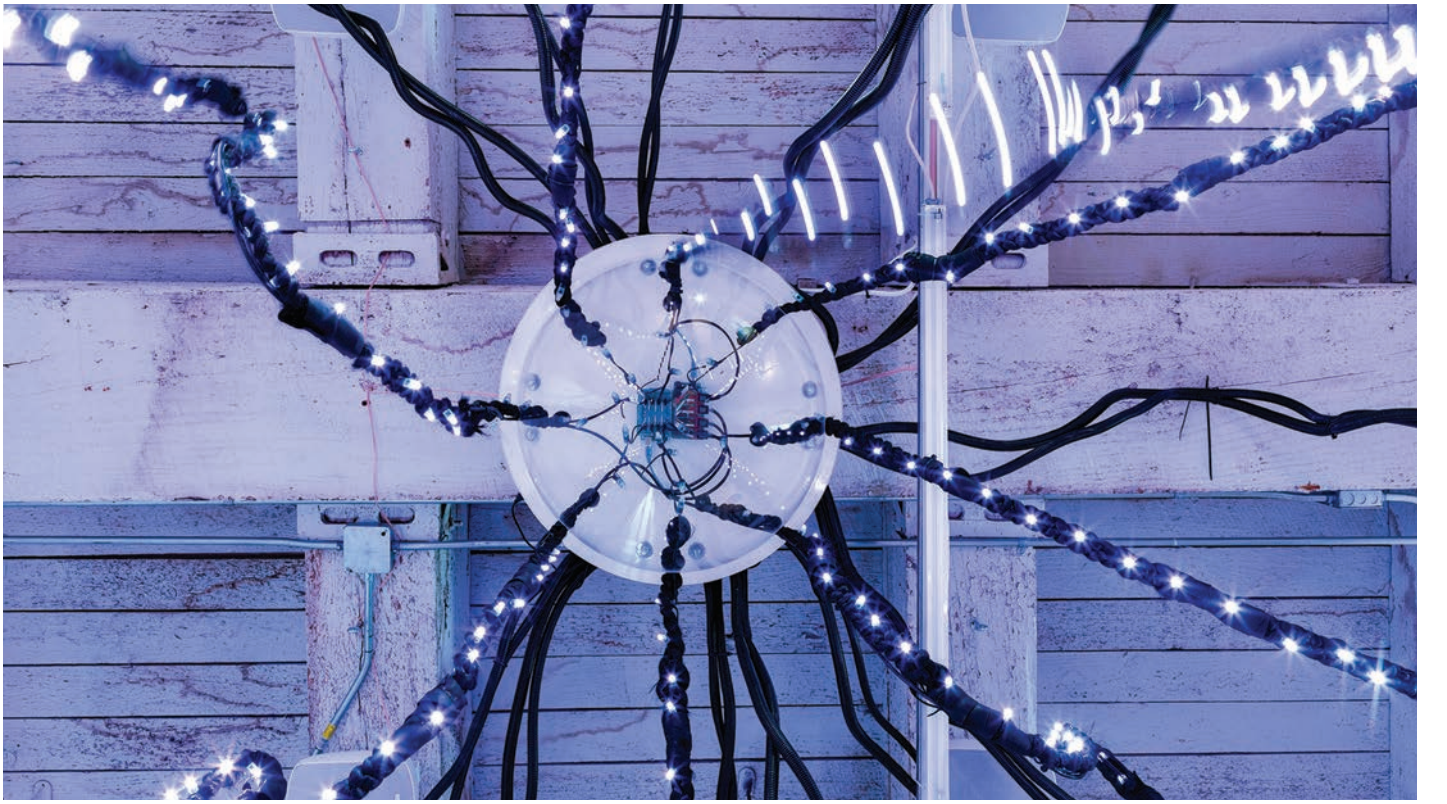
COURTESY OF THE ARTIST



Wičhíŋčala Šakówiŋ (Seven Little Girls)

2023

For Kite, the fundamental flaw of Western technology is its severance of knowledge from the body. In this installation, a four-meter hair braid with embedded sensors translates the artist's body movements into machine-learning algorithms. During her live performance, Kite dances while the braid reads the force and rhythm of her gestures, generating audio responses that fill the museum gallery of the Institute of American Indian Arts in Santa Fe, New Mexico. Below her, stones arranged in patterns reflecting Lakota star maps anchor the performance in traditional astronomical knowledge.





Nicholas Galanin

Aáni yéi xat duwasáakw
(I am called Land)

2025

Galanin's mechanical drum installation stages a conflict between machine motion and human memory, asking what happens when culture is performed without a consenting body. A box drum—an instrument historically carved from red cedar and hung with braided spruce root—is here made of cherrywood and suspended from the ceiling at the MassArt Art Museum in Boston as is traditionally done in Tlingit plank houses. Played at tribal meetings, celebrations, and ceremonies, these drums hold sonic memory as well as social function. A mechanical arm strikes, unfaltering, at the tempo of a heartbeat; like a warning, the sound pulses with the tension between automation and ancestry.



I think it goes like this (pick yourself up)
2025

This Herculean bronze sculpture cast from deconstructed faux totem blocks serves to indict settler sabotage of Native technology and culture. Unlike today's digital records—from genealogical databases to virtual versions of sacred texts like the Bible—Tlingit data is carved in wood. Galanin's totem poles underscore their function as information systems, their carvings encoding history, mythology, and family.

COURTESY OF THE ARTIST

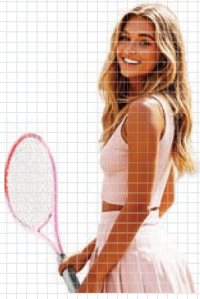
The AI Hype Index

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

UTOPIA



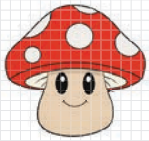
Good news: A technique called "machine unlearning" could help **combat harmful audio deepfakes**.



Mia Zelu's career as an influencer took off after she attended this year's Wimbledon tennis tournament. The catch? **She's AI-generated**.



OpenAI is going to **extreme lengths to protect its trade secrets** from spies.



People are talking to chatbots about their feelings while they **trip on psychedelics**.

The Trump administration is trying to crack down on what it calls "**woke AI**."





Meta is reportedly spending **hundreds of millions of dollars** to entice AI researchers to join its "superintelligence" team.



Google's new video-generating AI model Veo 3 keeps **slapping nonsensical subtitles on its creations**, even when users tell it not to.



xAI **signed a deal with the Pentagon** mere days after its chatbot Grok went on a vile antisemitic rant.



Uber founder Travis Kalanick is doing "**vibe physics**" with AI chatbots, and he is convinced he's close to making some big breakthroughs (he has zero background in physics).



Slippery slope? Netflix has **used AI tools** in one of its TV shows for the first time.



Grok **looks up Elon Musk's opinions** before responding to people's questions on controversial topics.

People with body dysmorphia are asking AI models to **rate their appearance**—and then give them advice on how to improve themselves.



OpenAI's latest agent is designed to **complete work on your behalf** via its own "virtual computer."



Oh dear—the White House has created **AI slop videos of the Founding Fathers**.

Predictably, the newly launched AI companions powered by Grok are already **discussing sex and how to kill children**.





DOOM

HYPE

REALITY

MIT Technology Review (ISSN 1099-274X), September/October 2025 issue, Reg. US Patent Office, is published bimonthly by MIT Technology Review, 196 Broadway, 3rd Floor, Cambridge, MA 02139. Entire contents ©2025. The editors seek diverse views, and authors' opinions do not represent the official policies of their institutions or those of MIT. Periodicals postage paid at Boston, MA, and additional mailing offices. Postmaster: Send address changes to MIT Technology Review, Subscriber Services, PO Box 1518, Lincolnshire, IL 60069, or via the internet at www.technologyreview.com/customerservice. Basic subscription rates: $120 per year within the United States; in all other countries, US$140. Publication Mail Agreement Number 40621028. Send undeliverable Canadian copies to PO Box 1051, Fort Erie, ON L2A 6C7. Printed in USA. Audited by the Alliance for Audited Media.

ADOBE STOCK (CASSETTE, MONEY, MARKER); STEPHANIE ARNETT/MIT TECHNOLOGY REVIEW (SURFER, MIA, MIRROR, FOX); ALAMY (GET SMART); COURTESY OF AMAZON STUDIOS (STILL); GETTY IMAGES (MUSK)

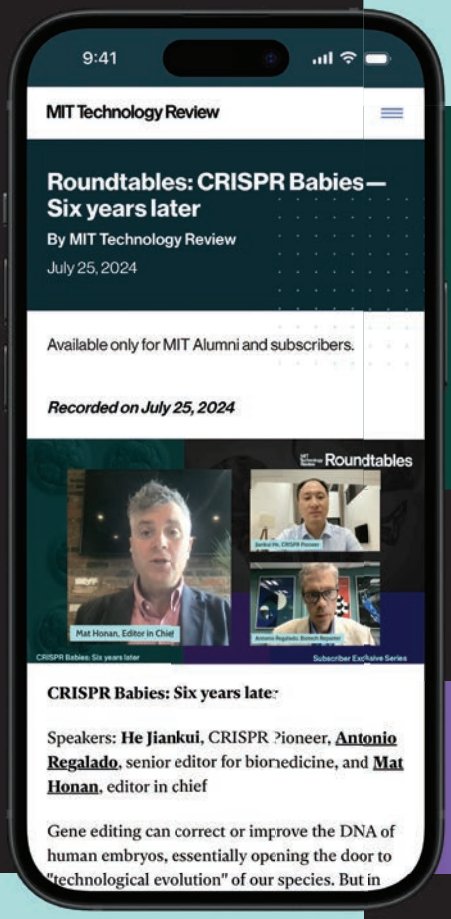
MIT Technology Review **Roundtables**

Subscriber Exclusive Series

Real-time tech conversations with the experts.

"Like having coffee with Einstein"

Subscribers have full access to our award-winning journalism with Roundtables, a subscriber-only online events series that keeps you informed on what's next in emerging tech in just 30 minutes.



Scan this code to watch past sessions, view upcoming events, and learn more, or visit **TechnologyReview.com/Roundtables**

Not a subscriber?
Visit TechnologyReview.com/EventOffer to unlock full access.

MIT Technology Review

The smartest gift you can give.

Give the gift of knowledge with an annual subscription to MIT Technology Review.

A gift subscription includes access to:

- Expert insights on the latest industry news
- Our new mobile app with innovative features
- TechnologyReview.com and magazine archives
- Roundtables, our subscriber-only online event series



Scan here to give a gift
or visit **technologyreview.com/GiveAGift**