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JANUARY 2026 VOLUME 79 NUMBER 01

A brief guide to SCIENCE OUTREACH

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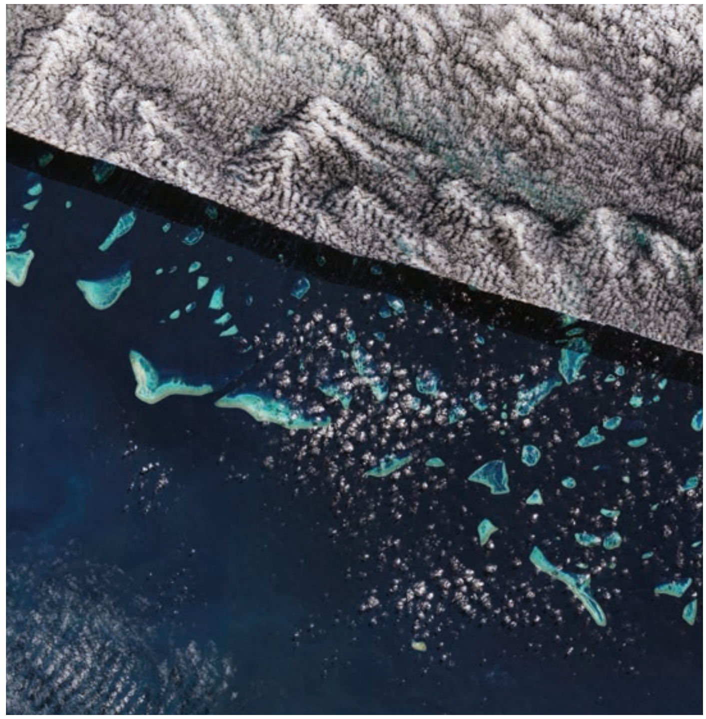

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DEPARTMENTS

ON THE COVER

Do you want to inspire younger generations to care about science? Persuade someone to fund your work? Fight the deluge of mis- and disinformation in society? If so, you might consider getting involved with science outreach. There are many possible audiences and many possible formats for reaching them: podcasts, artist collaborations, public talks, blogs, lobbying, books, and more. Don Lincoln's feature article on **page 24** can help you define your goals and pick your approach.

(Cover design by Masie Chong using an image by iStock.com/ThongSam and icons by Freddie Pagani.)

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PT PHYSICS TODAY

TO READ ABOUT RESTRUCTURING AT LOWELL OBSERVATORY, TURN TO PAGE 17

A refreshed *Physics Today*

By Richard J. Fitzgerald

Physics Today's 75th anniversary two years ago not only provided an opportunity for us to look back at *PT*'s history but also prompted us to look ahead to its future. In particular, we took stock of the multifaceted changes in the ways that people engage with science, with news, and with each other—changes accelerated by the growing international and interdisciplinary nature of science, the increasing speed of communication, and the explosion of competition for audiences' attention.

An essential part of *PT*'s future was immediately clear: The monthly rhythm of a print magazine was insufficient for keeping up with both the pace of science and the pace of events affecting the scientific community. We thus embarked on a digital transformation, the results of which you can see at https://physicstoday.org. No longer will you need to wait until the next monthly issue to read our latest content; it is now produced on a continual basis, with most content subsequently appearing in the next print issue. The website, too, has a new look and is on a new platform, which offers a modern, more magazine-like experience that makes it easier to find content you care about.

This issue marks another milestone in our transformation. Our move to a new online home has enabled us, for the first time, to unify our online and print designs. For all the advantages presented by the new *PT* website, we know that many of you continue to look forward to receiving a physical magazine that you can hold, browse, and happen across new things in, so we leapt at the opportunity to refresh and update its look, which makes its debut in this issue. Beyond our new *PT* logo, you'll see cleaner layouts, fewer distractions, larger and more readable fonts, and other changes designed to present a more inviting, enjoyable, and consistent reader experience.

Although our look has changed, the content remains true to our mission: to be a unifying influence on the physical sciences by cultivating a shared understanding, appreciation, and sense of belonging among scientists. Through feature articles, reports on research advances, news of trends affecting the scientific community, profiles of trailblazers, and unique voices, we cover the physical sciences without regard to disciplinary boundaries and capture the experience of being a scientist today.

In this issue we present advice on how to get started with science outreach, a deep dive into the science behind the 2025 Nobel Prize in Physics, and an analysis of the oversight needs for climate-intervention strategies. It reports on recent research on quasicrystals and a 160-year-old study of snowflake crystals. The issue includes trends in US physics and astronomy faculty numbers and a short interview with a physics PhD who pursued a career in the international public sector, outside of academia. And it introduces a new regular feature: a physics-themed crossword.

PT's evolution, of course, is not over. Nor do we want it to be. Even as we remain familiar, we will also remain fresh—and that requires continued change and innovation. And since *PT* is a magazine for and about you, it will also evolve with feedback from you—whether at conferences, in reader surveys, or via https://contact.physicstoday.org or pteditors@aip.org.

Welcome to the new *Physics Today*. PT

A quasicrystal engulfs obstacles to grow without defects

The behavior emerges from atomic-scale rearrangements of nonperiodic ordered structures, according to real-time observations and molecular dynamics simulations.

By Alex Lopatka

"Quasicrystals have always fascinated me," says Ashwin Shahani of the University of Michigan, "because they break the usual rules." Like regular crystals, quasicrystals have ordered structures, but the structures are nonperiodic. At least two unit cells arranged repeatedly in space without any overlaps or gaps are required to form a quasicrystalline structure. Dan Shechtman's 1982 discovery of quasicrystals was initially met with disbelief by crystallographers. (For more on the finding, see *PT*'s 2011 story "Nobel Prize in Chemistry honors the discovery of quasicrystals.")

One defining feature of quasicrystals is that they have symmetries that regular crystals don't. The crystallographic restriction theorem states that crystals look the same after being rotated a certain angle. (A rectangle, for example, looks the same when it's rotated 180°, so it has 360°/180° = 2-fold rotation symmetry.) For regular crystals, the allowed values are 2-, 3-, 4-, or 6-fold rotation symmetries. But quasicrystals exist with 5-fold and 10-fold rotation symmetries, which allow them to grow into different structures than crystals.

As crystals grow, disruptions in their lattices interrupt the periodic order of the structures. Such material defects can be responsible for grain boundaries and twinning, in which two or more crystals symmetrically share lattice points. Some evidence suggests that growing quasicrystals are immune to such disruptions. In 2021, a team including Shahani and Michigan colleague Sharon Glotzer found that even after two growing quasicrystals collided with each other and became misoriented, they rearranged their structures to form a single perfect quasicrystal.[1]

Shahani's and Glotzer's research groups—which include Kelly Wang, now a data scientist at Rhombus Power; Domagoj Fijan, a research investigator at Michigan; and Insung Han, now a professor at Kyungpook National University in Daegu, South Korea—have recently demonstrated similar phenomena for a single quasicrystal with 10-fold symmetry that formed in a disruption-laden environment. It initially grows around noncrystalline obstacles in a molten alloy, deforms, and then re-forms without defects.[2]

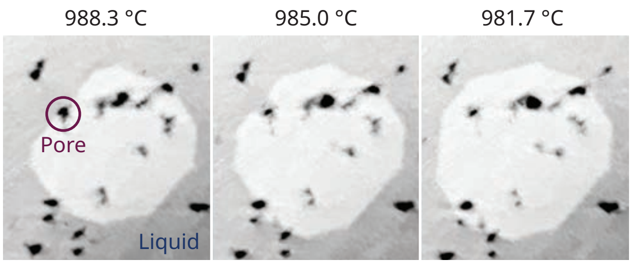


Figure 1. A quasicrystal grows defect-free. As a 150-μm-wide, 10-sided quasicrystal (white) cools and solidifies from an aluminum-cobalt-nickel liquid alloy over a few minutes, it encounters shrinkage pores (black specks). The obstacles initially distort the shape of the quasicrystal. But because of its ability to rearrange its lattice points while preserving the ordered structure, the quasicrystal forms without defects. (Images courtesy of Insung Han and Ashwin Shahani.)

The defect-free growth is possible because of quasicrystals' ability to subtly rearrange their structure. The new results are more than just a validation of that ability. That a 10-sided quasicrystal with 10-fold rotation symmetry can self-heal as it grows in nonpristine settings could make some quasicrystals appealing for various applications.

Unexpected pores

To study quasicrystals, researchers typically grow them in a lab. It's a challenging task, mostly because thermodynamically stable forms are possible in only a handful of alloys. One of the most common ones to study is the aluminum-cobalt-nickel alloy $Al_{79}Co_6Ni_{15}$.

The internal structures of the opaque samples of $Al_{79}Co_6Ni_{15}$ can be observed nondestructively only with high-energy x rays produced at synchrotrons. After a sample has solidified, some basic features of quasi-

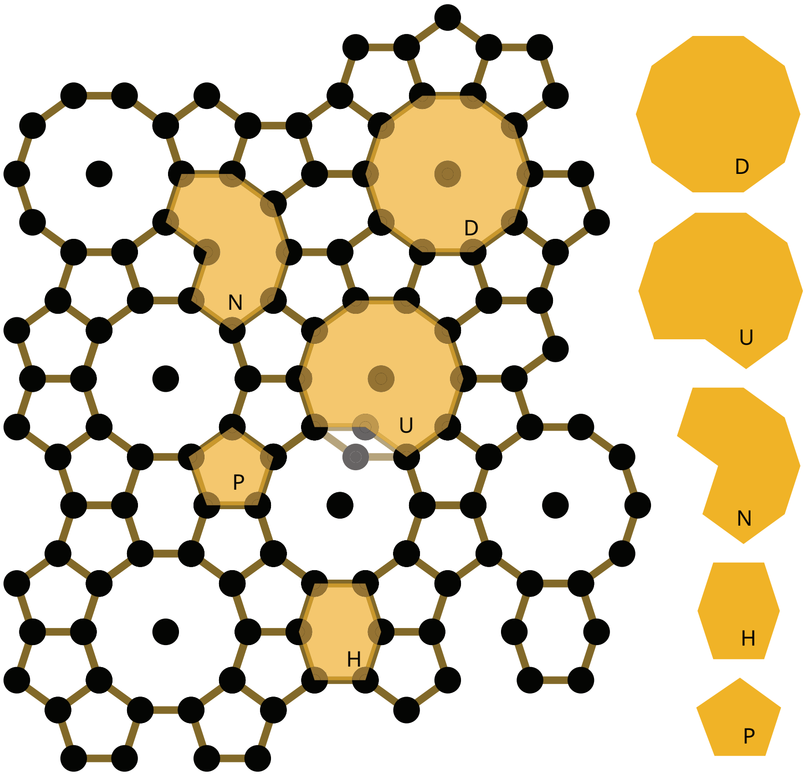


Figure 2. Quasicrystals have a nonperiodic ordered structure—in this 2D case, it's made with five tiling shapes—that fills a space without gaps. If the gray lattice point is displaced downward from its original position, the labeled U tile becomes a D tile, and the D tile below it becomes a U tile. That switch, known as a phason flip, preserves the ordered structure. Phason flips relax the strain that's induced when the growth front of a quasicrystal collides with an obstacle and allow the quasicrystal to grow without defects. (Illustration courtesy of Domagoj Fijan.)

crystalline growth can be recovered, but detailed observations of real-time growth are impossible once the quasicrystal has formed. X-ray radiography measures some of the dynamics of quasicrystals as they grow in a liquid, but the method provides only 2D observations with limited precision.

In the 2010s, developments in beamline optics, high-speed detectors, and reconstruction algorithms provided quasicrystal researchers with a new capability: real-time 3D x-ray tomography. The technique involves rotating a sample and collecting numerous 2D images over a short period of time. The images are then processed together to create a 3D reconstruction. Using the technology in 2019, Han, Shahani, and colleagues published 3D observations of quasicrystals' growth.[3]

For the most recent study, the goal was to better observe the growth of quasicrystals from a liquid alloy. Initial observations, however, showed something unexpected: air pockets in the molten liquid. During solidification, as the viscous liquid-metal alloy reduced in volume, voids, also called shrinkage pores, formed. The emergence of the pores provided the researchers with an opportunity to study what happens when a growing quasicrystal encounters such obstacles.

Figure 1 shows three snapshots, taken at the Advanced Photon Source at Argonne National Laboratory in Lemont, Illinois, of a quasicrystal as it solidifies from the liquid $Al_{79}Co_6Ni_{15}$ alloy. As the growth front at the solid–liquid interface encounters a shrinkage pore, the crystal face initially distorts. But within a few minutes, the quasicrystal engulfs the defect and returns to its pristine, 10-sided morphology.

When a quasicrystal's growth front encounters a defect—whether that's a grain boundary, a pore, or some other obstacle—the entire structure becomes strained. The strain to a crystal's structure often leads to irreparable defects. But for a quasicrystal, the strain can be relieved through complex rearrangements of the material's particles. The rearrangements, known as phasons, are unique to quasicrystals and arise from their 5-fold, 10-fold, and other unusual symmetries. The phasons enable the quasicrystals observed by the research team to adjust to and engulf the defect yet still preserve the quasicrystals' long-range positional order and structure.

The thorny mathematics behind phasons describes quasicrystals as 3D nonperiodic projections that arise from higher-dimensional periodic lattices.[4] A phason displacement of a lattice point is illustrated in a simplified way in figure 2.

Return to order

To better understand the phason repair mechanism, Wang and Fijan conducted molecular dynamics simulations of quasicrystal growth. When studying crystals, glasses, and many other systems, researchers often use box models with periodic boundaries: If a particle moves out of the simulation box on one side, for example, it comes back on the other side.

For the new research, the simulations modeled the growth of both a quasicrystal and a common body-centered cubic crystal around a shrinkage pore. To suppress artifacts from periodic boundary conditions, a liquid-like phase was added to the edges of the simulation box and prevented unwanted boundary interactions with the quasicrystal.

The simulations included about 5 million particles—other crystal simulations typically have on the order of thousands of particles. On top of that challenge, the researchers had to run several hundred simulations on a supercomputer to understand the statistics of the dynamic system. "I think that's why people generally don't do this sort of simulation," says Wang. "It's not that it's impossible. I think there's just easier things to do with your time."

The simulations quantified a series of parameters that describe the degree of order in the material structure. In the quasicrystal case, the calculated order parameters initially decreased after the growth front collided with and engulfed the pore. Then they increased over time and returned to their precollision values. The increase is consistent with quasicrystals' capability of structural rearrangement. Once the common crystal encountered the pore, however, the order parameters decreased and never recovered.

Beyond validating theoretical models, the new simulation and experimental results suggest that quasicrystals could be incorporated into materials to make them tolerant of defects. The durability and low friction of quasicrystals have made them possible candidates for nonstick coatings and other surface treatments. Because of their unique structural properties and their capacity for growing defect-free, quasicrystals may have other potential applications too. Some research has examined their use as reinforcements in metal composites and polymer materials.[5] **PT**

References

1. I. Han et al., "Formation of a single quasicrystal upon collision of multiple grains," *Nat. Commun.* **12**, 5790 (2021).
2. K. L. Wang et al., "Defect-free growth of decagonal quasicrystals around obstacles," *Phys. Rev. Lett.* **135**, 166203 (2025).
3. I. Han et al., "A side-by-side comparison of the solidification dynamics of quasicrystalline and approximant phases in the Al–Co–Ni system," *Acta Cryst. A* **75**, 281 (2019).
4. C. Janot, *Quasicrystals: A Primer*, 2nd ed., Oxford U. Press (2012).
5. W. Wolf et al., "Recent developments on fabrication of Al-matrix composites reinforced with quasicrystals: From metastable to conventional processing," *J. Mater. Res.* **36**, 281 (2021).

UPDATES

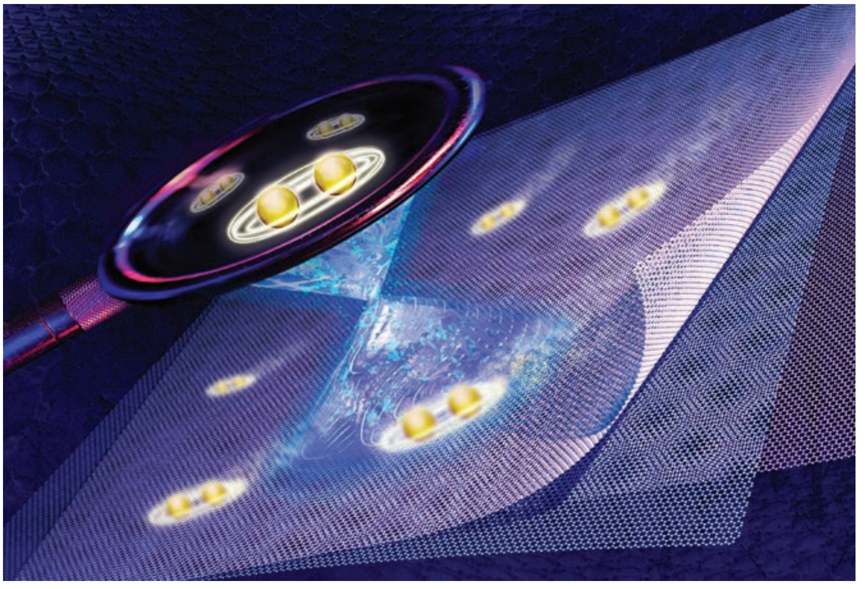
Energy scales of superconducting graphene come into focus

To get a handle on how a superconductor forms its electron pairs, researchers first need to know what it takes to rip them apart.

By **Johanna L. Miller**

It's one of the most stubborn open questions of modern physics: What's the mechanism of high-temperature superconductivity? All superconductors need some way of binding their electrons, which are fermions, into quasiparticles called Cooper pairs, which act as bosons. The low-temperature superconductivity in metals is well described by the Bardeen-Cooper-Schrieffer theory, which states that the pairs are held together by phonons. But in 1986, cuprate ceramics were discovered to superconduct at a much higher temperature via a different, unknown mechanism. Despite four decades of research and the discovery of many other unconventional superconducting materials, their mechanism remains a mystery.

So the condensed-matter physics community took note when, in 2018, superconductivity was found in magic-angle graphene: two or more layers of the atomically thin carbon material stacked with a relative twist of 1.1°. Its allure is in its tunability: With a single graphene device, researchers can explore regions of the superconducting phase diagram that otherwise would require the synthesis of several new materials. But despite that advantage, magic-angle graphene has until now resisted a basic measurement: the size of the hole in the density of states called the su-

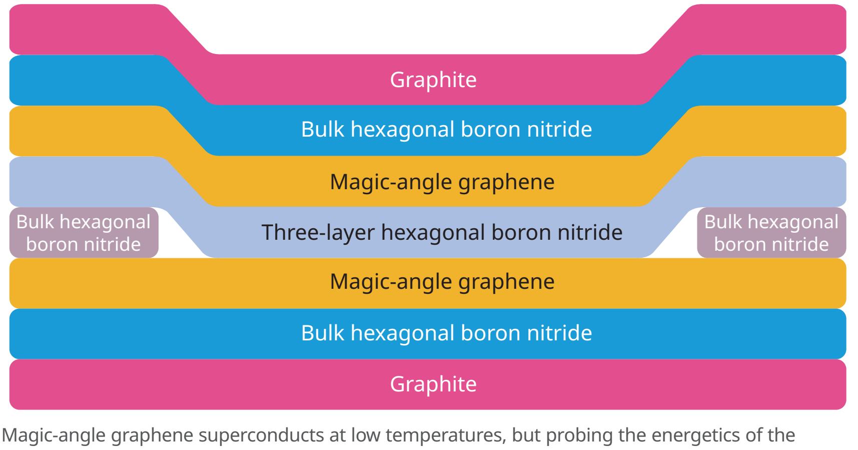


When sheets of graphene are stacked at just the right angle, their electrons form Cooper pairs at low temperatures, and the material becomes a superconductor. (Illustration by Sampson Wilcox and Emily Theobald, RLE, MIT.)

perconducting gap, a measure of how much energy is needed to break apart a Cooper pair.

It's not that the density of states couldn't be measured. That could be done using tunneling spectroscopy, a technique related to scanning tunneling microscopy. The trouble lay in confirming that the gap being measured was really a superconducting gap. Other phases of matter—for example, insulators—also have gaps in their densities of states, and magic-angle graphene hosts a rich array of phases that all lie close to one another in parameter space and thus could be easily confused. (For details, see the 2024 *PT* feature article "Twisted bilayer graphene's gallery of phases," by B. Andrei Bernevig and Dmitri K. Efetov.)

Now Princeton University's Jeong Min Park, her former PhD adviser Pablo Jarillo-Herrero at MIT, and their colleagues have overcome that challenge. They've developed a way to simultaneously measure magic-angle graphene's density of states and its charge-transport properties so that they know whether the phase that they're probing is superconducting.[1] Their experimental device, sketched below, was intricate to construct. Several of the layers are atomically thin, the two graphene layers each have electrodes attached at several points, and the central layer of bulk hexagonal boron nitride has a precisely etched hole through which the adjoining layers must smoothly contact each other.



Magic-angle graphene superconducts at low temperatures, but probing the energetics of the superconducting state has been a challenge. With this multilayered device, researchers can simultaneously measure the charge transport and density of states of the elusive superconductor. (Figure adapted from ref. 1 by Freddie Pagani.)

With their device, the researchers discovered that magic-angle graphene's density of states features two distinct energy gaps: the superconducting gap, which disappears above the critical temperature, and another, higher-energy gap called a pseudogap, which persists at higher temperatures. That observation is not yet enough to clarify the Cooper-pairing mechanism of magic-angle graphene—or any other unconventional superconductor—but it does point to a possible similarity between them: Many other unconventional superconductors also feature pseudogaps that resemble the one seen in graphene. If magic-angle graphene's pairing mechanism can be discovered, it could lead to the design of new superconductors—maybe even ones that superconduct at room temperature and pressure. **PT**

Reference

1. J. M. Park et al., "Experimental evidence for nodal superconducting gap in moiré graphene," *Science* (2025), doi:10.1126/science.adv8376.

Professional societies introduce AI for organizational tasks

AI can help scientists sort conference offerings, find grants, identify peer reviewers, and meet potential collaborators.

By Toni Feder

Which sessions at a ginormous conference should I participate in? Who should I connect with professionally? Where can I apply for research money? Those are some of the questions that professional societies are starting to delegate to AI.

"AI is redefining what's possible for professionals," says Michael Jones, vice president of mobile technologies at Results Direct, a company that works with trade associations. The associations have a wealth of data, he says, and AI makes the data more accessible.

Blazing the trail is the American Geophysical Union (AGU), which began testing AI-based programs for its members and conference attendees in summer 2025 and implementing them in the fall. Other professional societies are also experimenting with AI.

A wealth of data

When a member logs onto their AGU account, they see suggestions for professional contacts. "People you should know" is one of several new AI tools that AGU has developed to exploit its database.

Natalie Raia is a researcher at the University of Arizona who works at the intersection of Earth sciences and information science, and as a member of AGU's Digital User Group, she is testing the society's AI tools. She has made four new connections through the suggestions that popped up on her AGU home page, she says. "The suggestions can be based on career stage or on work." It's up to the individual whether they want to follow up, she says, "but it could be really good for someone seeking collaborators or a postdoctoral adviser."

AGU doesn't collect data on how often suggestions are pursued, says Thad Lurie, the society's senior vice president of digital and technology. "It's too invasive. We are sensitive to privacy."

AGU's AI tools plumb member profiles, which include publications, abstracts, and institutions. If members have linked to their ORCID identifiers, their profiles will have that information too. The tools also use data from nonmembers' publications in AGU journals and their contributions to its conferences. The data are all publicly available, but the AGU's AI tools and recommendations are accessible only to members.

Another new AGU tool called Grant Finder generates customized suggestions for applying for research funds; it works both from the society's database on members' publishing history and from keyword searches. For example, a researcher could input "air quality," "metamorphic geology," or "groundwater aquifer modeling." In testing the pilot, Raia says the tool saved her time by bringing together options from federal, state, and local agencies and philanthropies. "I was able to sift through opportunities that I probably otherwise would not have discovered." Those in-

◂ Attendance can be in the many thousands at some meetings, like this one by the American Geophysical Union in 2024. AGU and other professional societies are working to improve their members' experience with AI tools to optimize schedules and meet people. (Photo by Beth Bagley/AGU.)

clude, she says, grants through NSF that she may not have found "because of the bins and structures of the NSF website."

The goal of another tool, Session Finder, is to help conference participants figure out which sessions to submit their abstracts to and which ones to prioritize attending. AGU annual meetings are large, with roughly 25 000 attendees, more than 50 concurrent sessions, and a couple thousand talks. With Session Finder, the whole abstract is digested by AI, which then suggests relevant sessions.

For choosing which sessions to attend, the approaches until now were keyword based. "You would try to find session descriptions that matched, but things were easily missed," says Heather Lent, AGU's digital product director. For example, she says, a search for "plume" could miss relevant talks that instead mention "ash." The AI tool solves that problem by connecting the concepts.

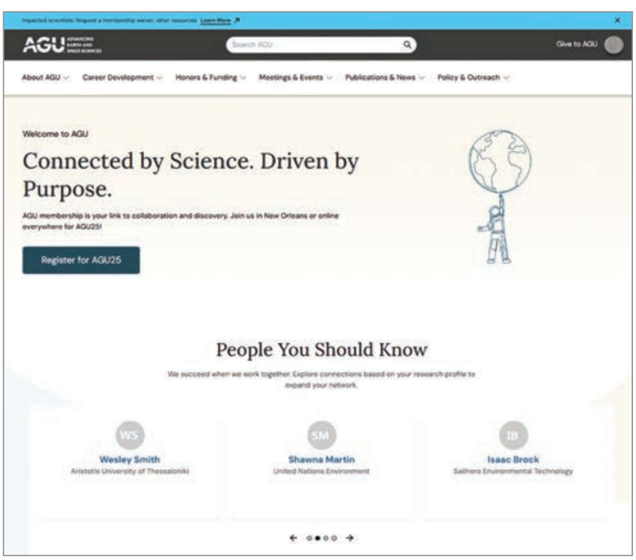
With the Session Finder, says Raia, "I tell the program, 'Here is my research. Tell me what is of interest.'" The tool finds related research in seemingly unconnected disciplines, she says. "It will challenge people to look at new topics. I think that's exciting and will lead to more mixing of people." The Session Finder, she says, will also help newcomers and students "cut through what could be a large, overwhelming program and find their spaces faster."

Diversifying peer review

AGU is also using AI to help its journal editors identify peer reviewers. "I handle hundreds of papers each year," says Sarah Feakins, an AGU editor and Earth sciences professor at the University of Southern California. Traditionally, she says, she and other editors have found peer reviewers through their own networks, author recommendations, and online searches. To get two or three reviewers, she says, she would have to make about eight requests. "Finding reviewers is a challenge."

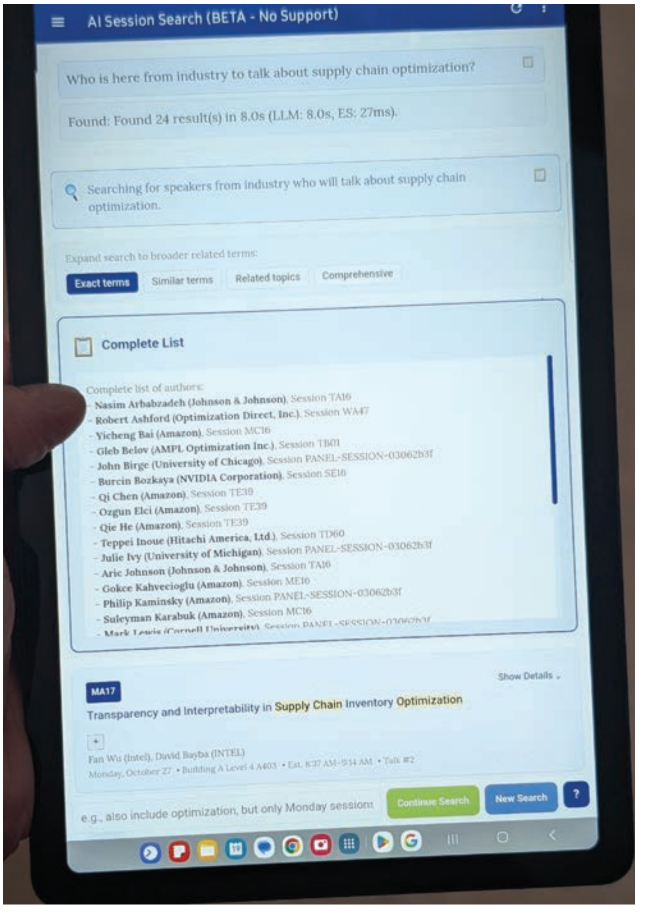
To find reviewers with the AGU AI program, the editor pastes in a paper's abstract and specifies how many suggestions they want. The program spits out names with scores that rate the match. A postdoc or student who has published only on that specific topic will have a high matching score, says Feakins, "whereas someone who has published in a wide range of areas will have a diluted score." She and other editors say that they vet suggested reviewers. Still, says Feakins, "the potential of AI to speed up workflow is vast."

Anna Wåhlin has been an editor for the *Journal of Geophysical Research: Oceans* for four years. "We always struggle to find good reviewers," says Wåhlin, a professor of physical oceanography at the University



◂ When an AGU member logs onto their account, they are now met with AI-generated suggestions for professional connections. (Screenshot with fictionalized data courtesy of Heather Lent/AGU.)

This app uses AI to help conference goers find talks, meet people, and plan their schedules. A pilot version debuted at the INFORMS annual fall meeting. (Photo by Warren Hearnes.)



of Gothenburg in Sweden. "And we tend to focus on male, senior scientists that are well known." Using the full AGU database, she says, the AI tool "does a better job than I would do" at finding candidate reviewers. In particular, she says, the pool is more diverse in terms of reviewers' gender, age, and geography. "This has brought in more reviewers from Asia that I may not have thought of before," she says.

Wåhlin has also found that she's getting a higher positive response rate from potential reviewers. "Maybe it's because these are people who haven't been asked as often," she says.

So far, the AGU peer-review tool is limited to the AGU database. That's not a big concern, says Feakins, because the database includes not just society members but anyone who has published in an AGU journal or presented at an AGU conference. That's most of the field. And partnerships with other geophysical societies in Europe and Asia may be forged in the future, says Wåhlin.

Privacy, note Feakins, Wåhlin, and others, is key to the process, which is why the AGU program is self-contained and the editors are not using ChatGPT or other widely available AI platforms. "Finding peer reviewers is an excellent use of large language models," says Wåhlin. "It helps our work as editors. And authors should be happy, too, because it speeds up the review time by about two weeks."

Enhancing value for members

Other professional societies are dipping their toes into AI along the same lines as AGU. In preparation for its January 2026 meeting, the American Astronomical Society (AAS) built a tool to sort session abstracts. "We were able to sort abstracts reliably and efficiently," says AAS CEO Kevin Marvel. "And the AI system suggests accurate session titles and organizes the sessions following our timing rules."

Overall, says Marvel, the aim is to "amplify the work of volunteers and staff." They will be freed from busywork that AI can do and be able to use their time for creative things that enhance the value for members, he says.

Warren Hearnes, the former chief data scientist at Best Buy, is vice president of technology strategy for the Institute for Operations Research and the Management Sciences (INFORMS), a professional society for decision and data sciences. He created a prototype app that debuted at the society's annual conference in October. The app is meant to help conference goers navigate the nearly 5000 talks that take place over three and a half days. It does not dive into member data but rather accesses abstracts and other conference information and uses generative AI to address queries, says Hearnes. "It tries to mimic how people think and ask questions. It helps people discover talks without having to explicitly list every keyword or topic."

The types of questions people posed to the app included things like who from industry would be talking about supply chain optimization and who the international speakers were. Those got helpful responses. But common questions like where an ATM or the bathroom was went unanswered. The program, says Hearnes, does not use location information.

"The app elevated my conference experience," says INFORMS vice president for practice Robin Lougee, who tested the prototype. "I was interested in agentic AI in industry and asked what was going on in that area on Tuesday," she says. "The app served up suggestions." It was convenient and fast, she says. "But more than fast, I found things I probably wouldn't have without it."

"We are taking baby steps," says Hearnes. "We are testing the use of large language models to get more engagement and connection at our conference and potentially on message boards. As a society, if people get value out of their society membership, we will have less churn, better conferences, and the field will be better off." PT

With eye on future, Lowell Observatory shaves jobs, focuses science

As scientists scramble to land on their feet, the observatory's mission remains to conduct science and public outreach.

By **Toni Feder**

Staff astronomers at Lowell Observatory learned on 9 October that they would lose tenure effective 1 January 2026. The 130-year-old independent observatory in Flagstaff, Arizona, is switching the dozen scientists' employment to be contingent on their bringing in grants; they were given two and a half months to reconfigure existing grants to pay their salaries, rustle up new funding, or seek other employment.

Eliminating tenure is part of a larger restructuring plan that, observatory director Amanda Bosh says, sets Lowell on course for long-term success. "Organizations are always working on their financial sustainability," she says. "This was a difficult decision. If I had other options, I would have pursued them."

Tenure has been increasingly debated in recent years. In 2023, Florida introduced post-tenure reviews that effectively eliminate tenure in the state's public universities. Many scholars worry that removing tenure restricts academic freedom. The changes at Lowell are a morale blow for the broader astronomy community, says Diego Muñoz, an assistant professor of astronomy at Northern Arizona University who collaborates with Lowell astronomers.

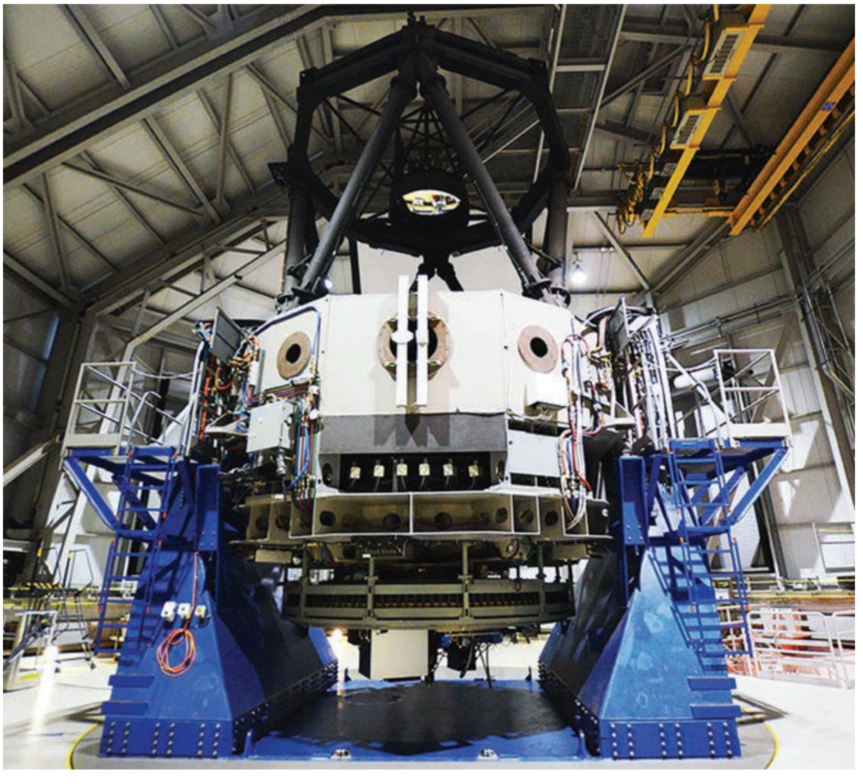
The observatory is also narrowing its in-house scientific focus to two areas of existing strength: planetary defense and exoplanets.

A venerable observatory

The observatory is perhaps best known for its 1912 radial velocity measurements of a spiral nebula, which were the first observations of the expanding universe, and for the 1930 discovery of Pluto. The first identification of water on an exoplanet was made in 2007 by a Lowell astronomer.

Today, the observatory's 4.3-meter Lowell Discovery Telescope, which saw first light in 2012, and several smaller telescopes are used by both in-house astronomers and institutional partners for research in planetary science, galactic and stellar astrophysics, extragalactic astronomy, and other fields. Some of the in-house astronomers rely on other ground- and space-based facilities.

Although Lowell's staff astronomers have always been encouraged to contribute to their salaries through grants, their pay was guaranteed. Historically, they collectively covered around a third of their salaries through grants, according to Bosh. In 2024, that amounted to about $2.3 million. But with grant



Selling time on the 4.3-meter telescope at Lowell Observatory is part of the strategy for increasing revenues for the cash-strapped facility. (Photo by Sarah Gilbert/Lowell Observatory.)

money from federal agencies getting tighter, the burden increasingly falls on the observatory, says Bosh. "That is unsustainable."

Lisa Prato, who joined Lowell in 2004, studies young binary stars. She says she has been successful at pulling in grants, which she uses to conduct research in areas that have passed through peer review. Support from the observatory, she notes, has allowed her to explore new topics. And, she says, "I've been happy to know that if I were to have a dry year, the observatory had my back."

Prato says that her funding will run out a few weeks into the new year. "I'm exploring multiple opportunities," she says. Not only will she and others whose grants are running out be effectively unemployed, but unless they can bring in three-quarters of their salaries at Lowell through grants, they will also lose their health insurance in 2027. Several Lowell astronomers told *Physics Today* that they wouldn't have taken jobs at the observatory without the salary guarantee. (They requested anonymity out of fear of retribution.)

A blow to science and morale

Gerard van Belle joined the observatory in 2011 and became its science director in early 2024. On 6 October, he quit in part to protest the decision to revoke tenure and switch astronomers to external funding that they bring in themselves. As a member of the executive team, he says, "I couldn't in good conscience be part of that decision."

Bosh declined to explain the observatory's financial predicament. She says that minus the current uncertainties surrounding federal funding, "Lowell might not be in this situation." Based on a presentation by Bosh from last June, Lowell's annual running costs are about $22 million, with a deficit of roughly $8.5 million, says van Belle.

Although the threats to federal funding are an "aggravating factor, they are not the root cause," says van Belle. Instead, he and other current and former Lowell astronomers and members of the observatory's advisory board point to a new visitors' center and the construction of the Lowell Discovery Telescope, with twin tabs of $53 million; delays and rising costs from the 2008 economic crash and COVID-19; and long-term mismanagement.

Van Belle predicts that most of the staff astronomers will leave within a year. Some will leave because they have no external funding. And the ones with grants, he says, will "be attractive and will move to greener pastures."

A road to recovery

Bosh acknowledges that Lowell science could see a downturn in the near term. But, she says, "We have a plan that we believe will see us through this period of uncertainty."

That plan includes focusing resources on the strategic areas of planetary defense—tracking potentially hazardous asteroids and comets—and exoplanet research, both of which the observatory judges to have a good chance of getting federal funding. Each area will be led by an in-house astronomer whose salary is covered in roughly equal parts by the observatory and grants. Externally

The visitors' center at Lowell Observatory opened in November 2024. (Photo by Abe Snider/Lowell Observatory.)

funded independent scientists and emeritus astronomers will retain access to observatory facilities, including office space, email, and telescopes. And the observatory will continue hosting postdoctoral astronomers.

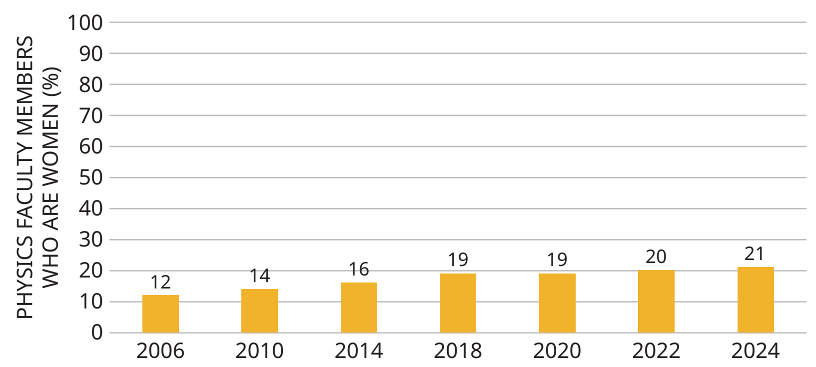
Over time, Bosh says, the plan is to establish endowed chairs, akin to those in university departments, as a way of building back the in-house science capacity. And the observatory will emphasize building revenue streams by, among other measures, attracting more visitors and selling more time on the Lowell Discovery Telescope to academic, military, and commercial customers.

Lowell's dual mission of doing and disseminating science is not changing, says Bosh. "As a scientist, and as a human being, I feel strongly that support for basic research is really important both to learn something and to feed our souls." Lowell has faced challenging times in the past, she says. "I think we will get through this too." **PT**

Upward trend in percentage of women physics and astronomy faculty in US

By Tonya Gary

Women made up 21% of faculty members in US physics departments in 2024, up from 16% a decade earlier (see the figure). The percentage of women faculty members in the nation's astronomy departments rose from 19% in 2014 to 25% in 2024. Those are among the findings in a recent report on the academic workforce by the statistical research team at the American Institute of Physics (publisher of *Physics Today*).



(Figure adapted from A. M. Porter, J. Oman, J. Tyler, *The State of the Academic Workforce in Physics and Astronomy, 2000–2024*, American Institute of Physics, 2025.)

The report includes data on full-time-equivalent faculty members—full-time members were counted as one, and part-time members were counted as a fraction according to the amount of work performed—in the US. Overall, that number grew from 9800 in 2014 to 10 160 in 2024. From 2022 to 2024, faculty employment rose by 4% in the physics departments that grant PhDs and declined by 7% in the departments in which the highest degree awarded is a bachelor's. The closing of some bachelor's-only departments may have contributed to that drop.

Physics departments hired 611 new faculty members for the 2023–24 academic year and astronomy departments hired 42. The numbers of both hires and departures in physics and astronomy departments have increased over the past few years. In 2024, 29% of physics department new hires and 34% of astronomy new hires were women. Although those percentages are lower than those in 2020 and 2022, they remain greater than the current percentages of women faculty members overall.

Other metrics related to physics and astronomy faculty, including retirement trends and tenure status, can be found in the workforce report at https://doi.org/10.1063/sr.d25c029227. **PT**

Q&A: Kate Marvel on the physics and emotions of climate change

The astrophysicist turned climate physicist connects science with people through math and language.

By Jenessa Duncombe

"Climate change is not an asteroid hurtling toward us that we can't do anything about," says Kate Marvel. A climate physicist at NASA's Goddard Institute for Space Studies (GISS) in New York City, she sees climate change as a solvable problem. Initially interested in astronomy, she pivoted to climate science during her postdoctoral studies. Her work approaches Earth's climate from a global perspective, and she served as a lead author of the US's Fifth National Climate Assessment, released in 2023. "We understand climate change, which means we know how to fix it," she says, "and that is a beautiful thing."

One of Marvel's passions is talking about climate science. Her 2017 TED Talk on clouds and climate has more than 1 million views, and she's appeared on *Meet the Press* and *The Ezra Klein Show*. Her first book, *Human Nature: Nine Ways to Feel About Our Changing Planet*, was published in June. But she says she doesn't see herself as a science communicator. "I am a writer, and I write about interesting things," she says. "And the most interesting thing in the world to me right now is climate science."

Can you tell me about your path into research?

Unlike probably most readers of *Physics Today*, I did not want to be a scientist when I was a kid. I thought high school physics was boring. It focused on stuff like balls rolling down inclined planes, and I didn't care about that. Then, in college at the University of California, Berkeley, I took astronomy. The class was amazing. I learned that there's a black hole at the center of our galaxy and about the Big Bang. The idea that physics could describe interesting things blew my mind.

My long-term plan had been to double major in drama and something like philosophy or English and, after college, to go be a movie star. Instead, I decided to switch my major to both astrophysics and physics.

What did you study in your doctorate in theoretical physics?

I was interested in the cosmological constant problem, which is the enormous disagreement between quantum theory and experimental data on the value of vacuum energy. A lot of my PhD work at the University of Cambridge was on what are called Coleman–de Luccia instantons. I studied bubble nucleation as a possible resolution of the cosmological constant problem.

During that time, I got used to the idea of math as a language. I don't consider myself particularly good at math, but I learned to use it as the language in which we describe reality. Learning this also made me a little bit omnivorous, willing to try to use math tools for any problem even if they are typically applied in other areas of study.

Can you give an example?

In my first postdoc, at Stanford University, I ended up using random matrix theory—which was originally developed for atomic physics using Wigner matrices—to model

Kate Marvel (Photo by Elisabeth Smolarz.)

the instabilities in the electric grid.

How did you get interested in climate science?

Some contacts recommended I try climate modeling during my first postdoc, so I went and talked to climate modeler Ken Caldeira. We ended up writing this crazy paper together. It was about hypothetically putting wind turbines in the jet stream. If we did that, how much energy could be extracted before we shut down global wind?

I was intrigued because the research question was nuts. I came from astrophysics, this field that tries to explain the entire universe. And I found myself being surprised that we didn't know how much wind we have in the jet stream. I liked climate science because it addressed questions that seemed big and interesting and expansive but also relevant.

I also came from a hypercompetitive theoretical-physics department during my PhD where every seminar felt like a blood sport. Going to a seminar in climate science, I noticed that people were asking questions about things they were curious about as opposed to feeling the pressure to know everything. I liked the culture a lot better.

Tell me about your journey to NASA.

After my second postdoc, at Lawrence Livermore National Laboratory, I moved to New York because my husband got his dream job there. I made this move for personal reasons, meaning I couldn't apply to academic jobs just anywhere because I had geographical restraints. I basically talked my way into a soft-money job in 2014 at NASA GISS through Columbia University. I had to raise my own salary. It was hard being on soft money. I had the opportunity to become a civil servant in 2024.

I find the expectation in academia that you are supposed to move all the time and you are not supposed to have a family pretty silly. I have felt supported by my immediate group at NASA.

What are you working on now?

I study physical and biogeochemical feedbacks in the climate system. How will clouds rearrange in response to warming, and how much will this affect the global temperature? And how will climate-induced changes to natural systems affect the amount of carbon dioxide that the biosphere can take out of the atmosphere? I'm fascinated by what the climate states of the past can teach us about the future. I use Bayesian methods to draw inferences from data; those methods are a language and way of seeing the world that makes sense to me as a physicist.

You did a one-year stint in 2023 at the nonprofit Project Drawdown. The organization conducts research on and helps implement science-backed climate solutions. What did you take away from the experience?

When you look at climate change from my global perch as a researcher, it can seem overwhelming. But when you get down to the nitty-gritty, you see that the solutions are almost boring, like balls rolling down inclined planes. And I find that comforting.

We know what is causing climate change. To use particle-physics language, this is like a 10-sigma thing. We know exactly what is making the climate get warmer, and that means we know exactly how to stop the warming. And so Project Drawdown is, in my mind, the absolute best science-based nonprofit thinking about what we can do. I did some attribution work thinking about the relative roles of aerosols versus methane versus carbon dioxide. I learned a lot about where emissions come from and possible solutions for reducing those emissions. Working there actually made me optimistic.

What inspired you to write your first book?

I always knew that I wanted to write a book because I see myself as an artsy person who also fell in love with science. The book makes the case that you don't have to choose between getting the science right and being a whole, thinking, feeling human being who is drawn to stories and the arts and history.

The book uses nine different emotions as a lens to look at climate change. In each chapter, there's an emotional through line, a scientific through line, and a story through line. The guilt chapter, for example, is about attribution science. It talks about how climate scientists know that humans are causing climate change. But it also mentions historical climate change. In Europe during the Little Ice Age, you start seeing a spike in the number of people being accused of witchcraft. It's fascinating to me because that is something that we as physicists are not equipped to understand. $F = ma$ doesn't apply to people's emotions. When you apply force to a person, what's going to happen?

Do you have any advice for scientists who like writing?

I'm in a writing group, and I love it. We've got two stand-up comedians, two people who are writing young adult fiction, and two people who are writing amazing, gorgeous novels with the most exquisite sentences. The diversity of writing has been great because it drags me out of my scientist mindset. And being able to get feedback from people who I have been working with for eight years now is great. That's my top advice—find a writing group of people who are better writers than you.

People tend to react strongly to climate change because it has been politicized. What is your perspective on strategies for writing about climate change in a way that reaches people?

Be honest, and don't pretend to know stuff you don't. We're all human and entitled to our political beliefs, but our expertise in science doesn't give our views more weight.

Is there anything you want to address with respect to the changes to federal science policy in the US this year?

Science is an important part of our democracy. Attacks on science writ large are attacks on democracy. They're attacks on the ability to know things that we are not just told by people in charge. And for me, it's important to make that connection. I take a lot of pride in being a publicly funded scientist. Whatever we find out, whatever we know, that's for everybody: That's for the American people

New fusion office created in DOE restructuring

By Lindsay McKenzie

The Department of Energy announced in November a major reorganization that creates several offices and merges, moves, or renames others. Some offices at the agency appear to have been eliminated. It is unclear whether the actions will lead to staff reductions.

Darío Gil, undersecretary for science, will now manage the existing Office of Science plus four other offices, including the newly created Office of Fusion and Office of Artificial Intelligence and Quantum.

It is unclear whether the Office of Fusion will take over the entirety of the Fusion Energy Sciences division, which is currently housed in the Office of Science. The Fusion Industry Association welcomed the creation of a stand-alone Office of Fusion. "This shift has been a long-standing FIA priority, and we're encouraged to see DOE take this step to streamline and elevate fusion programming," the trade association said in a statement posted on social media.

The Office of Energy Efficiency and Renewable Energy is not listed on the latest DOE organizational chart, but reports suggest that EERE will form part of the new Office of Critical Minerals and Energy Innovation. The Office of Fossil Energy appears to have been transferred to the undersecretary of energy and renamed the Hydrocarbons and Geothermal Energy Office—a name that suggests that it will take on geothermal R&D programs previously managed by EERE.

The Office of Clean Energy Demonstrations is not listed on the new organizational chart. Energy Secretary Chris Wright signaled his desire to shutter the office earlier this year. The Advanced Research Projects Agency–Energy, which President Trump sought to eliminate in his first term, remains on the new chart.

Department of Defense narrows R&D priorities

By Lindsay McKenzie

The Department of Defense has pared its list of critical technology areas from 14 down to 6, reflecting a desire to more quickly deliver applied technologies in a smaller number of priority areas.

The six critical areas are as follows:

- Applied AI to embed AI into command-and-control systems and achieve "decision superiority."
- Biomanufacturing to produce critical minerals at scale.
- Contested logistics technologies to ensure access to critical resources in difficult environments.
- Quantum and battlefield information dominance to modernize communication and sensing technologies and operate in contested electromagnetic environments.
- Scaled directed energy to counter emerging threats by using high-energy lasers and microwave technologies.
- Scaled hypersonics to deliver Mach 5+ hypersonic weapons at scale.

The new list ditches areas such as renewable energy generation and storage and microelectronics, which were priorities during the Biden administration. But it keeps the focus on other areas such as biotechnology, quantum science, and AI.

White House's Genesis Mission aims to boost science with AI

By Lindsay McKenzie

President Trump issued an executive order in November that launches the Genesis Mission, a national effort led by the Department of Energy to advance scientific discovery using AI. A DOE press release says the mission aims to "double the productivity and impact of American science and engineering within a decade." Undersecretary for Science Darío Gil, who will serve as the project's director, said in a letter that DOE's national laboratories will aim to achieve those gains in "half that time."

The mission will focus on three key challenges: securing US energy dominance, advancing discovery science, and ensuring national security. Energy Secretary Chris Wright said that the mission would call on the nation's brightest minds and industries in a similar manner to the Manhattan Project and the Apollo program.

The centerpiece of the Genesis Mission, according to the executive order, will be "an integrated AI platform to harness Federal scientific datasets" that will be used to "train scientific foundation models and create AI agents to test new hypotheses, automate research workflows, and accelerate scientific breakthroughs."

The AI platform, which will be known as the American Science and Security Platform, will use DOE's supercomputers at national labs and other resources and will cover data across many scientific domains that have yet to be selected. The effort represents a significant expansion of plans to develop the "world-class scientific datasets" outlined in the AI action plan that was published by the Trump administration in July.

The executive order does not commit any funding to the project. It directs Michael Kratsios, director of the White House Office for Science and Technology Policy and assistant to the president for science and technology, to work with research agencies to incentivize private-sector participation. PT

For more from *FYI*, the science policy news service at AIP, visit https://aip.org/fyi.

Corrections

December 2025, page 34 — An editing error mischaracterized Richard Garwin's fusion experiment. It showed that thermal x rays generated by a fission explosion could be used to compress and heat deuterium and induce fusion reactions.

December 2025, page 54 — Figure 1 shows the seeds of a sandbox tree, not those of a hairyflower wild petunia. PT

A BRIEF GUIDE TO SCIENCE OUTREACH

Don Lincoln

Figuring out how to communicate with the public can be overwhelming. Here's some advice for getting started.

(Design by Masie Chong with icons by Freddie Pagani and artwork adapted from iStock.com artists cnythzl and Alabady.)

As a child, I was interested in all things scientific, from dinosaurs to space travel. But there was a problem. The environment in which I grew up was woefully devoid of scientists as role models and sources of information. My parents never went to college; indeed, my father never finished high school. My high school guidance counselor had no clue what a physicist did or how to begin a career in the field.

Luckily, as a young science enthusiast in the 1970s, I had access to the writings of people like Isaac Asimov, Carl Sagan, and George Gamow, who took care to share the world of science with public audiences. And I was a voracious reader, which allowed me to learn from those legendary communicators. Without them, I would likely not have become a physicist. I owe them and others a great debt.

After earning a PhD, I was determined to settle my intellectual tab by paying it forward, hoping to help some other young person living in an academically impoverished environment view the world with scientific eyes. I began visiting schools and giving tours of my particle-physics laboratory, and I believe that I sparked interest in a few youngsters. A handful went on to receive PhDs in science. It was quite gratifying.

As the years rolled on, my interest in science outreach broadened. Because I saw too many examples of public policy that ran afoul of established science, I decided not to limit my interest in science outreach to only young people. Over the past few decades, I have spent an increasing fraction of my time doing public engagement with other sets of audiences, and I have tried to persuade other scientists to join me (see my recent *Physics Today* piece “A defense of science communication” and reference 1).

Although I have not been universally successful in convincing my peers, I have encountered a few who also want to share both the fascinating principles that govern the behavior of matter and energy in the universe and their own personal journeys into the world of professional science. A few wish to concentrate on the science itself, while others are more interested in teaching their audience the importance and power of the scientific method. And, of course, there are those who don’t see people like themselves represented in common historical narratives of science. For them, letting others like them know that they belong is of utmost importance. Each person has their own motivations. Over the years, some of these aspiring communicators have asked me for advice on how to communicate science effectively. This article outlines some of what I’ve learned.

Education	Outreach
K–5	Policymakers
Middle school	Media
High school	General public
Undergraduate	
Graduate	

Figure 1. Education and outreach are distinct efforts, and each can be subdivided. Outreach can happen on different scales, such as national or local, and with different levels of formality. (Figure by Freddie Pagani.)

Education versus outreach

So you’re interested in doing science communication. The first thing to do is understand exactly what you mean. Many physicists tell me they want to educate when they mean do outreach and vice versa.

Education presupposes that the recipients—the students—want the knowledge the teacher is giving them, whether for the sake of learning, applying the ideas to a career, doing well on a test, or something else. Outreach presupposes no such desire. It is a bit more like advertising, which is to say that you are trying to connect with an audience with little to no prior interest. Both education and outreach are themselves subdivided into even smaller audiences, as illustrated in figure 1.

Given that most scientists I speak with have ample experience being a student and possibly have teaching experience, education is often the easier of the two for them to engage with. In education, the audience is expected to put in effort, and, accordingly, the task of transferring information requires less work for the presenter.

On the other hand, in outreach, you must grab your audience’s attention and hold it. If you don’t, people will flip the page, change the channel, or move on to the next YouTube video.

Note that you’re not going to interest all people, so don’t try. And if your goal is to do outreach to people who don’t have a preexisting interest in science, realize that doing so will require considerably more effort and different techniques than you would use for science enthusiasts. For those new to outreach, I recommend beginning with audiences that might be called “sci curious.”

The message you want to convey is very important. Many scientists who do outreach have in the back of their mind a young version of themselves, and they want to try to nurture a lifelong interest in science in similar individuals. That sort of outreach looks to the distant future. Others have more of an interest in the now and are worried about the vocal and influential antiscience voices that one finds both in society at large and, more worryingly, the corridors of power. The message you want to convey will influence the manner in which you tell it.

The audience you are trying to reach will also influence how you give the message. If you were giving a lecture in the Piazza Navona in Rome and you wanted to communicate effectively, you'd speak in Italian. You must make similar considerations for any audience. If you are speaking with teenagers, you cannot assume that they know the language of even an introductory physics class. And even many older audience members never learned (or don't remember) Newton's laws. Of course, if your audience is a roomful of retired engineers, you can use the overlapping vocabulary you have with them and don't need to do as much work to make your material seem relevant.

Knowing your audience is more than knowing their language. It's knowing their values. You would take a very different approach when speaking with a group of high school physics teachers than you would with a community group focused on social change. You would take another approach for a group of retired veterans, as they might be more interested in funding Veterans Affairs hospitals than scientific research.

Furthermore, the better you know your audience, the better you can tailor both your message and your approach. Figure 2 gives a sense of the diversity of audiences you might encounter if you were interested in lobbying policymakers. Each group has its own language, values, and arenas of interest.

For those looking for advice for a specific effort, this article will not answer all questions, as each situation is different, but here is a checklist of some of the questions you need to ask yourself before undertaking an outreach or education effort:

- ❑ What are you trying to do?
- ❑ What audience do you need to engage with to accomplish your outcome?
- ❑ What language (broadly defined) should you use?
- ❑ Are there cultural sensitivities you should consider? (For example, a religious audience will require a different approach than an atheist one.)
- ❑ Are you speaking to inspire? To inform? To persuade? To call to action?
- ❑ What is the approach that you want to employ?
- ❑ How will you know if you are successful?

Answering those last two questions requires knowing

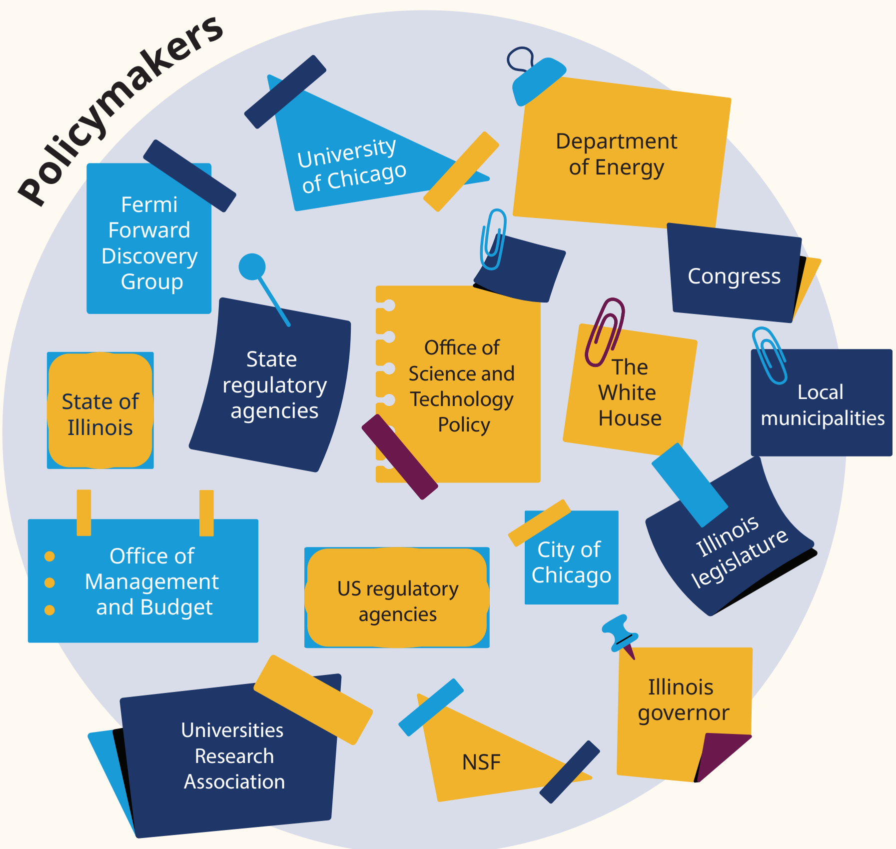


Figure 2. For a person interested in informing or guiding public policy, there are many possible audiences, each with their own concerns and sensitivities. If you want to speak to those in power, the better you understand the people to whom you're speaking, the more effective you will be. So, for example, if I was lobbying for resources or simply hoping to connect with influential people, these are some of the policymakers I would consider contacting. For your institution or needs, different organizations would apply. (Figure by Freddie Pagani with artwork adapted from iStock.com artist designrecs.)

what approaches are effective and what considerations you might encounter for each one.

Approaches

As I mentioned earlier, many readers of *Physics Today* will have many years of experience with education from their time as students and perhaps also as teachers. Furthermore, the American Physical Society has a great deal of resources for educators and offers the ability to join its Forum on Education.[2] Because of that, I will concentrate more on the field of public outreach, often called engagement.

Many approaches can be used, including giving public lectures in small or large venues, using traditional media, and attempting to harness the vast potential of the internet. Figure 3 lists a few ways to do outreach. Although there is some overlap in the way the different approaches work, each one has its own idiosyncrasies. Before you pursue some sort of outreach effort, I suggest that you talk with someone who is successfully doing outreach and using a technique that's similar to the one you envision using. There is no need to reinvent the wheel.

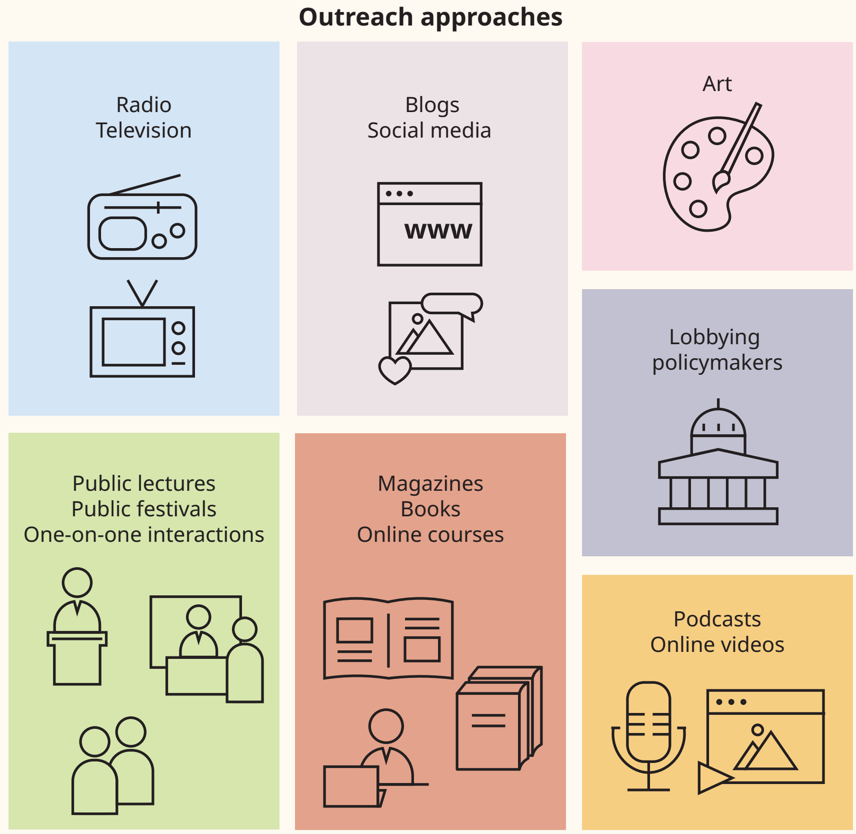


Figure 3. If you want to do outreach, first consider how you want to connect with your desired audience. The above graphic shows some possible approaches. (Figure by Freddie Pagani.)

Public talks

Probably the simplest way to do outreach is to give a public talk. It could be done as part of an event, like a conference, or another established effort, like a monthly meeting of a civic or social group. The important thing is to speak with your host to better understand your audience. Sometimes, venues will host gatherings such as Nerd Nites and Cafes Scientifiques that combine having drinks, socializing, and learning. You can also nominate yourself online to speak at a TED conference, which features talks, interviews, workshops, and other events that highlight ideas from various fields, or contact a TEDx organizer about speaking at an event. Those talks are often posted online as well. (For more about those events and other resources, see the box on page 31.)

If you are giving a talk at a recurring social event, consider attending one or two before you speak to get the vibe of it.

Lobbying Congress or other policymaking bodies

One action that can be influential is lobbying policymaking bodies, such as Congress, because they have the resources and power to effect real change. But how do you convince people who make policy to execute some action that you want?

Now, it could be that you happen to be both charming and persuasive. But charm is not always enough. What convinces most members of elected bodies are the elections that put them there, and winning elections means getting votes. Furthermore, it is rare that convincing one person is sufficient to change public policy. Thus, it's most effective to try to mobilize many voices to influence many policymakers. That means joining a large group effort, such as the American Physical Society's annual Congressional Visits Day. If you prefer to get your own group going, then speak to people who have participated in the society's visits or similar efforts to get some pointers.

Art

Art and science are often thought to be diametrically opposed disciplines: One is concerned with aesthetics and perceptions, and the other revolves around facts and numbers. But some people combine the two in what are called STEAM (science, technology, engineering, the arts, and math) events. The motivation for many of these efforts is the hope that science-averse audiences can be more receptive if information is presented in an aesthetic and engaging way.

Perhaps the most effective way to reach art enthusiasts is to work with someone who is already established in the field. By collaborating with artists and carefully translating scientific topics into an artistic form, you can teach a little science at art events. It is important to leave the nuts-and-bolts numbers behind and talk about big ideas. It's also important to remember that even if the audience absorbs only a little of the science, simply destigmatizing and humanizing technical topics is a valuable outcome.

Many art–science efforts have had success. For example, at Yale University, physics professor Sarah Demers has collaborated with dance professor Emily Coates[3] (both are pictured in figure 4) on a class about the physics of dance, on public events, and even on a book.[4] Their *Incarnations* project was performed in New York's East Village and was mentioned in *The New York Times*.

Figure 4. Dancer Emily Coates (left) and physicist Sarah Demers (right) have collaborated to share the physics of dance. Their work *Incarnations*, which explored science–dance connections through both lecture and performance, was featured in *The New York Times* arts section. (Photo by Paula Lobo.)

Fermilab, where I work, has a guest artist and composer program,[5] and CERN has similar programs.[6]

Books

Books are a more conventional way to connect with large audiences, although the publishing industry is facing challenges. The keys to writing a book are being able to write clearly and engagingly and having something interesting and innovative to say. A popular book is quite different from a textbook, and the competition is fierce. Brian Greene's 1999 book, *The Elegant Universe: Superstrings, Hidden Dimensions, and the Quest for the Ultimate Theory*, was successful because it was written in the early days of the public awareness of M-theory. Nowadays, a similar book would have a harder time gaining an audience. And if you wanted to write about dark matter, you would have to say something new about what has become well-trodden ground.

If you want to write a popular-science book, you begin with a book proposal, a writing sample (say, a chapter), and a specialized CV that highlights both your expertise and why you're the right person to write the book. You send these documents to an agent or acquisitions editor. If they accept your proposal, then you write your book.

Publishing a book can be accomplished through a university press, a popular press, or self-publishing. (I'm not a fan of the last one, primarily because of the lack of marketing and editorial oversight that could establish that your book is commercially viable in the first place.) University presses tend to be looking for more niche books and will accept more modest sales numbers. Even better, academic credentials will make you more attractive as an author to university presses. For them, you send your proposal package directly to the university press's acquisitions editor.

In contrast, publishing with a publisher not affiliated with a university usually requires that you have an agent, who can be quite difficult to get. The competition is fierce, and popular presses typically want to see books that will sell a lot of copies.

Except for a lucky few, book publishing is not particularly lucrative. But having a popular-science book published is often a way to demonstrate that you are a serious writer, which can open up other opportunities—such as media exposure, paid speaking engagements, and even offers to appear in documentaries.

Blogging, social media, online videos, and podcasts

In today's world, many of the most influential voices in popular science have a significant online presence. The good thing is that only a small initial investment is needed to generate online content. The bad thing is that only a small initial investment is needed to generate online content. Low initial investment means that countless people are out there, all wanting to be heard. Rising above the cacophony is incredibly challenging.

For those who rise to the top, however, the returns can be significant. Given how search engines work, people with a significant online presence are often found by journalists when they need someone to supply a comment for an article or (occasionally) when they need someone to appear on radio or television.

There are several keys to success online. The first is creating high-quality content: You want to provide a product that is entertaining and insightful. The second is releasing content reliably and regularly. Depending on the outlet, your readers or viewers may expect to see content weekly, daily, or even several times a day.

You can have an online presence in many sorts of ways, including blogs, social media, videos, and podcasts. But you have to be patient: Don't expect to immediately become a viral phenom. It's a long and difficult grind. Initially, you will wonder if anyone is paying attention, a sentiment illustrated in figure 5. One of my favorite sayings about this sort of thing is that it takes 10 years of soul-crushing and persistent effort to become an overnight sensation.

Connections can help you achieve online success. A guest appearance or mention on a popular website can do wonders for your viewership numbers. For example, it took years for me to grow my Facebook following to 500 people. Then, I was mentioned on a successful site, and I gained 1000 followers overnight. My current following consists of nearly 30 000—a small number compared with professional communicators but a reasonable one for a person who continues to stay connected to the research world.

Each online platform is quite different. Podcasts and YouTube can require a larger monetary investment than many others do because you will need recording equipment and editing software. Producing a high-quality episode is considerable work and, if your approach involves interviewing others, you'll have the constant grind of finding guests.

Figure 5. The initial phase of attempting to do online science outreach can be disheartening. (Image adapted from iStock.com/Tatiana Smirnova.)

For social media, the entrée is easier, but you need to know the personality of your platform. Not all messages are well matched to all platforms. Facebook is great for sharing material, and the demographic skews older than the youth-friendly Instagram, which is more of a visual and image-centric platform.

In addition, you should consider recent evolutions in the world of social media. Twitter, now X, is not as influential as it once was. TikTok has been on the rise. Expect to constantly reinvent yourself.

Furthermore, you should take regional preferences into consideration. For example, in 2023, a survey showed that WhatsApp was used by 83% of adults in Mexico but only 29% of adults in the US.[7] Depending on the audience you want to reach, you should pick your platform carefully.

Big picture

Attempting to communicate with the public can be a daunting prospect. Many people are indifferent to science. Some may have learned in school that mitochondria are "the powerhouse of the cell" but do not understand what science really is: a way of f iguring things out. Others are frankly hostile toward the scientific enterprise. The world is rife with mis- and disinformation. If fighting that deluge is your goal, it can feel like a thankless, never-ending game of Whac-A-Mole.

And yet science outreach can be greatly rewarding. You can open new vistas to young people who will one day be scientists or encourage people to be interested in and supportive of science. You can shape public opinion and nudge science policy in the direction of research and reason. On a practical level, you can possibly increase public funding of science and, more self-centeredly, persuade funding agencies to support the work that interests you.

If you're inclined to do science outreach, I hope you start. If you'd prefer to let others take on that burden, that's OK too, but you should be supportive of—indeed, grateful for—their work. After all, effective communicators are making society more open to hearing about your research and public officials more likely to support you when you ask for resources.

We live in a connected world, with a sometimes-deafening hubbub of voices. We should work together to ensure that the voice of science is heard. PT

Resources for outreach

- The American Physical Society (APS) has several initiatives focused on public engagement.
- The American Association for the Advancement of Science offers trainings in science communication and diplomacy.
- The Alan Alda Center for Communicating Science at Stony Brook University offers in-person and virtual professional development programs in science communication.
- *Thinking Like Your Editor: How to Write Great Serious Nonfiction—and Get It Published*, by Susan Rabiner and Alfred Fortunato (published by W. W. Norton in 2002), offers wisdom for aspiring authors.
- *Don't Be Such a Scientist: Talking Substance in an Age of Style*, by Randy Olson (published by Island Press in 2009, 2nd ed. in 2018), provides lessons from the author's journey from professor to filmmaker.
- APS Congressional Visits Days are an opportunity for the society's members to get together and meet with policymakers on Capitol Hill.
- Nerd Nite, TED, and Cafe Scientifique offer opportunities to give presentations.

References

1. M. Smith, D. Lincoln, "To save science, talk with the public," *APS News*, 8 December 2022; D. Lincoln, "To the ramparts: Defending science!," *SPS Observer*, 1 May 2018; American Physical Society (APS), "Statement on public engagement," ethics and values statement (18 November 2024).
2. For more on APS's educator resources, see "Preparing future physicists" and its Forum on Education.
3. J. Heimlich, "Are dancers secretly physicists in disguise?," *Dance Magazine*, 16 January 2019.
4. E. Coates, S. Demers, *Physics and Dance*, Yale U. Press (2019).
5. For more on the arts at Fermilab, see the Guest Artist and Guest Composer Program at Fermilab, https://events.fnal.gov/art-gallery/guest-artist-and-guest-composer-program-at-fermilab/.
6. For more on CERN's arts program, see "Arts at CERN," https://arts.cern/.
7. J. Poushter, *WhatsApp and Facebook Dominate the Social Media Landscape in Middle-Income Nations*, Pew Research Center (22 March 2024).

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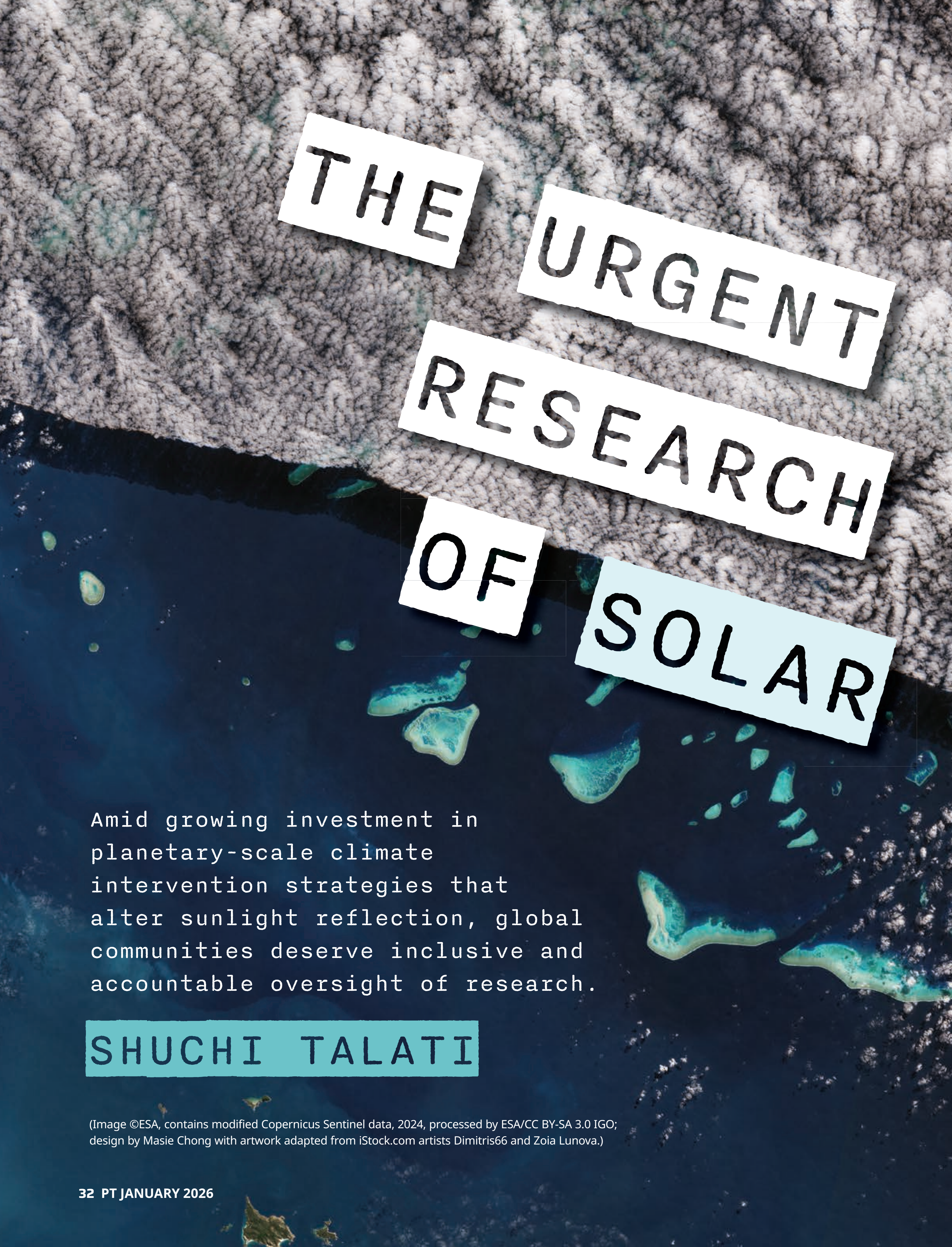

THE URGENT RESEARCH OF SOLAR

Amid growing investment in planetary-scale climate intervention strategies that alter sunlight reflection, global communities deserve inclusive and accountable oversight of research.

SHUCHI TALATI

(Image ©ESA, contains modified Copernicus Sentinel data, 2024, processed by ESA/CC BY-SA 3.0 IGO; design by Masie Chong with artwork adapted from iStock.com artists Dimitris66 and Zoia Lunova.)


NEED FOR
GOVERNANCE
GEOENGINEERING

The idea that some of the worst impacts of climate change could be curtailed by human interventions to cool the planet has, over the past few years, moved from the margins of climate discourse into a more visible and contested space. Solar geoengineering—a set of theoretical, large-scale interventions to rapidly cool the planet, primarily by increasing the amount of sunlight reflected into space—has drawn greater attention from media, funders, and policymakers. Also known as solar radiation management, it is not a new idea: It has existed in theory for decades, with early references dating from the 1960s. The concept rose to greater prominence after a 2006 paper from Nobel laureate Paul Crutzen calling for research and consideration of solar geoengineering,[1] but it subsequently remained on the fringes of climate research for several years.

Mounting climate impacts, the insufficiency of mitigation policy, and the reality of volatile politics are now shifting solar geoengineering from a long-standing taboo to a subject of broader inquiry. Research efforts are still limited, focused mainly on modeling, but are growing to include small-scale outdoor experiments. Attempts to do experiments that are visible to the public have been met with strong pushback and, in some cases, cancellation, even as similar efforts advance in less visible settings. At the same time, more funding is rapidly entering the field, and press coverage, including misinformation, is climbing. In the context of growing hype and public distrust, responsible research is crucial to developing a clearer understanding of the potential risks, benefits, and uncertainties of solar geoengineering. But the development of such research will require thoughtful implementation of governance and oversight.

Stratospheric aerosol injection, the most prominent solar geoengineering approach, involves scattering reflective particles into the upper atmosphere, as shown in figure 1. It mimics the cooling effect of large volcanic eruptions, such as the 1991 Mount Pinatubo eruption in the Philippines, shown in figure 2, that temporarily lowered global temperatures.[2] Stratospheric aerosol injection has the potential to be implemented relatively quickly and cheaply. Marine cloud brightening, the second most researched strategy, aims to increase the albedo of low-lying marine clouds by spraying aerosolized sea salt into the air. The method mimics ship tracks,

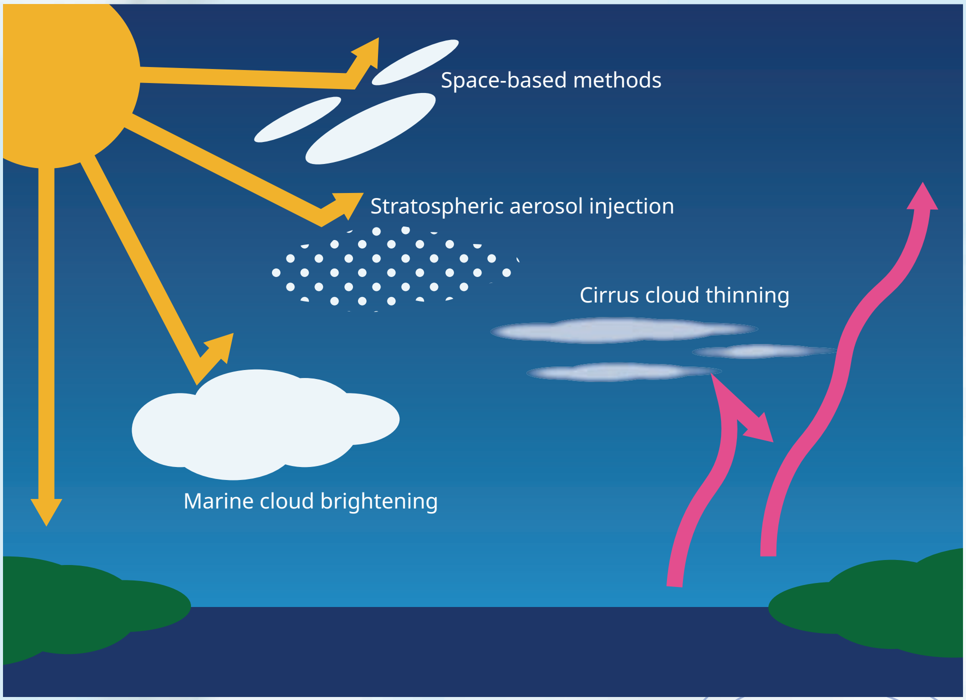

Figure 1. Several strategies for the modification of solar radiation have been explored over the past several decades. The most prominent is stratospheric aerosol injection, in which aerosols are placed in the stratosphere to increase albedo and reflect a small fraction of sunlight. Marine cloud brightening, another widely researched approach, is the spraying of aerosolized sea salt into the air to increase the albedo of low-lying marine clouds. Approaches in the earlier stages of development include space-based reflection methods and cirrus cloud thinning, which aims to thin high-altitude clouds so more outgoing thermal radiation could escape. (Illustration by Freddie Pagani, adapted from NOAA/Chelsea Thompson, Chemical Sciences Laboratory.)

the aerosol pollution emitted from ships that sometimes leads to brighter clouds, as shown in figure 3.

Cirrus cloud thinning and space-based methods that use mirrors or sunshades are two other approaches, illustrated in figure 1, that are in earlier phases of research. (There are also geoengineering strategies that are not focused on solar modification, such as glacier stabilization and ocean iron fertilization, which I am not addressing here.)

Scientists have a reasonably good understanding of solar geoengineering's potential impacts on global temperature. But they still are uncertain about how both stratospheric aerosol injection and marine cloud brightening will affect physical systems (such as weather systems, biodiversity, and agriculture) and social systems (such as human displacement and geopolitics) across different regions.

That uncertainty is a core reason for the controversy around solar geoengineering: Changing how sunlight interacts with the atmosphere could, for example, shift rainfall patterns, affect regional monsoons, stress ecosystems, or create unequal climate outcomes, where some areas see relief while others face new risks. Potential impacts may be beneficial or harmful, and they need to be understood in the context of changing climate impacts on physical and social systems. The research and policy communities are also grappling with important questions of how to ensure that robust mitigation, adaptation, and carbon dioxide removal are not deterred in pursuit of solar geoengineering research.

In short, solar geoengineering is rife with complexity: It may have the potential to limit harm and suffering, but it also has the potential to exacerbate harm and injustice. How decisions are made, by whom, and toward what outcomes are by far the most challenging questions the field faces, and it must start to address those questions now, in the early stages of research.

Outdoor experiments: A flash point

The vast majority of solar geoengineering research to date has been conducted through computer modeling. Modeling allows researchers to develop an understanding of how solar geoengineering might influence global and regional climate systems, including temperature and precipitation, under different scenarios and assumptions. Models have provided valuable information thus far, such as an understanding of the variability in efficacy from different deployment strategies and initial analyses of interactions with other systems such as air quality and energy generation. More work that is important remains to be done in the modeling space, especially to better understand potential impacts in different regions.

Modeling has limitations, however, and being overly prescriptive with imperfect information carries significant risks. Models simplify complex systems, and relying too heavily on them without accounting for uncertainty, variability, and real-world dynamics can lead to misleading conclusions or false confidence in how solar geoengineering could unfold.

In recent years, researchers have proposed more outdoor experiments that are small scale and do not pose significant environmental or human risks. They include equipment testing and limited particle release, such as an experiment that sends out roughly 1 kilogram of aerosols, far less than the emissions of a plane flight. The work has been proposed or initiated with the goal of improving understanding of processes that modeling and lab-scale experiments can't capture. Those processes include climate and atmospheric dynamics, stratospheric aerosol chemistry, and aerosol distribution mechanisms. Small-scale outdoor experiments can provide data to help refine climate models and modeling studies and, importantly, also contribute to a deeper understanding of what might not work.

Many types of research are safely implemented at scales similar to or larger than what is being proposed in solar geoengineering, including in climate change research. One example is large-scale forestry. The US Forest Service has a wide network of experimental forests used to understand ecological changes and vegetation over long periods of time. The Swedish University of Agricultural Sciences just launched an outdoor experiment to simulate future climate conditions in forests. In ocean-based research, experiments have been performed to explore ocean alkalinity enhancement, a carbon dioxide removal approach. For those experiments, researchers injected thousands of liters of lime-enriched seawater into the Apalachicola estuary in Florida.

No matter the field, emerging-technology research that moves from closed environments to open ones carries more environmental and political risks. That reality, layered with the controversial nature of solar geoengineering, creates a challenging context for outdoor experiments. But such experiments offer a tangible entry point into what is otherwise a theoretical field. As such, they've become flash points—they raise not only scientific questions but also the bigger societal and governance questions that any move toward larger-scale deployment would inevitably provoke.[3]

Figure 2. The 1991 Mount Pinatubo eruption flooded the stratosphere with aerosols that reflected sunlight and slightly cooled the planet. Volcanically driven cooling of the atmosphere served as inspiration for the solar geoengineering approach of stratospheric aerosol injection. (Photo by V. Gempis, from the Records of the Office of the Secretary of Defense/National Archives photo no. 6472281.)

Finally, the controversy around outdoor experiments is amplified by the rapid spread of misinformation, disinformation, and conspiracy theories. Those narratives distort public understanding and shift attention away from relevant, valid questions, such as who is making decisions, under what authority, and with whose input. In a moment when public trust in science is already fragile, those dynamics make open, good-faith research harder to pursue.

Experiments interrupted

Two examples of proposed outdoor experiments, both canceled in 2024, offer a window into the unique social and political contexts that the field exists in and the governance that it requires.

The Stratospheric Controlled Perturbation Experiment, or SCoPEx, was a small-scale outdoor experiment first proposed by researchers at Harvard University in 2014 to better understand aerosol dynamics in the stratosphere.[4] It was to use an engineered balloon platform, illustrated in figure 4, to release a few kilograms of calcium carbonate and possibly other materials—less than what is released by a typical plane flight—into the stratosphere and subsequently

observe changes in air chemistry. The experimental results would have been used to improve stratospheric models.

Notably, the research team identified it as a solar geoengineering experiment. Because that designation was unprecedented in the research community, Harvard established a formal independent advisory committee in 2019 to provide guidance on legal compliance, safety, transparency, scientific review, and public engagement. (Note: I was a member of this committee.) The governance framework was notable for being proactive and multidisciplinary, but it was introduced relatively late in the project's development.

In 2021, researchers proposed a test in a Sami community in Sweden to see whether the engineering platform, not the experiment itself, worked properly. But the researchers called off the test because of strong opposition from Indigenous Sami leadership and recommendations from the advisory committee. Although the researchers considered proceeding with the experiment in a US location, it was ultimately canceled in March 2024. The committee found that an ad hoc approach to governance of outdoor experimentation is immensely challenging, and solar geoengineering requires a more coordinated, consistent approach across civil society, research institutions, and both public and private funders. Such an effort would provide clear guidance for researchers and accountability to communities.[5]

In contrast, an experiment in Alameda, California, led by the University of Washington and supported by the nonprofit organization SilverLining, had a very different approach to governance. The experiment involved spraying sea-salt particles (less than 100 tons annually) from the deck of the USS *Hornet* to study aerosol size and dispersion and to assess the efficacy of their engineered sea-salt sprayers over water.[6]

The institutions that organized the Alameda experiment did not create a formal governance or engagement process before conducting the experiment. Rather, they ensured legal compliance in advance and subsequently launched a public engagement campaign after the experiment started and was announced in the media. At that point, it became clear that local officials and residents were unaware of its full scope until after the fact. The Alameda City Council paused and subsequently stopped the experiment. Although independent studies found no harm to public health or the environment, the lack of transparency and consultation led to political and civic backlash. The governance in this case was largely reactive and relied on only existing regulation; no anticipatory governance or oversight was planned.

The two cases highlight contrasting approaches to governance in early outdoor solar-geoengineering research. SCoPEx exemplified a formal, committee-led model that aimed to embed responsibility and transparency into the research process, yet the actors involved still struggled to determine when and how to engage local communities near the platform test. The cancellation of the Alameda project demonstrates the risks of proceeding without transparency or robust local public engagement before implementation. Together, the examples underscore the importance of early, inclusive, and transparent governance structures—and the repercussions of mistakes—when conducting solar geoengineering research.

Continuing outdoor research

Currently, some researchers and funders are engaging in outdoor work and trying to heed those lessons, while others are blatantly ignoring them. Most prominently, the UK government recently announced research funding for 22 solar geoengineering research projects, including five controlled, small-scale outdoor experiments.[7] That work is being funded through the Advanced Research and

Invention Agency (ARIA), a relatively new, independent government agency that was launched in 2023. ARIA assembled an independent oversight committee to guide the governance of its research, especially outdoor experiments. (Note: I currently sit on this committee.) The committee supports transparent oversight and is helping shape norms for responsible research. Importantly, though, ARIA has oversight over only the research that it funds.

In contrast, some emerging private companies are starting to do outdoor work with no oversight or governance whatsoever. For instance, Stardust Solutions, a startup that recently announced it had raised $60 million from venture capitalists and billionaires, is developing a proprietary aerosol particle with the intention to patent and license the technology commercially and sell the product to governments.[8]

Though Stardust's limited public messaging emphasizes integrity and professionalism, it has drawn scrutiny for its complete lack of transparency and public engagement. For example, it has not shared public information about its outdoor activity, but the company makes strong claims about the potential effectiveness of the aerosols. To date, it has offered no peer-reviewed research, no third-party oversight, and no signs of engaging the communities that could be affected by its work. Its website announces that peer-reviewed publication of its findings are coming at the beginning of 2026, but it has not always delivered on previous promises of transparency. Meanwhile, it has started lobbying the US government.

When solar geoengineering research occurs in secrecy, risks extend beyond a simple lack of oversight. Opaque research efforts could exacerbate geopolitical tensions and fuel mistrust between countries or suspicion about unmonitored experimentation. Secretive research funded by private entities or countries that can afford it could limit equitable access to potential benefits and disproportionately advantage those powerful nations or actors. Furthermore, uncontrolled experimentation conducted without public accountability heightens the risk of unintended environmental and societal consequences, which have the potential to cause harm that governance frameworks are explicitly designed to prevent.

Because ARIA is a public institution, it is accountable to elected officials and an oversight committee, and it is subject to public debate. At the same time, because it is public, ARIA has drawn criticism from prominent scientists for engaging in solar geoengineering at all and supporting outdoor experiments.[9] The program has also received Environmental Information Regulations requests (similar to US Freedom of Information Act requests).[7] Stardust's work, however, has garnered little public attention until recently.

What those examples illuminate is that public questioning and controversy is inherent to solar geoengineering. Because of that, some scientists are considering whether being less transparent in their work is the better path forward.[10] If there are not mechanisms in place for research to succeed openly, it will be developed in quieter corners in the private sector or by militaries with no public oversight or opportunities for democratic decision-making and could lead to worse outcomes for society.[11]

Many people already assume powerful actors are making decisions in secret. For example, multiple US states have been subject to calls from some of the public and lawmakers to ban nonexistent geoengineering such as chemtrails[12] —the subject of a debunked conspiracy theory that contrails from airplanes are chemicals being spread to control the weather. Amid growing anger at political corruption and the undue influence of billionaires on public institutions, hidden forms of research will almost inevitably face even stronger backlash when they come to light.

What is clear is that science does not operate in a vacuum. It exists as and within political institutions, and it must also be understood through a political lens. The field needs to take governance seriously if it wants to enable the research that is necessary to answer critical questions.

What now?

The solar geoengineering field is at a pivotal juncture for reflection on what is required to protect society's ability to pursue research, but it needs to do so in ways that elicit trust and do not exacerbate harm. Doing so is important not just for science but for the people that science is built to serve. Critics of solar geoengineering frequently express legitimate concerns about unintended environmental impacts, potential distraction from essential emissions mitigation, and ethical considerations.[2] Those concerns are well founded and underscore the necessity of transparent and accountable governance.

Robust governance frameworks that are built into research plans early and have clear environmental safeguards, real and equitable participation from vulnerable communities, and stringent accountability measures could directly address many of the concerns. Rather than dismissing or sidelining them, effective governance incorporates such concerns as a mechanism to ensure research remains aligned with societal needs and ethical standards.

Importantly, the need for governance is not specific to solar geoengineering. A useful lesson can be drawn from AI development, in which technology has leapt ahead of governance, which continues to lag behind. There is incredible excitement, investment, and a flurry of sweeping claims about how AI technologies will transform the world. But such hype is leapfrogging ahead of determining what the benefits to society will ultimately be. Though AI has clear potential value, it also comes with apparent and widespread risks. Despite that, AI has rapidly proliferated without the guidance of a shared global governance framework. There is no consensus on oversight and little to no transparency around who is building those systems and for what purposes.

With AI, the prioritization of technological use and profit before regulatory environments can catch up has led to the rapid spread of extremist content, racially biased surveillance, psychological damage that has not yet been fully understood, and forms of harm that are not yet known. Ultimately, the lack of governance to manage those risks and the eventual public response of shaping, slowing, or even stopping its use may be harmful to the development of AI to serve societal needs. In contrast, there is still a narrow window of opportunity to address the governance gap in solar geoengineering.

Building good governance

Of course, the question of what research governance in solar geoengineering should look like is not a new one. Norms in emerging technology development can help enable and shape science while also ensuring that technologies are being built to serve society. Principles for solar geoengineering governance that guide how research should proceed were introduced as early as 2009, with

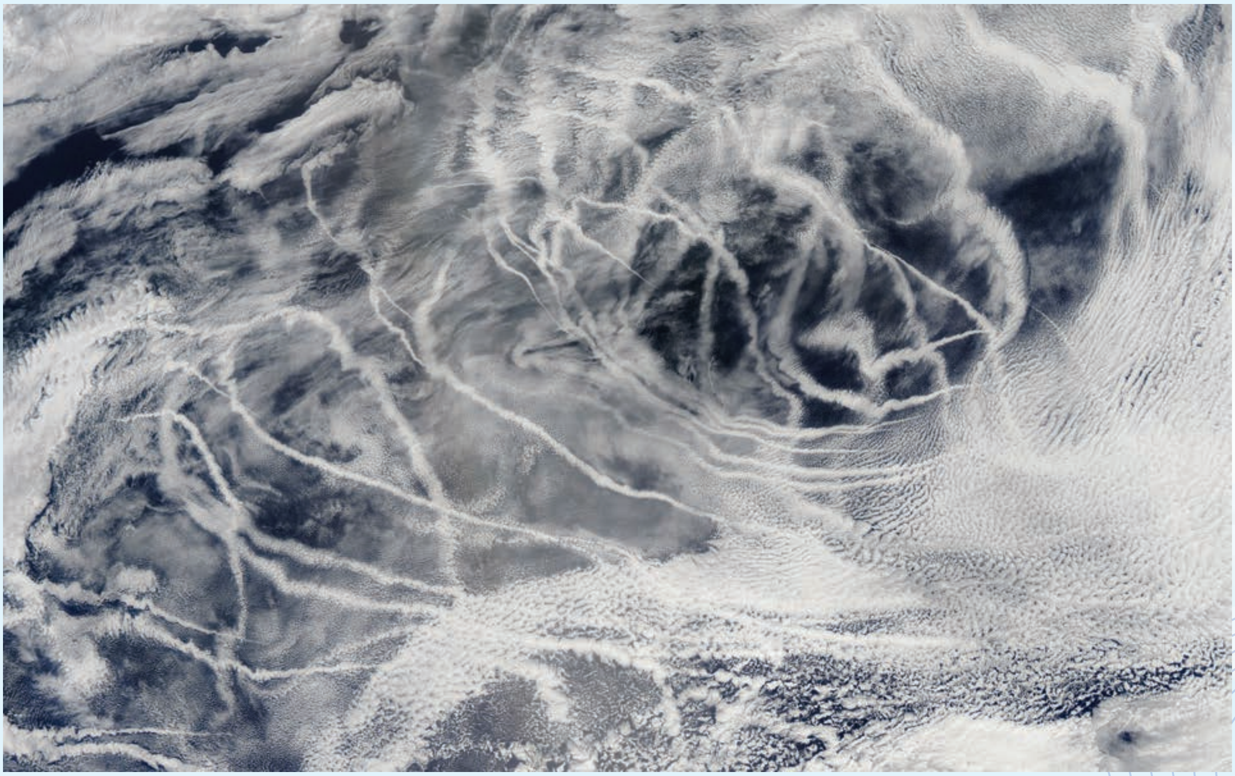

Figure 3. Aerosol emissions from ships can seed cloud formation and create ship tracks—a similar effect to marine cloud brightening aimed at increasing the reflection of solar radiation. (Image courtesy of NASA Goddard Photo and Video photostream, NASA/GSFC/Jeff Schmaltz/MODIS Land Rapid Response Team.)

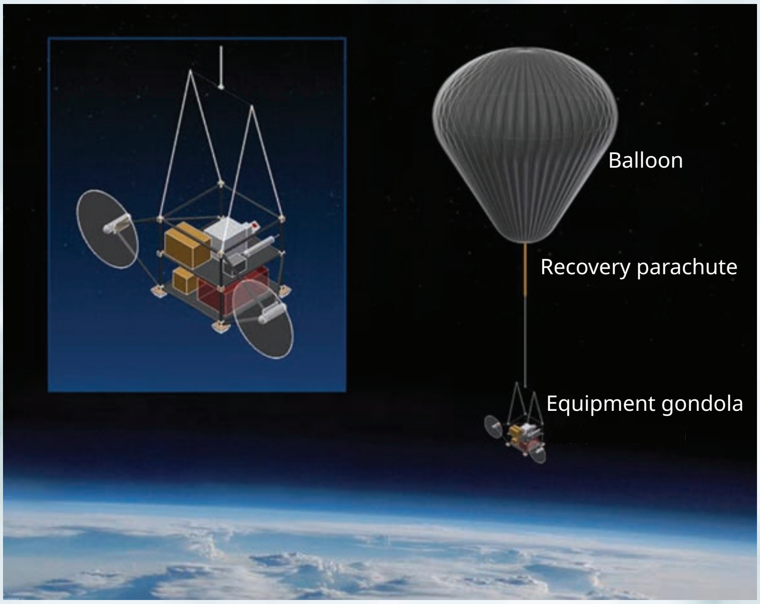

Figure 4. SCoPEx, the Stratospheric Controlled Perturbation Experiment, was proposed by Harvard University researchers in 2014 but was canceled 10 years later despite transparent efforts to engage with the public about the limited environmental impacts it would have. (Figure courtesy of the Keutsch Group at Harvard.)

the Oxford Principles,[13] and as recently as 2024, with the American Geophysical Union's ethical framework for climate intervention.[14] Though those two sets of principles are nuanced and have important differences, they both have similar overarching themes: transparency, public engagement, scientific merit, justice, and informed decision-making.

The critical question now is, What does governance look like operationally? Currently, no existing governance institution or international body, such as a United Nations agency, can or is willing to serve as a governing body for solar geoengineering research. How can the research and governance communities create a system with clear guidance—one that researchers can understand and follow, that holds them accountable, and builds public trust? What's needed is a coordinated oversight structure that not only provides direction but also enforces standards, ensures transparency, and evolves alongside the science itself.

Engagement poses a particular challenge. Though it's often treated like a single checkbox, engagement does not mean just one thing. It can serve a range of purposes, such as co-creation in research design, input into important decisions such as experiment location, and facilitation of free, prior, and informed consent. Those distinct types of engagement could be parallel processes that are all needed for one experiment.

The solar geoengineering field needs to move beyond the use of vague rhetoric and the treatment of engagement as a simple binary—as if the choice is simply to engage or not. That means thinking concretely about who to engage with, how, and to what end and understanding that the answers to those questions may look different at every stage in the research process. Engagement during early agenda setting looks different from engagement around a specific field experiment. But unless the field clearly defines what types of engagement are possible across scales of research, when it should happen, and how input will be taken seriously, engagement risks becoming a hollow promise.

No single organization can work across the spectrum of research governance needs. Good governance will require a collaborative approach to building a system that can help researchers succeed, build accountability, and serve the public good. Although no coordinated approach has taken shape in the field, a myriad of organizations are starting to build various facets of research governance to serve different goals.

In academia, social scientists are exploring public perception, equity, and policy design. A key example is the GENIE (Geoengineering and Negative Emissions Pathways in Europe) project, a multi-institutional effort funded by the European Research Council.[15] The project's researchers are sharing knowledge on public and stakeholder perceptions of solar geoengineering around the globe, in countries across different regions.

Civil society is also engaged in multiple aspects of developing governance infrastructure. One example is my organization, the Alliance for Just Deliberation on Solar Geoengineering. We are working to build inclusive, science-informed frameworks for decision-making through capacity-building workshops, policy writings, and collaboration with policymakers and civil society in climate-vulnerable regions.

In recent years, intergovernmental entities and national scientific academies have also taken first steps into the discussion. In its 2023 *One Atmosphere* report, the UN Environment Programme calls for international governance frameworks to guide solar radiation management research and potential deployment.[16] The report emphasizes the importance of transparency, inclusivity, and global coordination, and it recommends that any future decisions on solar radiation management be made collectively and cautiously, grounded in robust science, and in alignment with climate justice and sustainability goals. In 2021, the US National Academies of Sciences, Engineering, and Medicine released a report on the research and governance of solar geoengineering,[2] and in November 2025, the Royal Society in the UK published a policy briefing on the science and governance of the field.[17] Both reports made similar observations.

Looking forward

Solar geoengineering is evolving rapidly, and research efforts are advancing quickly. For research to proceed in a way that addresses public concern and is beneficial to communities, a careful and coordinated approach to its governance is necessary. Without it, there is a risk that private actors or powerful governments will define the terms of how the field is built in a way that sidelines public accountability and deepens global inequities.

Responsible research requires more than technical safeguards. It demands clear rules, meaningful engagement, and systems that are transparent, are inclusive, and evolve along with the science. Solar geoengineering is not an idea that will disappear. Without mechanisms for such research to succeed, geoengineering may develop in ways that are instead built for individual, company, or government profit or power rather than for society's benefit. It is not the first time that society has needed to create new research governance mechanisms for emerging technologies, and it won't be the last. It is incumbent on scientists, policymakers, and civil society to create a framework that balances trust and scientific progress to serve the public good. **PT**

References

1. P. J. Crutzen, "Albedo enhancement by stratospheric sulfur injections: A contribution to resolve a policy dilemma?," *Clim. Change* **77**, 211 (2006).
2. National Academies of Sciences, Engineering, and Medicine, *Reflecting Sunlight: Recommendations for Solar Geoengineering Research and Research Governance*, National Academies Press (2021).
3. S. Talati, P. C. Frumhoff, "Strengthening Public Input on Solar Geoengineering Research," issue brief, Union of Concerned Scientists (June 2020).
4. J. Tollefson, "Divisive Sun-dimming study at Harvard cancelled: What's next?," *Nature*, 27 March 2024.
5. S. Jinnah et al., "Do small outdoor geoengineering experiments require governance?," *Science* **385**, 600 (2024).
6. C. Flavelle, "Warming is getting worse. So they just tested a way to deflect the Sun," *New York Times*, 2 April 2024, updated 30 September 2024.
7. Advanced Research and Invention Agency, Exploring Climate Cooling program.
8. R. Skibba, "A mysterious startup is developing a new form of solar geoengineering," *Wired*, 22 March 2025.
9. R. Pierrehumbert, M. Mann, "The UK's gamble on solar geoengineering is like using aspirin for cancer," *Guardian*, 12 March 2025.
10. D. Gelles, "This scientist has a risky plan to cool Earth. There's growing interest," *New York Times*, 1 August 2024, updated 30 September 2024.
11. S. Talati, H. J. Buck, B. Kravitz, "How to address solar geoengineering's transparency problem," *Proc. Natl. Acad. Sci. USA* **122**, e2419587122 (2025).
12. V. DiFonzo, "Alluding to 'chemtrail' conspiracy theory, Mastriano floats ban on climate mitigation techniques," *Pennsylvania Capital-Star*, 10 June 2025.
13. S. Rayner et al., "Memorandum on draft principles for the conduct of geoengineering research," submitted to the UK House of Commons Science and Technology Committee enquiry into the regulation of geoengineering (2009); S. Rayner et al., "The Oxford Principles," *Clim. Change* **121**, 499 (2013).
14. American Geophysical Union, *Ethical Framework Principles for Climate Intervention Research* (2024).
15. GENIE, "Solar Radiation Management–Knowledge Hub."
16. United Nations Environment Programme, *One Atmosphere: An Independent Expert Review on Solar Radiation Modification Research and Deployment* (2023).
17. Royal Society, *Solar Radiation Modification: Policy Briefing* (2025).

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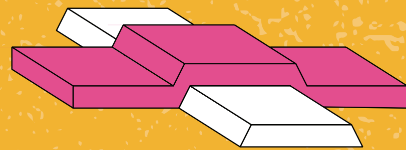
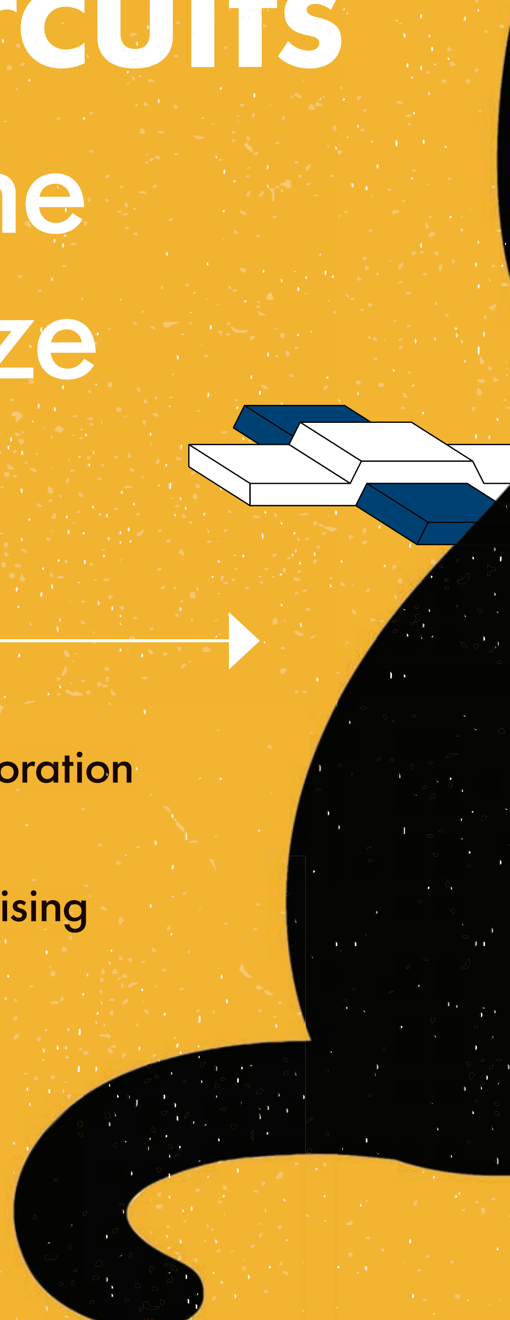


Superconducting quantum circuits

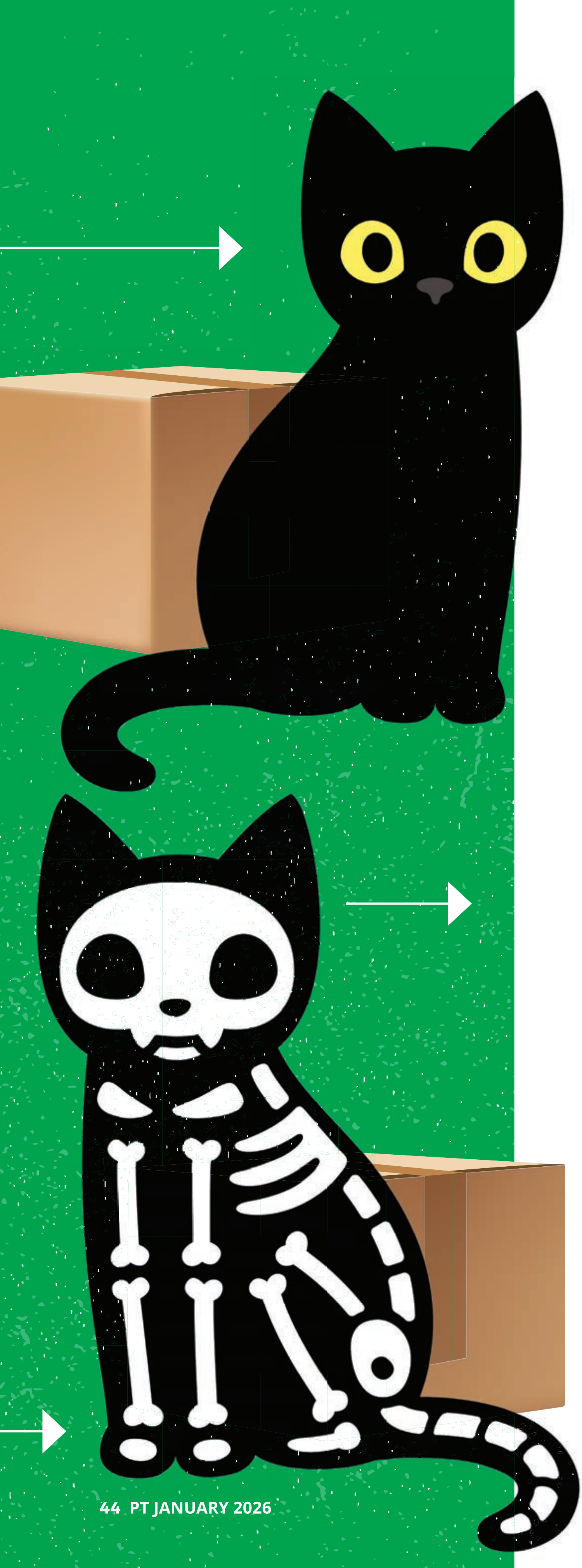
At the heart of the 2025 Nobel Prize in Physics

Johanna L. Miller

Although motivated by the fundamental exploration of the weirdness of the quantum world, the prizewinning experiments have led to a promising branch of quantum computing technology.



(Design by Masie Chong with artwork adapted from Shutterstock.com artist Sudowoodo and iStock.com artists Aerial3, Perkasa Rambe, and Alexey Yaremenko.)



All cats, as far as anyone can tell, are either dead or alive—but atoms can be in two places at once. The crisp boundaries and deterministic behaviors we experience in the classical, macroscopic world seem at odds with the inherent fuzziness and randomness of quantum mechanics. From the early days of quantum theory, physicists have struggled to intuitively reconcile the quantum and classical realms and to locate the boundary between them, if one exists.

The 2025 Nobel Prize in Physics honors a series of landmark experiments[1–3] from the mid 1980s by John Clarke, Michel Devoret, and John Martinis (all, at the time, at the University of California, Berkeley) that convincingly demonstrated that quantum tunneling and energy-level quantization can occur in a millimeter-scale electronic circuit. The experiments are noteworthy less for their results—it would have been far more surprising if the circuits didn't obey the predictions of quantum mechanics—than for their ramifications. The laureates showed that the macroscopic quantum world could be brought under experimental control. And their work laid the foundations for the superconducting qubits that are at the cutting edge of quantum computing research today.

Posing the question

In one sense, "Why don't we see quantum effects in the macroscopic world?" is easy to answer: Planck's constant $\hbar$ defines a physical scale that, compared with most of what we encounter in our everyday experience, is small. Beginning students of quantum mechanics are often amused to find that they can calculate the probability of some classically absurd thing—walking through a wall, for example, or part of your left earlobe spontaneously appearing on Jupiter—and that that number is not identically zero. But it might as well be. The time it would take a human body to tunnel through a wall, multiplied by the energy barrier it would have to overcome to do so, is so large relative to $\hbar$ that the tunneling probability has a gargantuan negative exponent, and the event would never happen. (For some pandemic-era musings on other unphysical calculations, gargantuan negative exponents, and the meaning of "never," see the 2020 *PT* column "A pea, the Sun, and a million monkeys.")

In another sense, "Why don't we see quantum effects in the macroscopic world?" evokes a different easy answer: We do. The flow of persistent currents in superconductors is a quantum phenomenon. So is the photoelectric effect. So are the existence of crystals with well-defined facets and chemicals with well-defined colors. So is the mere existence of solid matter. The echoes of quantum mechanics in our everyday experience are not sparse. But in each case, the entities behaving quantum mechanically are atoms or subatomic particles, not macroscopic collective variables like the position of a bowling ball or a person. Microscopic quantum effects make themselves known at the macroscopic level, but a macroscopic system showing its own tunneling or energy-level quantization would be an entirely different thing.

In yet a third sense, the question becomes significantly more subtle. The time-dependent Schrödinger equation states that systems' wavefunctions evolve deterministically, and it makes no allowance for the probabilistic collapse of those wavefunctions during measurements. It would seem like any system set in motion would accumulate many superpositions of macroscopic states, of the type that Erwin Schrödinger highlighted with his eponymous cat paradox, that are never observed in the real world.

In a 1991 *Physics Today* feature article, "Decoherence and the transition from quantum to classical," Wojciech Zurek made the case that those superpositions are not observed because dissipation and decoherence conspire to destroy them. No real-world system is perfectly isolated from its environment, and all the minute couplings and exchanges of energy break down the coherence between widely separated parts of a wavepacket. In effect, they transform the spookily quantum "The cat is simultaneously alive and dead" into the familiarly classical "The cat is either alive or dead, but we don't know which." And because large systems have more channels for interacting with their surroundings than small systems do, their superpositions disappear far more quickly. Regardless of how completely that argument explains the nonexistence of dead-and-alive cats, dissipation certainly makes it harder to observe pure quantum behavior in macroscopic systems.

So the question becomes, Can one create a macroscopic apparatus that exhibits behavior described by a collective coordinate, with energy and time scales that are not large relative to $\hbar$, and that is also sufficiently decoupled from its environment that its quantum states don't decohere? And the answer, as of the early 1980s, was "Maybe."

Designing the experiment

The key to observing quantum behavior in a macroscopic coordinate was that the coordinate could be something other than the physical position of a particle: Tunneling through a classically forbidden barrier doesn't have to involve literally walking through a wall. (More recently, researchers have started to harness the quantum behavior of position coordinates in mesoscopic and macroscopic mechanical resonators. For some examples from *PT*'s archive, see the 2025 Back Scatter "A macroscopic qubit," the 2023 news story "Macroscopic mechanical oscillator is herded into a Schrödinger cat state," the 2015 news story "A quantum squeezed state of a mechanical resonator has been realized," the 2010 news brief "Quantum properties in the mechanical world," and references therein.)

To see what such a quantum macroscopic variable could look like, consider the circuit in figure 1(a): The

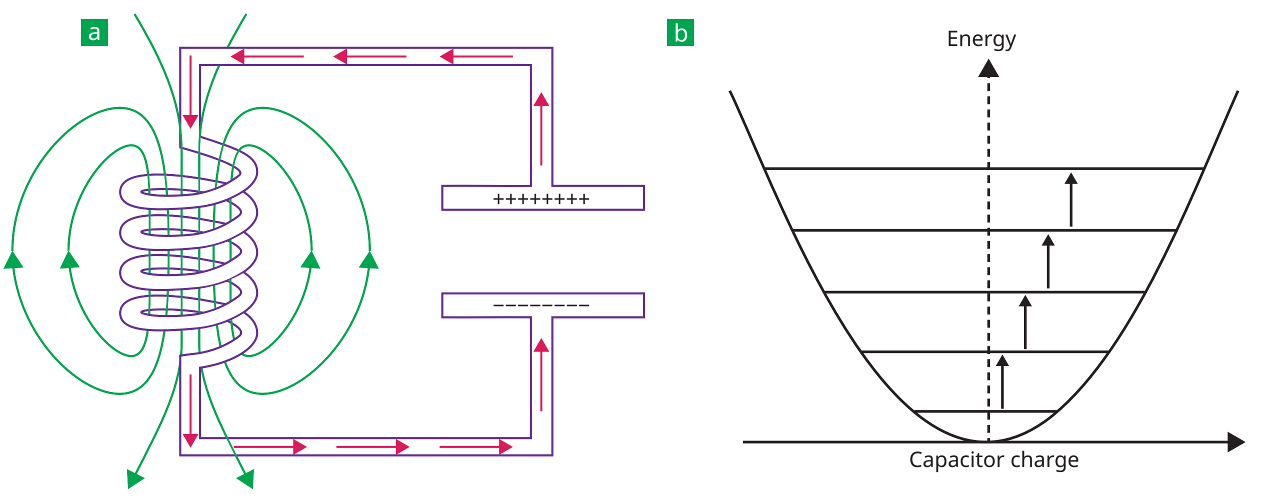


Figure 1. In an inductor–capacitor circuit **(a)**, charge bounces between the plates of the capacitor like a mass on a spring. The harmonic-oscillator potential **(b)** gives rise to a series of discrete energy levels. But because the levels are all equally spaced, observing their quantization would be difficult. (Figure by Freddie Pagani.)

state of the inductor–capacitor combination is characterized by the charge on the capacitor, which sloshes back and forth like a mass on a spring. The harmonic-oscillator potential, shown in figure 1(b), has equally spaced quantum states. As the laureates and colleagues have noted, with a temperature of 10 mK, an inductance of 350 pH, and a capacitance of 15 pF—all experimentally realizable values—the energy-level spacing would dwarf the system's thermal energy, and quantum effects would dominate.[4]

But how could you tell? You could try to observe the energy-level quantization by spectroscopically exciting transitions among the energy levels. But the levels are all equally spaced, and the frequency of transitions between them is equal to the circuit's classical resonant frequency, so there's no clear way to distinguish a quantum resonance from a classical one. Furthermore, there's no option to observe quantum tunneling, because with only one well in the energy potential, the system has nowhere to tunnel to.

Both those problems are solved with the switch from an inductor–capacitor circuit to a Josephson junction: two overlapping strips of superconducting material, as shown in figure 2(a), with a thin nonsuperconducting layer at the interface. Cooper pairs in the superconductors can tunnel through the interface—but importantly, the tunneling through that physical barrier is distinct from the macroscopic quantum tunneling that the laureates were seeking to demonstrate.

The state of the Josephson junction is characterized by the superconducting phase difference across the interface. That sounds like an exotic quantum mechanical quantity, but you can think of it as roughly analogous to the charge in the inductor–capacitor circuit: Both are macroscopic parameters that describe the collective state of all the charge carriers in the system. The phase difference is defined modulo 2π, and it follows a sine-wave potential rather than a parabolic one. The result, as shown in figure 2(b), is a series of energy levels that aren't equally spaced and plenty of energy barriers for the system to tunnel through.

If a Josephson-junction circuit is prepared in a low-lying state in one well of the sine-wave potential, classical physics would dictate that, barring any energy input into the system, it would stay there forever. But quantum mechanics predicts that the system has some probability of turning up in a different energy well: Despite lacking the energy to climb over the barrier, it can tunnel through it. And that tunneling probability can be made significant, even in a circuit that's not too small: In the one the laureates used, the interface between the superconductors was 10 μm by 10 μm. In a circuit of that size, tunneling through the energy barrier would involve the concerted motion of billions of Cooper pairs. Mathematically, it makes sense to describe their state as a single collective variable. But would that variable obey the Schrödinger equation, or would decoherence degrade or ruin its quantum behavior?

Clarke, Devoret, and Martinis weren't the first to appreciate that a Josephson junction could be an ideal

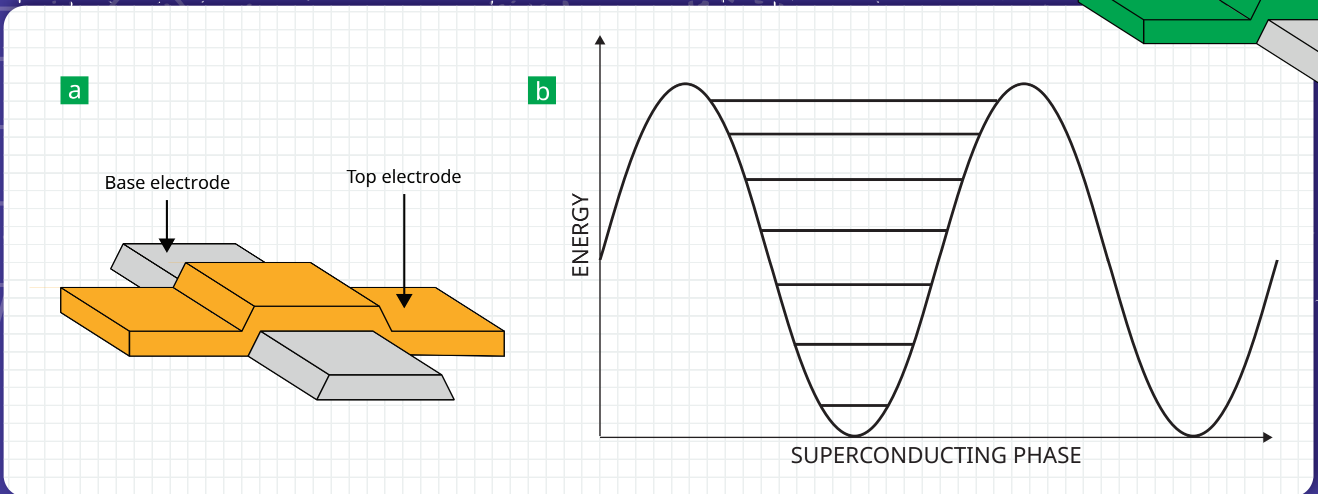


Figure 2. A Josephson junction **(a)**—two strips of superconductor separated by a thin nonsuperconducting interface—provided the ideal testing ground for macroscopic quantum effects. Its energy potential **(b)** is a sine wave, rather than a parabola, so its states are unequally spaced, and the system can tunnel from one energy well into another. (Panel (a) adapted from J. M. Martinis, M. H. Devoret, J. Clarke, "Quantum Josephson junction circuits and the dawn of artificial atoms," Nat. Phys. **16**, 234, 2020; panel (b) by Freddie Pagani.)

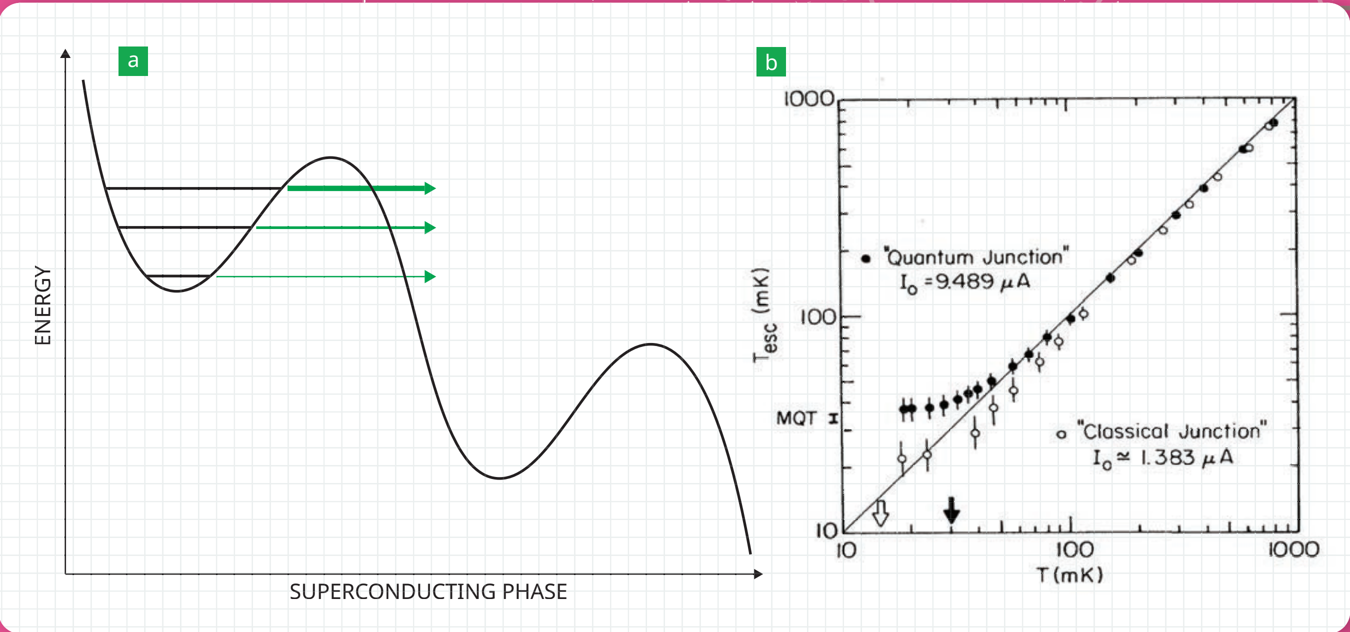


Figure 3. Applying a bias current to a Josephson junction transforms the flat sine-wave potential from figure 2 into a tilted one **(a)**. The system can then prove its quantum nature by tunneling out of the metastable energy well. The plot in **(b)**, from one of the laureates' landmark papers, shows one clear demonstration of the effect. The horizontal coordinate T is the system's real temperature, and the vertical coordinate T_{esc} is the temperature that would yield the observed escape rate if all the escapes happened classically. At higher temperatures the two are equal, but at lower temperatures they diverge: evidence of macroscopic quantum tunneling (MQT). (Panel (a) by Freddie Pagani; panel (b) from ref. 3.)

testing ground for macroscopic quantum effects.[5] Nor were they the first to attempt the experiment.[6] What set their work apart was the care with which they made their measurements—and, consequently, the clarity of their results.

They started by thoroughly characterizing the circuit in the classical regime to pin down the parameters of the sine-wave potential—complete with error bars—and therefore the tunneling probability that they could expect under any given conditions. Because cooling to absolute zero is impossible, there was always some lingering probability that the circuit could get enough of an energy kick from the environment to hurdle over the barrier rather than tunnel through it. They needed to understand the likelihood of the first possibility to demonstrate the existence of the second.

For the test itself, the laureates biased the Josephson junction with a small current, which transformed the level sine wave of figure 2(b) into the tilted one of figure 3(a). Now the tunneling entity had somewhere to go: If it escaped the metastable state in the energy well it started in, it would go tumbling down the potential-energy hill, which would be observable as the spontaneous appearance of a voltage drop across the Josephson junction.

Starting at 1 K and cooling the system to progressively lower temperatures, the laureates measured how readily the voltage drop appeared. In the upper part of the temperature range, there was still plenty of thermal energy for the system to surmount the energy barrier classically. But as the temperature fell, the classical probability diminished. If the voltage drop kept appearing, it would have to be due to quantum tunneling.

Figure 3(b) shows one way of plotting their results. The horizontal axis is the actual temperature, and the vertical axis is the temperature that would yield the escape rate that they observed, assuming that all the escapes happened classically. In the upper right part of the plot, those temperatures are equal, but in the lower left, the effective escape temperature levels off while the real temperature continues to fall: clear evidence of tunneling.

In another series of experiments, the laureates used microwaves to excite the Josephson-junction circuit from the lowest metastable energy level to a higher one. Rather than varying the microwave frequency to home in on the quantum resonance, they varied the bias current, which changed the tilt and shifted the energy-level spacings. When it was in resonance with the microwaves, the circuit was excited to a higher energy level, which had less of an energy barrier to tunnel through, so the researchers observed the excitation as an enhanced escape rate from the metastable well. And the resonances always appeared

where quantum mechanics said they would.

But qubits?

The energy-quantized Josephson junction wasn't yet a qubit. For one thing, in 1985, the word "qubit" didn't even exist—and it wouldn't be coined by Benjamin Schumacher until a decade later, after Peter Shor discovered that a hypothetical quantum computer could find the prime factors of a large number faster than a classical computer could. The advent of Shor's algorithm helped launch the study of quantum information from a niche intellectual pursuit into something with potential real-world applications. (For more on the algorithm and its genesis, see the annotated version of David Zierler's interview with Shor published in *PT* in April 2025.)

For another thing, the Josephson junction still had more quantum properties to reveal. The laureates had demonstrated tunneling and energy-level quantization. But a useful qubit also needs the ability to be prepared in a superposition of states, which can be manipulated in conjunction with other qubits to create complex entangled states.

There are several ways to create superposable states out of a superconducting Josephson-junction-based circuit. *Physics Today* has covered superconducting qubits at several stages of their development: To read about them in more detail, see the November 2005 feature article "Superconducting circuits and quantum information," by J. Q. You and Franco Nori; the 2002 news story "Two realization schemes raise hopes for superconducting quantum bits"; and the 2009 news story "Superconducting qubit systems come of age."

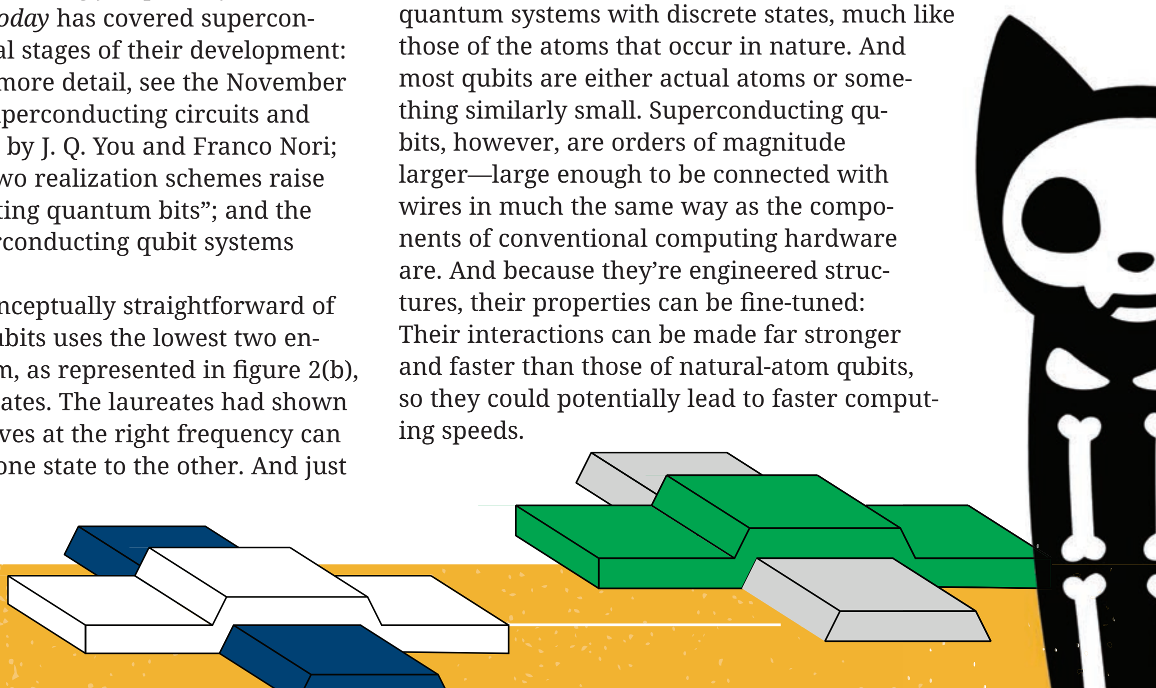
Perhaps the most conceptually straightforward of the superconducting qubits uses the lowest two energy levels of the system, as represented in figure 2(b), as the qubit's 0 and 1 states. The laureates had shown that a blast of microwaves at the right frequency can excite the circuit from one state to the other. And just like with other electromagnetically excitable systems, pulses of precise duration can partially transfer the system between the two states and thereby create any desired coherent superposition of 0 and 1.

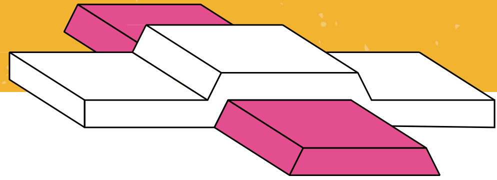
That approach, called a phase qubit, was pioneered in 2002 by Martinis and others.[7] But it was pre-dated by a different scheme, called a charge qubit, in which Cooper pairs are made to tunnel one by one across a Josephson junction to an isolated superconducting island.[8] The states with some number n and $n + 1$ Cooper pairs on the island are designated as the qubit's 0 and 1 states.

A refined version of the charge qubit, called a transmon,[9] is currently favored by many quantum computing research groups. Transmons are the basis, for example, of the Google Quantum AI team's Willow chip, which recently achieved a long-sought milestone in quantum error correction. To counter the inherent delicacy of quantum states, researchers have hoped to build redundancy into a quantum computer by combining the states of many physical qubits to make one logical qubit. But that strategy works only if the physical qubits have a low enough error rate that adding more of them makes things better, not worse. And the Willow chip has done just that.[10]

But Google researchers aren't the only ones to be making great strides in quantum error correction and other prerequisites to practical quantum computation. Other teams are right on their heels, with implementations that use neutral atoms or trapped ions rather than superconducting circuits. It remains to be seen which qubits, if any, will be the building blocks of the quantum computers of the future.

Of the leading qubit contenders, superconducting qubits stand out in several ways. All qubits are quantum systems with discrete states, much like those of the atoms that occur in nature. And most qubits are either actual atoms or something similarly small. Superconducting qubits, however, are orders of magnitude larger—large enough to be connected with wires in much the same way as the components of conventional computing hardware are. And because they're engineered structures, their properties can be fine-tuned: Their interactions can be made far stronger and faster than those of natural-atom qubits, so they could potentially lead to faster computing speeds.





Understanding the answer

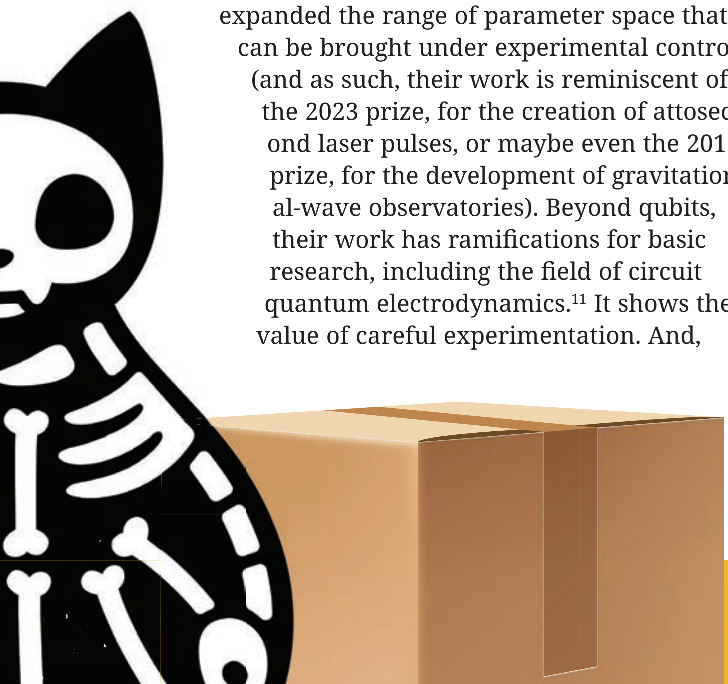
Despite recent advances, quantum computers are not yet a mature technology. In that respect, they stand in stark contrast to the neural networks—highlighted by the 2024 physics Nobel, covered in a December 2024 *Physics Today* news story—which are already having disruptive, world-changing effects throughout society, for good or for ill.

Of course, not every Nobel Prize in Physics is connected to a practical technology. The 2015 prize, for example, honored the discovery that neutrinos spontaneously change flavor as they travel (covered by *PT* in December 2015). Neutrino oscillations aren't the basis for any consumer products, and they probably won't ever be—although one never knows for sure.

But neutrino oscillations were an unexpected answer to a fundamental question about the universe. They're evidence that there's something going on in the subatomic world that's not well described by the standard model of particle physics, and they pointed toward places to look for answers to even deeper questions.

And that's not quite the story of the 2025 prize either. The fact that macroscopic collective variables obey the Schrödinger equation was, strictly speaking, not known for sure until it was observed. The observation did rule out some alternative theories that had been floated, such as the idea that above some suitably defined size scale, quantum mechanics just doesn't apply. But the results themselves weren't as revelatory as some years' prizes are.

No one who's not on the Nobel Committee can be sure of the reasoning for awarding any particular prize. But the value of the work by Clarke, Devoret, and Martinis seems to be in its effects on how physicists do physics. Their experiments expanded the range of parameter space that can be brought under experimental control (and as such, their work is reminiscent of the 2023 prize, for the creation of attosecond laser pulses, or maybe even the 2017 prize, for the development of gravitational-wave observatories). Beyond qubits, their work has ramifications for basic research, including the field of circuit quantum electrodynamics.[11] It shows the value of careful experimentation. And, through its implications for quantum computation, it may still change the world.



Many thanks to John Martinis, Andrew Cleland, Sue Coppersmith, Nathalie de Leon, Mark Dykman, Steve Girvin, Doug Natelson, Will Oliver, Rob Schoelkopf, and Clare Yu for helpful conversations that informed this article. PT

References

1. M. H. Devoret et al., "Resonant activation from the zero-voltage state of a current-biased Josephson junction," *Phys. Rev. Lett.* **53**, 1260 (1984).
2. J. M. Martinis, M. H. Devoret, J. Clarke, "Energy-level quantization in the zero-voltage state of a current-biased Josephson junction," *Phys. Rev. Lett.* **55**, 1543 (1985).
3. M. H. Devoret, J. M. Martinis, J. Clarke, "Measurements of macroscopic quantum tunneling out of the zero-voltage state of a current-biased Josephson junction," *Phys. Rev. Lett.* **55**, 1908 (1985).
4. J. Clarke et al., "Quantum mechanics of a macroscopic variable: The phase difference of a Josephson junction," *Science* **239**, 992 (1988).
5. See, for example, A. J. Leggett, "Macroscopic quantum systems and the quantum theory of measurement," *Prog. Theor. Phys. Suppl.* **69**, 80 (1980).
6. See, for example, R. F. Voss, R. A. Webb, "Macroscopic quantum tunneling in 1-μm Nb Josephson junctions," *Phys. Rev. Lett.* **47**, 265 (1981).
7. Y. Yu et al., "Coherent temporal oscillations of macroscopic quantum states in a Josephson junction," *Science* **296**, 889 (2002); J. M. Martinis et al., "Rabi oscillations in a large Josephson-junction qubit," *Phys. Rev. Lett.* **89**, 117901 (2002).
8. Y. Nakamura, Y. A. Pashkin, J. S. Tsai, "Coherent control of macroscopic quantum states in a single-Cooper-pair box," *Nature* **398**, 786 (1999).
9. J. Koch et al., "Charge-insensitive qubit design derived from the Cooper pair box," *Phys. Rev. A* **76**, 042319 (2007).
10. Google Quantum AI team and collaborators, "Quantum error correction below the surface code threshold," *Nature* **638**, 920 (2025).
11. A. Blais et al., "Circuit quantum electrodynamics," *Rev. Mod. Phys.* **93**, 025005 (2021).

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An interview series that profiles scientists who opted for careers outside of academia.

Joyful Mdhluli manages astronomy projects that benefit society

By Toni Feder

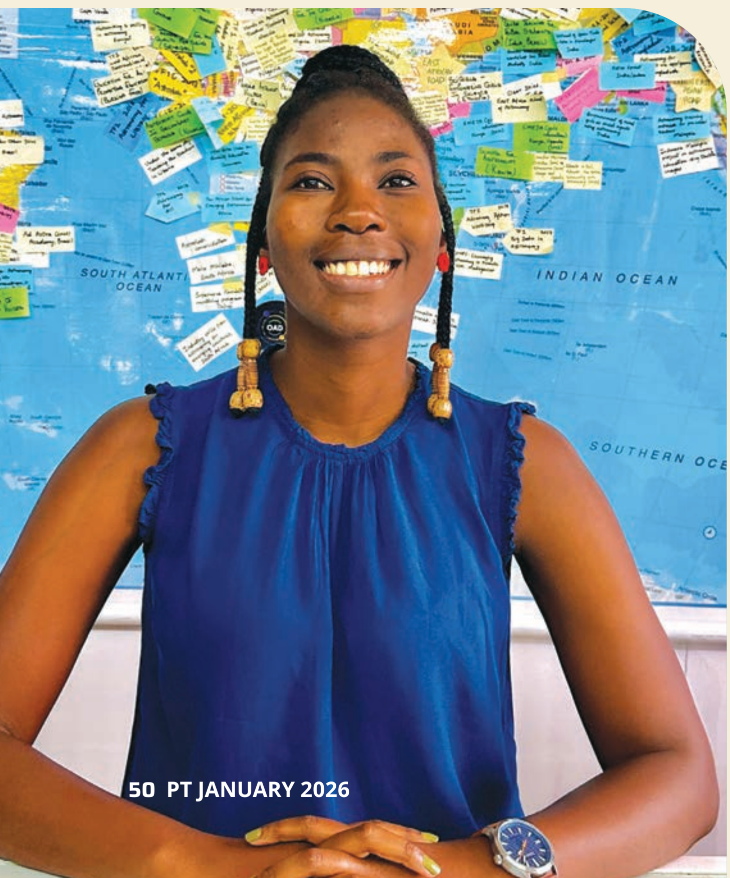
Project coordinator, International Astronomical Union's Office of Astronomy for Development, Cape Town, South Africa

BS, physics, University of the Witwatersrand, 2014
PhD, physics, University of the Witwatersrand, 2023

What was your research focus?

For my master's, I characterized properties of diamond after radiation damage. For my PhD, I conducted data analysis for the ALICE experiment at CERN's Large Hadron Collider. [Mdhluli discusses her PhD path in her 2022 *Physics Today* essay, "A journey of joy and uncertainty in physics."]

(Photo courtesy of Joyful Mdhluli.)



How did you make the transition to coordinating projects?

I woke up one day and realized I didn't want to stay in academia. Universities don't tell us what you can do with a physics degree—just that we have so many opportunities. I had volunteered for science fairs and other outreach activities, and I thought I'd like to do community development and make a tangible impact. I just didn't know how to go about it.

I spent six months applying for jobs. I was either overqualified or employers didn't see how I fit in. I reached out to the office where I now work to ask about their project on astronomy for mental health. I had no background in astronomy or mental health, but it sounded cool. They took me because of my experience with data analysis.

How do you spend your time?

In meetings. We try to build collaborations between astronomy and other sectors and look at how to use astronomy to benefit society. I document the work to create a database of astronomy-for-development knowledge and activities.

My main role is to coordinate three flagship projects: astronomy for mental health, astrotourism, and hackathons for development. Additionally, I support our annual open global call for proposals that include astronomy as a component to address a societal challenge.

People have brilliant ideas. We give them seed money. A project in Nigeria uses astronomy to help soon-to-be-released inmates reintegrate into society. Another project provides training to broaden employment options for marginalized students from Central America and the Caribbean.

How does your physics background come into your work?

It's difficult to say there is a direct line from my physics to what I am doing. I use critical thinking. And high-level scientists and people in government are more open to what I have to say because I have a PhD.

What do you like about your job?

I like engaging with new concepts and people from different parts of the world. PT

Read more interviews in the series at https://physicstoday.org/wcpd.

How twisted fibers could help robots move nimbly

Fibrous materials that can reversibly twist and coil can be coaxed to contract and elongate as part of lightweight exoskeletons and other bioinspired structures.

By Caterina Lamuta

Because of recent advances in AI, today's robots appear to think like humans in certain ways. But why do robots still struggle to move like humans? Despite remarkable progress in robotics over the past few decades, robots still tend to move in a segmented, stop-and-go manner. Rather than in seamless flows, their motions unfold in noticeable steps, much like the choppy gestures that inspired the robot dance made famous by Michael Jackson in the 1970s.

The root of the problem is that most robotic motion systems bear little resemblance to biological muscles. Many robots move with the use of actuators, such as electric motors and pneumatic and hydraulic systems. Those devices rely on rotors, stators, pistons, valves, and other rigid, bulky, and mechanically complex parts.

To replace conventional actuators, researchers are developing materials that mimic the soft, adaptable, and distributed nature of muscle tissue. One class of materials is the biologically inspired artificial muscle.

Artificial muscles are materials that can contract, expand, and twist in response to an external stimulus before returning to their original shape once the stimulus is removed. Unlike conventional actuators, artificial muscles operate with an actuation mechanism that is embedded in one continuous structure, whether it is composed of a single material or a composite of several materials. In that sense, artificial muscles share a conceptual similarity with skeletal muscles, which also function as a single component despite being composed of fibers, proteins, and connective tissues.

The overarching goal of researchers is to have artificial muscles replicate the low weight, high flexibility, and exceptional power-to-weight ratio of their biological counterparts. Among the various types of artificial muscles being explored, one category has recently drawn significant attention: twisted and coiled artificial muscles, usually known as TCAMs. First demonstrated in 2011, they stand out because of their low cost, simple manufacturing

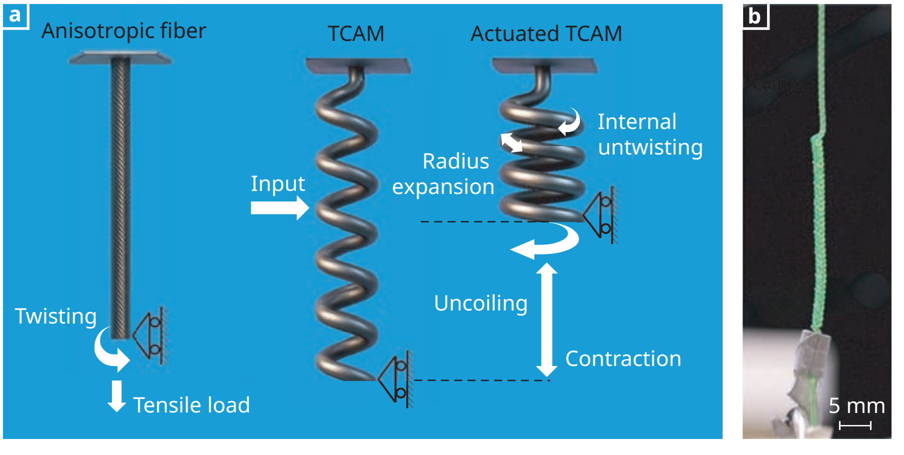


Figure 1. How twisted and coiled artificial muscles (TCAMs) work. **(a)** When an anisotropic fiber, such as a nylon fishing line, is twisted under tension, it will spontaneously coil. When the fiber retains the twisted and coiled shape, it forms a TCAM. When the TCAM heats up or swells in response to external stimuli, its radius expands, it untwists and uncoils, and it contracts linearly. **(b)** A nylon TCAM has its lower portion coiled and twisted, and its upper portion is only twisted.

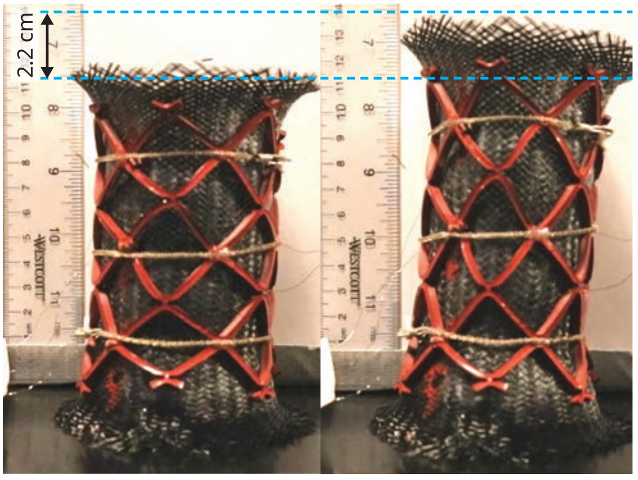


Figure 2. When an octopus-inspired sleeve is squeezed, it elongates by almost 20%. The motion is initiated by three twisted and coiled artificial muscles (brown) that are wrapped horizontally around the soft structure. In response to external stimuli, such as heat, the muscles contract and squeeze the composite sleeve. The red elastomer mesh distributes the load over the sleeve. (Image adapted from P. Kotak et al., *Soft Robot*. **11**, 432, 2024.)

process, and impressive performance. Although more research is needed before TCAMs can be used widely, they're a promising path forward in the quest for lifelike robotic motion.

What makes artificial muscles work?

Only fibers with the property of anisotropic volume expansion are suitable for TCAMs. That means that the fiber expands primarily in the radial direction without getting any longer.

When exposed to heat, a twisted and coiled anisotropic fiber untwists and becomes stiffer as its radius expands. As shown in figure 1(a), that untwisting leads to uncoiling, which in turn results in contraction—just like a muscle. Importantly, the actuation is reversible: When the heat source is removed and the fiber cools, the TCAM returns to its initial length, ready for the next actuation cycle.

TCAMs are relatively simple to construct. They can even be made at home with a fishing line and a hand drill. First, fix the upper end of a fishing line to a drill chuck. To keep the line under tension, hang a small weight from the lower end. Then, once the fiber is taut, start twisting it with the drill; be sure to constrain the torsion or the fiber will simply unwind. As the fiber twists, it will self-coil and form tight spirals, which can be seen in figure 1(b). Once the fiber is fully coiled, place it in an oven at 175 °C for an hour. (Make sure the fiber is still constrained to prevent it from untwisting.)

After it cools, the fishing line will hold its spring-like, coiled shape—it's now a TCAM. To see it in action, hang a small weight from the muscle to keep it under tension, then point a hair dryer or a heat gun at it. As it warms, the fiber will contract and behave like a linear actuator and mimic the function of a biological muscle.

Most fishing lines—made from materials such as nylon or polyvinylidene fluoride—exhibit anisotropic volume expansion because of the way they're manufactured. During the extrusion and drawing processes, the molecular polymer chains become aligned along the length of the fiber. That structural orientation allows the fiber to expand radially and for its length to stay nearly the same.

Researchers studying TCAMs have explored such materials as carbon fibers, carbon nanotubes, and natural fibers like silk and bamboo because they also exhibit anisotropic volume expansion. In some cases, such as with carbon fiber, the material doesn't expand enough. To boost the effect, fibers are embedded in a matrix material with a high thermal-expansion coefficient. Silicone rubber is a common choice.

Direct heating is not the only way to induce volume expansion in such materials. Actuation can be triggered either electrically by applying a voltage that generates internal heating or chemically through swelling, such as when a fiber absorbs a solvent. Certain silicone rubbers, for example, swell considerably when exposed to hexane. Swelling-driven actuation can be more energy efficient than heat-driven actuation because it does not require an external heat source. The actuation response in swelling-driven materials, however, is typically slower than in heat-driven materials because of the time it takes for the solvent to diffuse through the material.

Applications of bioinspired robotics

When it comes to performance, TCAMs deliver. With a low input voltage and just a few watts of power, they can lift more than 10 000 times their own weight. The strength of TCAMs originates from their fibers being twisted. Unlike a straight fiber, a twisted one redistributes an applied load more uniformly along it, which reduces stress concentrations and allows the material to withstand significant forces without failing. The principle is similar to the properties of ropes and load-bearing bridge cables: Twisting multiple strands together greatly increases the fiber's overall strength and structural integrity.

TCAMs mimic many of the properties and behaviors of skeletal muscles. They are compact and lightweight, and they can be embedded in soft tissue and passively stretched. Individual TCAM fibers can be arranged in parallel in a bundle, and specific fibers can be selected to perform a particular motion or exercise.

Researchers have already applied TCAMs in various bioinspired technologies, including lightweight exoskeletons for upper and lower limbs and smart fabrics made from TCAM fibers that adapt to changes in humidity. Inspired by the muscle architecture of octopus limbs, which are capable of bending, contracting, elongating, and twisting, researchers have demonstrated that TCAMs can be embedded into soft materials to replicate that architecture. Figure 2 shows TCAMs that elongate a soft robotic arm.

The full potential of TCAMs remains to be seen—researchers have achieved results in the lab, but no commercial technology using TCAMs exists yet. More work is needed to develop scalable, repeatable, and mass-produced manufacturing processes. In addition, researchers still need to improve the software algorithms that control the motion of TCAMs. With further development, TCAMs could become essential to the creation of lifelike robots whose muscle structures are capable of smooth, precise, and humanlike movement. PT

Additional resources

- ➤ S. M. Mirvakili, I. W. Hunter, "Artificial muscles: Mechanisms, applications, and challenges," *Adv. Mater*. **30**, 1704407 (2018).
- ➤ C. Lamuta, "Perspective on highly twisted artificial muscles," *Appl. Phys. Lett.* **122**, 040502 (2023).
- ➤ P. Kotak et al., "Octopus-inspired muscular hydrostats powered by twisted and coiled artificial muscles," *Soft Robot.* **11**, 432 (2024).
- ➤ T. Jia et al., "Moisture sensitive smart yarns and textiles from self-balanced silk fiber muscles," *Adv. Funct. Mater.* **29**, 1808241 (2019).

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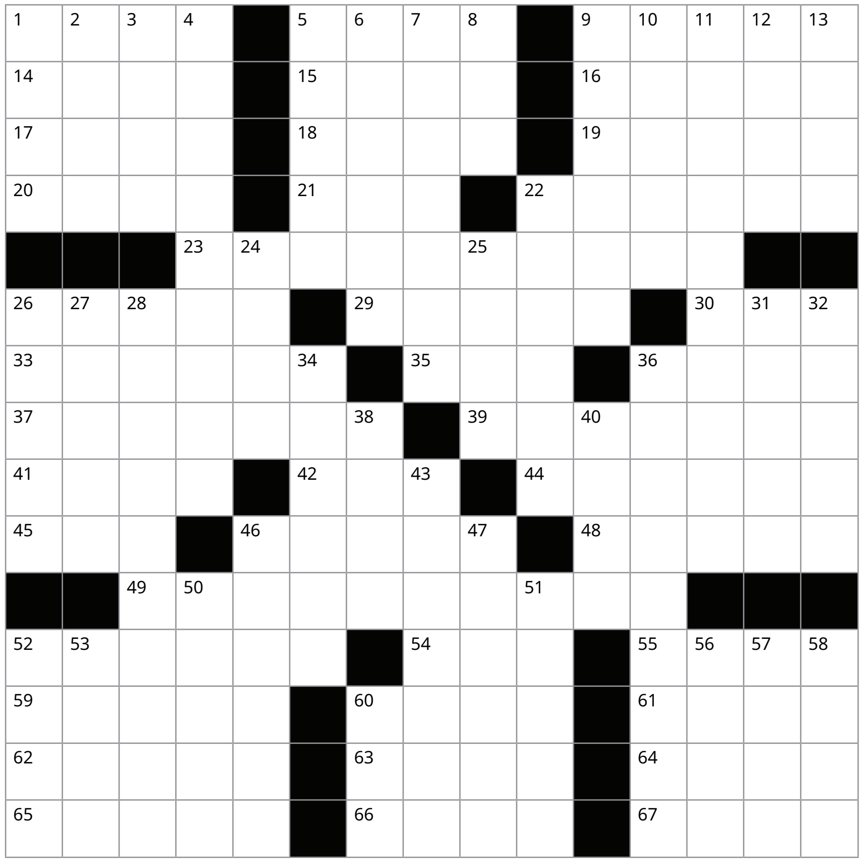
CROSSWORD



By **Doug Mar**

ACROSS

1 Shape that graces landmarks in St Louis and Paris
5 Not feral
9 Reef-building animal
14 It's found under an arch? (!)
15 Fundamental constant in the Heisenberg uncertainty principle
16 Cub Scout leader
17 Tableland
18 *Insecure* actress Rae
19 Church areas for the laity
20 Redundancy and performance storage option, for short
21 Series set in Westeros, for short
22 Subject matters
23 Physicist who developed mercury-in-glass thermometers
26 Language of many mottos
29 Kennel club classification
30 ___-Man, explorer of the Quantum Realm
33 Code of silence
35 Tended little ones
36 Antenna or waveguide type
37 Swedish scientist who held that water freezes at 100°
39 Thermodynamic temperature scale that is offset from 23-Across by 459.67
41 Assist in wrongdoing
42 Anti-drug-trafficking org.
44 Confiscates
45 Code for an airport whose city is often referred to without the code letters
46 First woman to be a Major League Baseball general manager
48 Butler portrayed by Clark Gable
49 Term that was replaced by 37-Across (avoiding confusion with a geometric term related to 43-Down)
52 Tundras and deserts, for example
54 Carrier with hubs at EWR and IAH
55 William Thomson, _____ Kelvin
59 Pet welfare org.
60 Vocal range for Tracy Chapman
61 Movie rating org. that was rebranded in 2019
62 Remove air from a fluid system
63 Frankfurt's river, a primary waterway
64 Be worthy of
65 Hoped-for responses to proposals
66 Aerodynamic force that is a downer for cyclists
67 "How do I love ___?"

DOWN

1 Audiovis. stimuli that can produce a tingling feeling
2 Moon that was once thought to be ringed like its planet
3 Major sci. museum in Columbus, Ohio
4 How to dive in with enthusiasm
5 Location of the longest muscle in the human body
6 Take in or take up
7 Degree that in some cases can be terminal
8 Our universe is currently in the Stelliferous ___
9 Used a dugout
10 Forest giraffe
11 Imbue with new life
12 Guinness of *Star Wars*
13 Scottish maiden
22 Angle symbols in trigonometry
24 Prefix that can modify matter but not energy
25 First spacecraft mission to approach, orbit, and land on an asteroid (433 Eros), for short
26 Not global
27 Single-celled organism (var.)
28 Hubble and James Webb, for example
31 Clio and her sisters
32 Stat. analysis that was developed for quality control of beer
34 Attends class without credit
36 Object with MIPS technology and advertised in *Powder* magazine
38 Prefix with colon or conductor
40 Hermione Granger, for one
43 Momentum that can be quantized
46 Massages
47 Latin motto "ars ___ artis"
50 Event host
51 ___ for the ride
52 Newborn
53 ____ of Man, whose native cat became the name of a type of comet
56 Fish that keeps its internal body temperature warmer than the surrounding water
57 Infrequent
58 Bohr or Ørsted, by nationality
60 Co. that manufactures Ryzen processors

Art and science of the snowflake

By Allison Rein

Cloud Crystals: A Snowflake Album, an illustrated volume of prose and poetry published in 1864, was the first widely circulated US work on the crystallography of the snowflake. One of the few things known about the author, Frances Chickering, is that she lived in Maine.

"The present collection originated in the accidental observation of the beauty of a snow crystal upon a dark window sill," she writes. "It was copied, and the interest thus awakened grew, as successive winters sent their white-winged, aerial messengers, within the reach of human notice and admiration, till about two hundred forms were carefully observed and cut in paper."

Chickering used dark fur or cloth to catch the snowflakes and a strong magnifying glass to see them, and then she quickly cut them out of paper from memory—several of them are shown here. She shared the work with Louis Agassiz, a Swiss-born natural scientist at Harvard University, who advised her to measure the air temperature and other environmental conditions as she examined the snowflakes. Chickering notes that a cold, still atmosphere is necessary for snowflake formation—any slight change in the temperature or humidity alters the shape of the crystals. Snowflakes that fall on warmer, humid days, she observes, have more rounded angles than snowflakes that fall on cooler, dry days. Her friends and Agassiz urged her to publish her observations, which eventually became this volume. A copy is held at the Niels Bohr Library & Archives of the American Institute of Physics (publisher of *Physics Today*) in College Park, Maryland. **PT**

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