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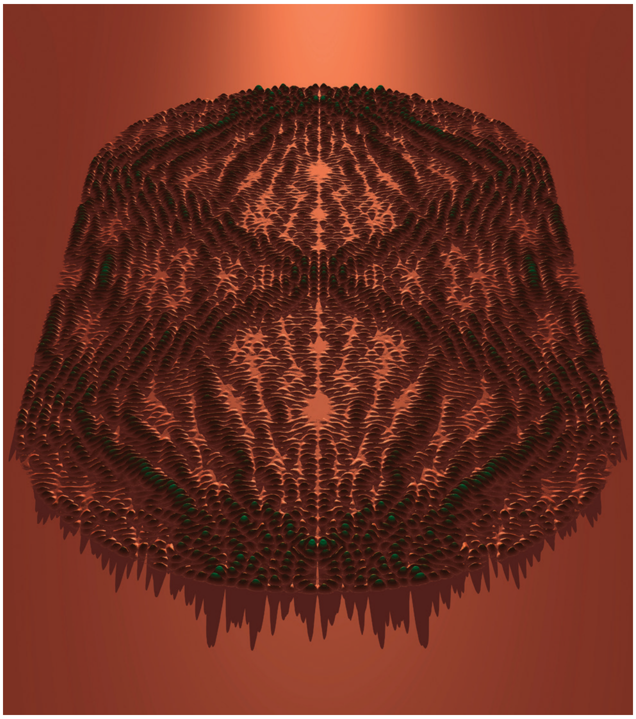
FEATURES



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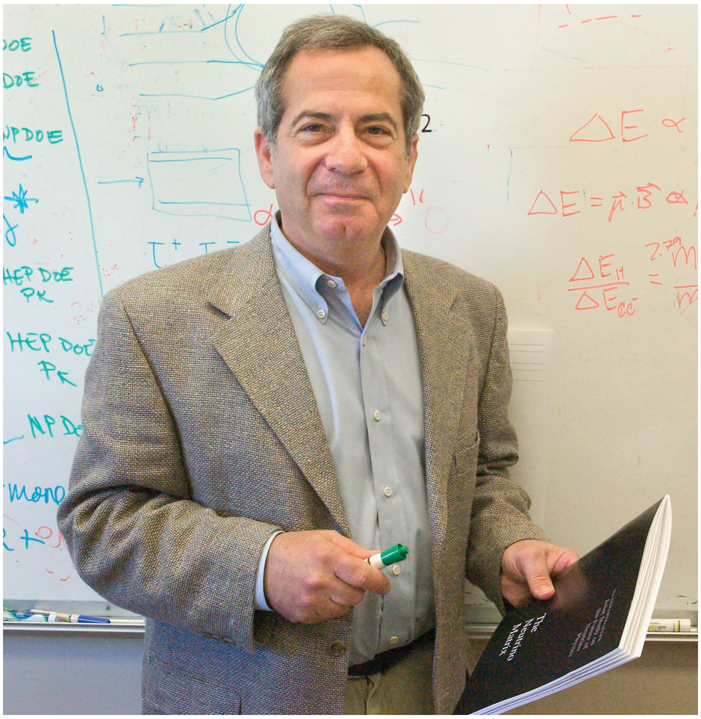

DEPARTMENTS

ON THE COVER

Cacio e pepe is a popular Italian pasta dish whose rich, velvety sauce is made of an emulsion of pecorino cheese and black pepper. Cooking a cacio e pepe sauce that deliciously clings to each piece of pasta is not just a culinary achievement but a scientific one. To learn how the physical properties of pasta ingredients interact to make the perfect sauce, read the Quick Study by Daniel Maria Busiello, Vincenzo Schimmenti, and Ivan Di Terlizzi on **page 52**.

(Photo by Simone Frau.)

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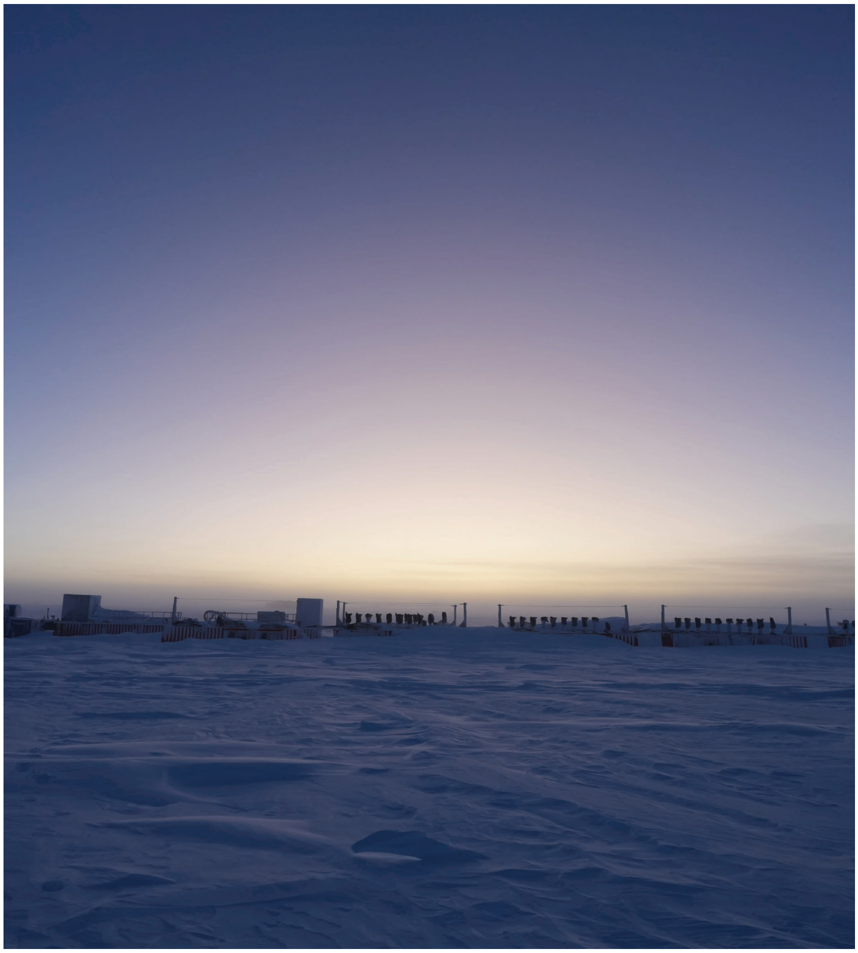

TO READ ABOUT ICECUBE'S NEUTRINO SEARCH UPGRADE, TURN TO PAGE 18

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Superhydrophobic tube stays afloat in extreme conditions

Inspired by a spider that holds an air bubble when it swims, the material could one day be used to design ocean sensors.

By Sarah Wells

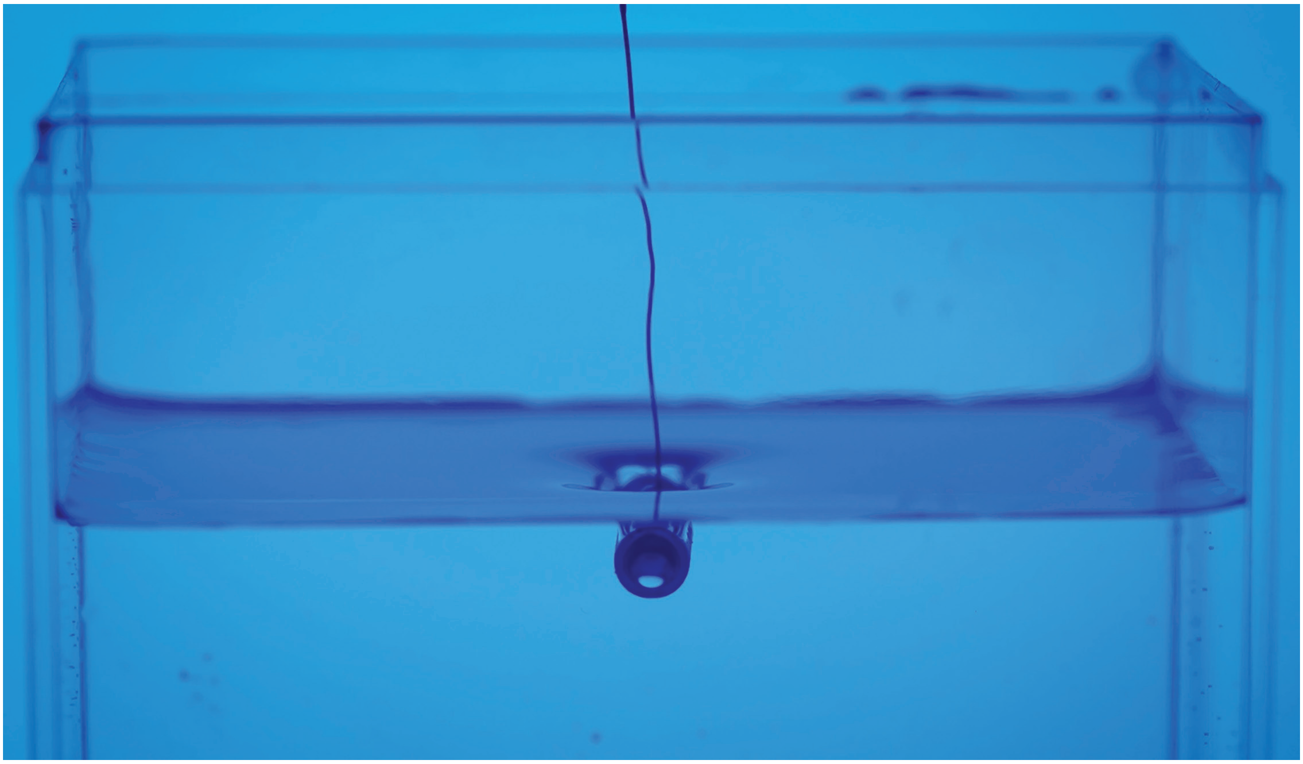

Figure 1. An aluminum tube displaces water around it as it is lowered into the water. Once water covers the top of the tube, a trapped air bubble allows the tube to maintain the required buoyancy to stay afloat. (Photo courtesy of the University of Rochester.)

A newly developed aluminum tube is almost impossible to sink. The superhydrophobic tubes, developed by Chunlei Guo and colleagues from the University of Rochester, trap an air bubble to maintain buoyancy even when sloshed around by waves.[1] The design was inspired by diving bell spiders, who breathe underwater with an air bubble that forms with the help of hydrophobic hairs on their belly and legs. If scaled up from the 25- to 100-mm-long prototypes, the tubes could be used to build structures, such as ocean sensors or rafts, that stay afloat in rough waters and resist corrosion.

As the tube is submerged, the superhydrophobic surface repels water to form a dimple (shown in figure 1), which supports the tube's initial buoyancy. In addition, micro- and nanopits etched on the interior of the tube enable the surface to repel water and trap an air bubble inside the tube. The team built a resin barrier (shown in figure 2) at the center to resist the hydrostatic pressure that would otherwise push the air bubble out. Once the tube is fully submerged, the air bubble takes over in enabling the tube to maintain the necessary buoyant force to float back to the surface.

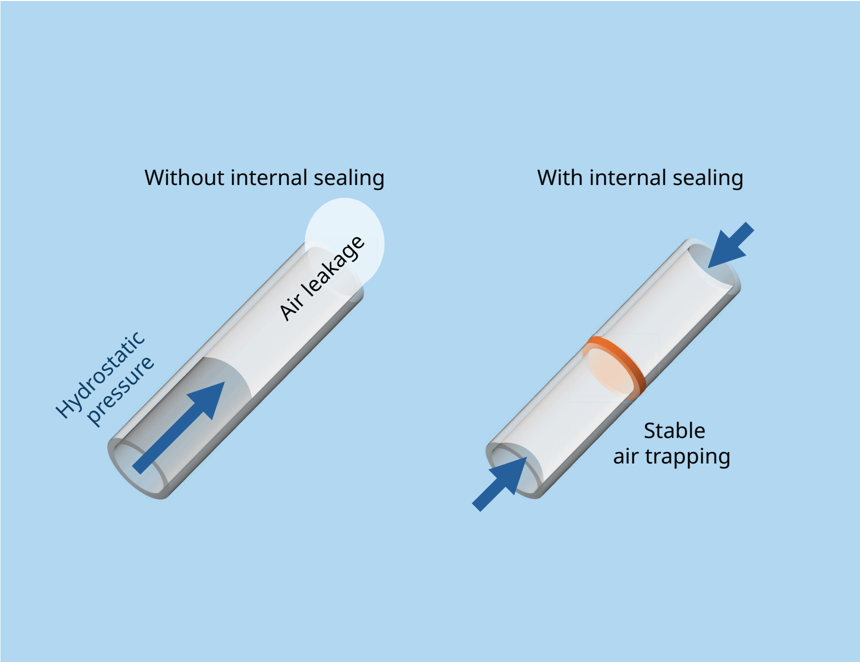

Figure 2. A resin seal at the center of the tube creates a barrier between the air–water interfaces at the open ends and thus prevents the air bubble from getting pushed out of the tube. (Image adapted from ref. 1.)

The researchers found that the inner diameter of the tube plays an important role: If the tube diameter is too low, the air bubble won't provide sufficient buoyancy; if the diameter is too high, water can leak in and collapse the air bubble. Through theoretical modeling and experimentation, the team found that the optimal diameter was equal to the maximum depth of the submerged tube's water dimple, or about 5 mm in the case of the 25-mm-long tube.

The team conducted experiments to see how the tubes would hold up in simulated ocean conditions. The researchers punched 15 holes in the aluminum surface to mimic a damaged ship, knocked partially submerged tubes around in a wave pool to imitate rough ocean conditions, and left the tubes in a solution with five times the corrosive ion concentration of seawater to mimic them being left in the ocean for three months. The team found that the trapped air bubble helped the tubes stay afloat and that the surface resisted corrosion.

The researchers say that it will be possible to scale the technology to design structures such as ocean sensors, energy harvesters, or even ships. As a step in that direction, the team built a small tidal energy harvester by bundling up to 15 tubes, wrapping them in copper wire, and attaching the assembly via wires to a magnet mounted above a wave pool. The device was submerged in the pool and generated electric current via electromagnetic induction as waves moved it closer and farther from the magnet. **PT**

Reference

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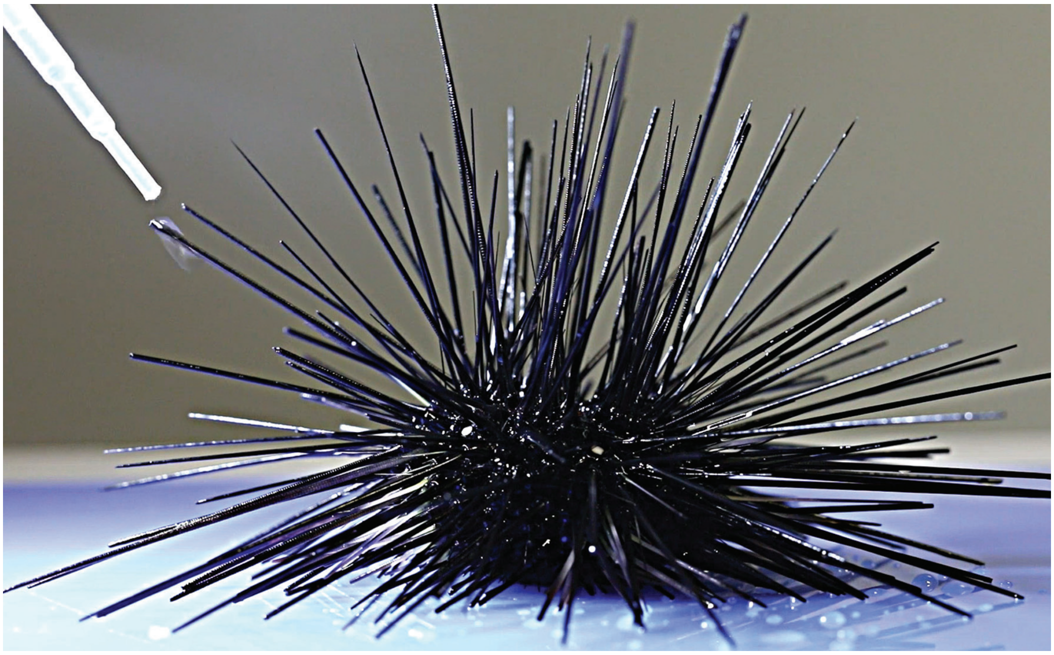
Sea urchin species discerns surroundings with electrically responsive spines

Capitalizing on a mechanoelectrical mechanism that arises from the spines' structure could yield useful sensors for marine environmental monitoring and other applications.

By Alex Lopatka



When a water droplet is applied to the tip of a spine of the sea urchin *Diadema setosum*, the spine rotates about 10° in one second. Each of the spines is 5–8 cm long. (Photo courtesy of Annan Chen.)

The sharp spines of a sea urchin defend it against predators. In at least one species, the spines appear capable of sensing flowing water too.[1] The new information about the spines' alternative function could lead to novel bioinspired designs for underwater monitoring and other applications.

Jian Lu (City University of Hong Kong) and his colleagues applied droplets of seawater to the spines of *Diadema setosum*, a species of long-spined sea urchin that's found throughout the vast tropical waters of the Indo-Pacific region. Within a second of making contact with the water, the spines rotated about 10° from their original positions. Nearby spines untouched by droplets showed no response.

The team further investigated the behavior with imaging and electrical measurements. The spines are hollow and gradually narrow in diameter from the base to the apex. When seawater was injected through the base of an underwater spine, the researchers observed an electric potential of tens of millivolts along the spine's length for both living and dead sea urchin samples. That even spines from dead sea urchins had measurable voltages, which dissipated immediately when the flow stopped, suggests that the electrical response is independent of living tissue and has a structural origin.

The researchers interpret from the electrical measurements that, upon contact with the water, the spine's interior surface acquires an electric double layer: A bottom layer of negatively charged ions quickly attracts a layer of positively charged ions. As the conductive seawater flows through the spine, it deforms the electric double layer and results in an electrochemical potential that peaks at the apex and is lowest at the spine base. The potential then triggers a response in the muscle fibers of the spine's joint, and that response makes the living sea urchins move.

Inspired by the biological mechanoelectrical mechanism, the researchers 3D printed spines with a geometric structure that resembles that of sea urchins. Initial exposures to flowing water yielded similar voltages and potentials in the 3D-printed spines as they did in the biological ones. The researchers also built a three-by-three array of printed spines and demonstrated that they could map the spatial distribution of water passing through. Such a sensor, the researchers say, could be useful for marine monitoring, measurements of water flow, and other applications. PT

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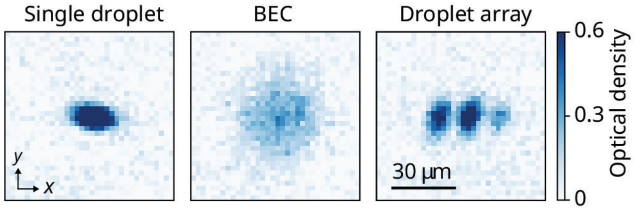
Quantum drops are spotted in ultracold gas of molecules

Strong and tunable long-range dipolar interactions could help probe the behavior of supersolids and other quantum phases of matter.

By Alex Lopatka

Two years ago, Sebastian Will of Columbia University and colleagues cooled a gas of sodium cesium molecules to nanokelvin temperatures inside an optical trap and formed the first Bose–Einstein condensate of dipolar molecules.[1] A key motivation of the research was exploiting dipole–dipole interactions—at such cold temperatures, they're more energetic than the molecules' kinetic energies—to form ordered structures such as supersolids, which flow with no viscosity. (For more on the 2024 findings, see the *PT* story "A Bose–Einstein condensate of dipolar molecules," by Daniel Garisto.) But the dipolar interactions in that initial demonstration were too weak to realize such phenomena.

Now, using a pair of linearly and elliptically polarized microwave



Absorption images show a droplet and a droplet array in a Bose–Einstein condensate (BEC) of ultracold dipolar sodium cesium molecules. Each picture is a three-image average taken along the *z*-direction. The strength of the molecular dipole–dipole interactions is controlled by an elliptically polarized microwave field. A large negative value of the ellipticity leads to the formation of a single self-bound droplet; a large positive value, to a droplet array. (Figure adapted from ref. 2.)

fields, Siwei Zhang (also at Columbia), Will, and colleagues have tuned the strength of the interactions between NaCs molecules to be much stronger than that in previous experiments.[2] As in the group's 2024 work, the resulting enhancements to the repulsive van der Waals forces stabilize the condensates by keeping the molecules from getting too close to one another and colliding.

As a consequence of the strengthened dipole–dipole interactions, the NaCs condensate transitions to the droplet phase. Dense single droplets and droplet arrays, shown in the figure, appear for various strengths and orientations of the applied fields. The most dense, strongly interactive molecular clouds persist for about 100 ms, long enough for the researchers to observe the effects of the molecular interactions.

Will and colleagues are investigating whether the droplets could be a superfluid, which flows without a loss of kinetic energy. If the droplet arrays have crystalline order, they could be supersolids. The new results may have broader applications. Ultracold dipolar molecules could be a test platform for researchers to study many-body systems with long-range interactions, novel self-organization processes, and other condensed-matter phenomena. PT

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2. S. Zhang et al., "Observation of self-bound droplets of ultracold dipolar molecules," *Nature* **651**, 601 (2026).

Stellarators are among the leading fusion energy candidates

Advances in computing have reignited interest in the approach.

By Toni Feder

Long an underdog in an underdog field, stellarators are now in the running to produce fusion energy. Both the stellarator concept—confining plasma with external magnets in a complex geometry—and, more broadly, fusion energy development have benefited over the past decade from scientific and technological advances, a push for green energy, and burgeoning investor interest. Stellarators gained attention in January when one startup, Thea Energy, was the first of eight companies pursuing five fusion concepts to complete an early design review as part of the Department of Energy's Milestone-Based Fusion Development Program.

DOE launched the program in 2023 to promote public–private partnerships in fusion. Modeled partly on NASA's Commercial Orbital Transportation Services program, which helped SpaceX succeed, the DOE program awarded $46 million total to the eight companies (see *PT*'s 2023 story "What's old is new in DOE's choice of fusion hopefuls"). Along with providing some federal funding, the DOE program validates company achievements and helps them raise private money, says Scott Hsu, who as lead fusion coordinator at DOE was the milestone program's chief architect; he is now at the climate-tech venture capital company Lowercarbon Capital.

Harder to build, easier to run

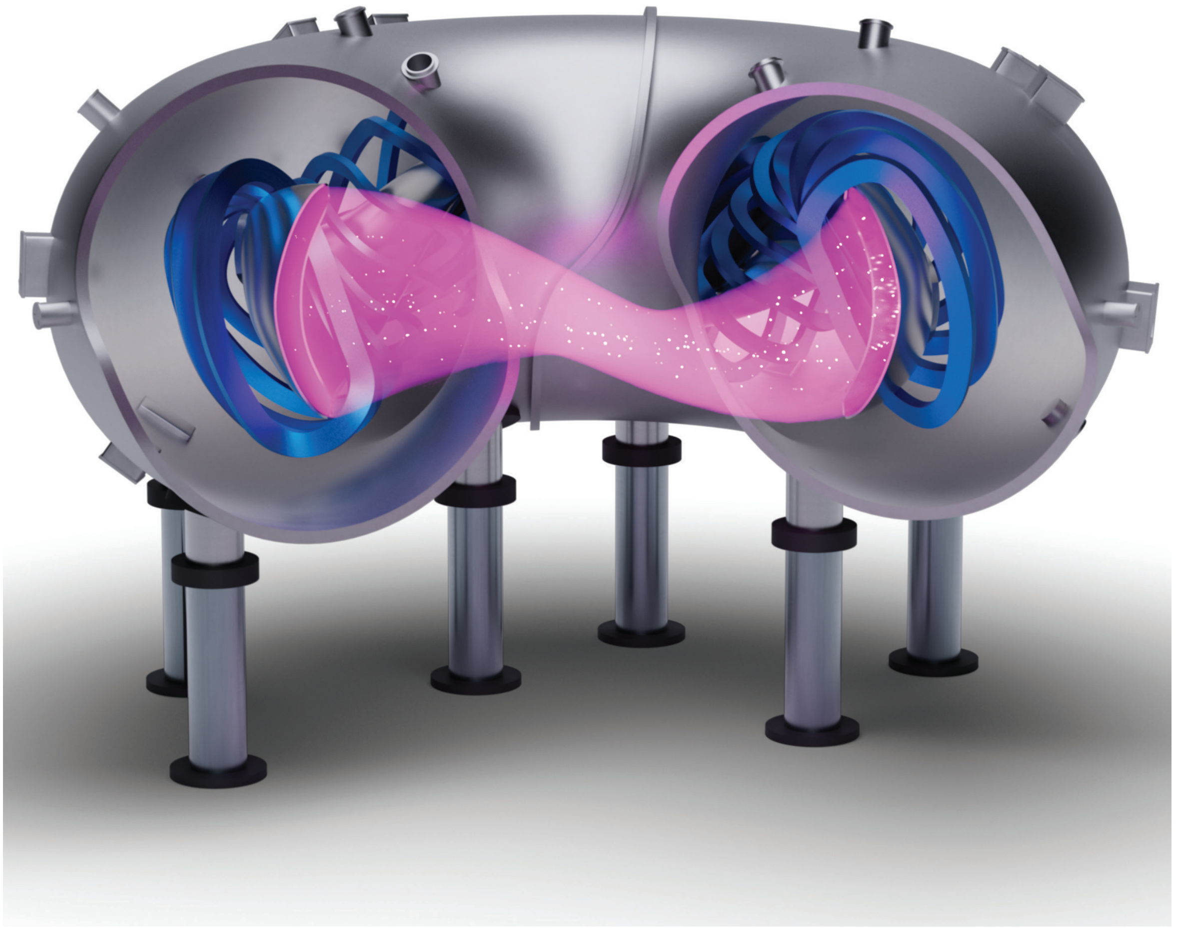
The entire fusion energy community got a shot in the arm with the 2022 demonstration of net gain at the National Ignition Facility. (See *PT*'s 13 December 2022 story about the achievement at NIF.) Two of the DOE milestone awards are to companies that similarly use inertial confinement fusion, which focuses high-powered lasers on a small fusion fuel capsule containing isotopes of hydrogen (see *PT*'s 2023 story "NIF success gives laser fusion energy a shot in the arm," about companies pursuing inertial confinement fusion).

Among the milestone awardees, two companies each are going the magnetic confinement routes of tokamaks and of stellarators; the other stellarator participant is Type One Energy. Stellarators were invented in 1951 in the US. Germany and Japan each have one, and research has continued in the US, but the concept fell behind tokamaks, which are the most studied of all the fusion energy approaches. Tokamaks "have the most people, the most experiments, and seem a safe path," says Felix Parra Diaz, who heads the theory department at the Princeton Plasma Physics Laboratory and served on DOE review committee panels for the milestone program.

But the tokamak has an Achilles' heel: It requires an electric current in the plasma as part of its confinement mechanism, and instabilities in the current can lead to disruptions. If that happens, says Parra Diaz, "the plasma cools, current goes to the wall, and the magnetic field creates forces that can damage the walls. You have to stop the machine and repair it." For tokamaks to reliably provide energy, he continues, "the game is either to be clever or to sacrifice performance to keep the plasma stable."

Stellarators, in contrast, have complicated geometries, but the plasma is sustained entirely by the externally applied magnetic field and is stable. They are harder to build but easier to run than tokamaks. The stellarator is still more than an order of magnitude behind the tokamak in terms of pure plasma performance, says Hsu. But, he adds,

High-temperature superconducting planar coils are being used by Thea Energy to simplify its stellarator design. The company has tested the coils; the next step is to build a prototype stellarator, which is scheduled to be operational by 2030. (Photo courtesy of Thea Energy Inc.)



A stellarator with geometrically complex magnets (blue) to confine plasma (pink) is to be built by Type One Energy, a participant in the Department of Energy's fusion development milestone program. Construction is slated to start in Clinton, Tennessee, late this year, with operations planned to begin in 2029. Roughly 12 meters across, the machine would serve as a test bed for a future stellarator that would produce electricity. (Rendering courtesy of Type One Energy.)

"all things being equal, the net electrical power to the grid will be higher for a stellarator."

Computational leaps

A steady beat of scientific advances has sparked new optimism about achieving fusion energy pilot plants within a decade and fusion energy on the electric grid by the mid 2040s. Among them, two stand out: the application of high-temperature superconductors and leaps in computing.

High-temperature superconductors allow for plasma confinement at higher magnetic fields and lower volumes. "That's a big deal," says Derek Sutherland, vice president of R&D at Realta Fusion, which is in the DOE milestone program and focuses on the magnetic-mirror confinement fusion concept. "With higher plasma density, the fusion rate increases," he explains. "If you double the magnetic field strength, you can generate 16 times the fusion output in a given volume." That, in turn, brings down cost.

And computational advances, including with AI, help with fusion machine design. That's particularly useful for the complex geometries of stellarators. Thea Energy's innovation is to use roughly 350 planar coils instead of a few complicated magnets, says Charles Swanson, the company's director of fusion systems. "You still need a twisted, elongated, donut-shaped magnetic field," he says, but the company's design is simpler to build than a traditional stellarator. "Without modern computational power, you couldn't come up with optimized stellarator designs," says Hsu.

More challenges

Scheduling breakthroughs for scientific challenges is impossible, says Hsu. But the remaining challenges are increasingly in engineering, he says, and they overlap for the various fusion concepts. Those challenges include mitigating materials damage from neutrons and breeding tritium for deuterium–tritium fusion reactions. Engineering challenges are "a different flavor" from scientific ones, he says, "and investment is a better predictor of progress to come. That is the transition that fusion is trying to enact now."

Another challenge for achieving commercial fusion energy is education, says Elizabeth Paul, an assistant professor of applied physics at Columbia University who focuses on stellarator theory and computation. "With more private companies involved," she says, "there is more emphasis on developing the workforce that will feed into companies and run fusion reactors."

The different fusion approaches each have pros and cons, says Paul, "and it's not obvious who will be the winner. It makes sense to explore different approaches in parallel."

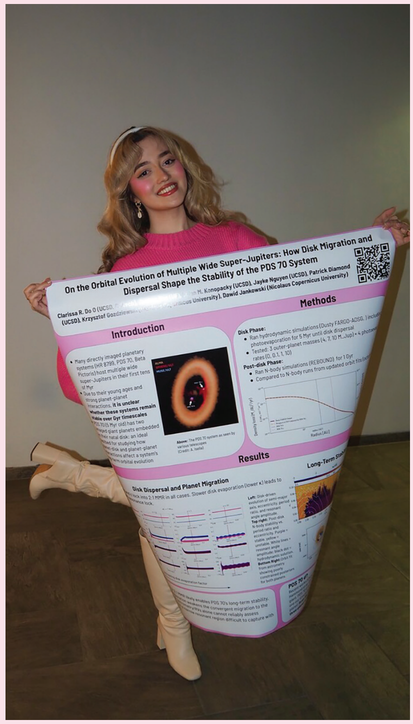
"It's healthy to have a competition of ideas," says Uri Shumlak, chief science officer and cofounder of Zap Energy, the milestone company that uses Z pinch to create fusion. "If any one of us is successful, having a carbon-free energy source will benefit society at large." **PT**

Astrophysics influencer uses social media to break science stereotypes

By **Toni Feder**

A scientist can wear nail polish, use makeup, and dress fashionably—and be taken seriously. That's the message that @thatastrogirlie conveys to her tens of thousands of followers on Instagram and TikTok.

Thatastrogirlie is Clarissa Do Ó, an astronomy postdoc at Caltech who is "passionate about exoplanets" and loves pink. In the photo, she holds up a poster she presented in February at a conference on high-contrast imaging. "I want to show that a scientist can look like anyone and have many interests," she says.



(Photo courtesy of Clarissa Do Ó.)

Do Ó credits childhood visits with her father to the planetarium in São Paulo, Brazil, for sparking her love of science. After high school, she came to the US to continue her studies, earning her bachelor's degree from the University of California, Santa Barbara, and her PhD from UC San Diego.

At Caltech, Do Ó tests potential instrument design architectures for the NASA flagship space telescope *Habitable Worlds Observatory*, currently planned for launch in the 2040s. The telescope's goal is to discover planets that are as much as 10 billion times fainter than their stars, she says. "To image Earthlike planets around Sunlike stars, the telescope will need picometer-level stability." On a separate project, for the *Nancy Grace Roman Space Telescope*, she charts the orbits of known exoplanets to plan for the first attempts to image exoplanets in reflected light.

After defending her PhD thesis in summer 2025, Do Ó posted a short video about the day on Instagram. "It showed my outfit, which I chose to feel comfortable and confident," she says. By the next morning, there were about 50 000 views.

That was the start of @thatastrogirlie: "The public is interested in what a science research career looks like," says Do Ó. "They had so many questions: How long did it take? What will you do next? And they liked that I showed my personality and my femininity. I realized that I could take those two aspects to broaden access to science." Most of Do Ó's followers are women aged 18 to 24, she says, and many are interested in science—not only astronomy.

"Every time I make a video," Do Ó says, "I think about younger me. I think younger me would have liked to see both the life of a scientist and the excitement about fashion and other things." **PT**

IceCube expands neutrino search to spot fainter signals

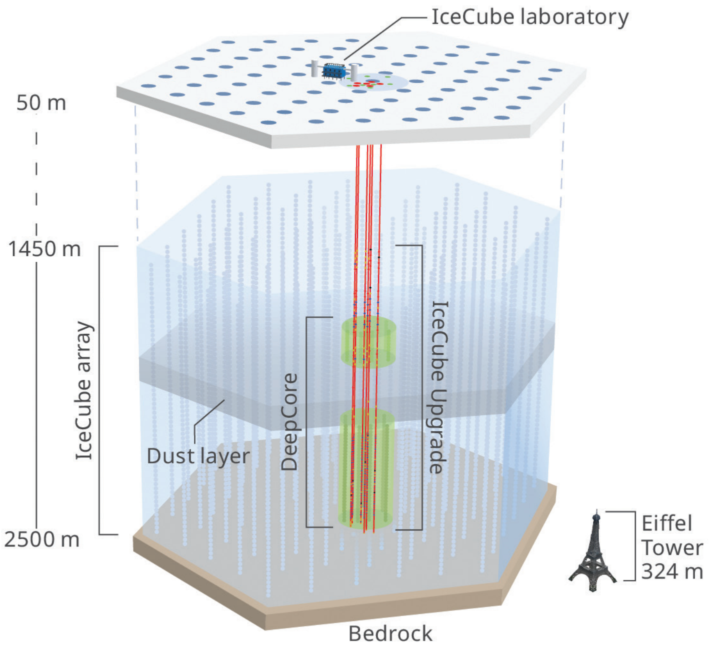
A major upgrade to the 15-year-old detector will aid in the study of neutrino oscillations.

By Jenessa Duncombe

The Sun rises over the IceCube Upgrade drill camp near the Amundsen–Scott South Pole Station in Antarctica. (Photo by Ilya Bodo, IceCube/NSF.)

Originally built for measuring energetic neutrinos from distant galaxies, the IceCube Neutrino Observatory has been fitted with more than 600 new sensors for detecting lower-energy neutrinos from closer to home. The $55 million IceCube Upgrade, which was completed in February, will enable researchers to closely analyze the flavor oscillations of neutrinos that are produced when cosmic rays collide with nuclei in Earth's atmosphere.

IceCube is a 1 km^3 Cherenkov detector near the geographic South Pole. Its more than 5000 photosensors are buried in the ice roughly 1.5–2.5 km deep. At such depths, no air bubbles cloud the ice. Collisions of neutrinos with atoms in the ice produce energetic muons, electrons, or tau leptons and other



IceCube's new sensor array, called IceCube Upgrade, is located at the center of the detector. Six new vertical strings, shown in red, have more than 600 sensors that are two to three times more sensitive to light than IceCube's older ones. (Image by the IceCube Collaboration.)

particles that result in flashes of blue-tinted Cherenkov radiation propagating through the icy darkness.

The closer together and more sensitive the sensors, the lower the energy of the original neutrino that IceCube can detect. DeepCore, IceCube's most densely spaced sensor array, detects roughly 100 atmospheric neutrino events per day at energy levels above 5 GeV. The new sensor array and DeepCore together should enable the detection of about 600 events per day at energy levels above 1 GeV. "With the upgrade, we will not only see more events, but we will have a much better chance to analyze them and determine the neutrino's direction, energy, and flavor correctly," says Albrecht Karle, the lead scientist for IceCube's upgrade.

As neutrinos travel, they oscillate between flavors: tau, muon, and electron. Studying the oscillations can reveal deeper truths about the particles, including the relative sizes of the three mass eigenstates that contribute to the three observed flavors. Two of the masses are close in size, and it's unclear whether the third mass is larger or smaller than the other two. This is known as the neutrino mass-ordering problem.

Tau neutrinos are hypothesized to appear at different levels in IceCube's detector depending on the mass-ordering solution. Karle says IceCube could publish its first mass-ordering result after three years of data collection. (See *PT*'s 2025 story "Next-generation underground neutrino detector in China up and running" to read about another mass-ordering experiment.)

At least 90% of IceCube's new sensors have frozen into the ice, says Karle, and the others will soon. The new sensors are two to three times as sensitive to light as IceCube's older ones. He expects regular data collection to begin midyear.

NSF contributed about 70% of the funds for the update; additional support came from Germany, Japan, South Korea, and Sweden. IceCube is operated by the University of Wisconsin–Madison and has more than 450 collaborators across 14 countries. (To read about IceCube's broader scientific goals, see the 2008 *PT* feature "Astronomy and astrophysics with neutrinos," by Francis Halzen and Spencer Klein.)

"We passed our entrance exam with the successful deployment of the upgrade," says Francis Halzen, the head scientist of IceCube. Now he's awaiting NSF's decision on initiating a much bigger build-out. Called IceCube-Gen2, the $500 million proposed project would enlarge IceCube's effective volume 10-fold and expand its search for extremely high-energy neutrinos. **PT**

Q&A: Friederike Otto assesses the role of climate change in extreme weather events

The physicist-philosopher's work on understanding climate change is also relevant for adaptation measures in health, law, and the economy.

By Toni Feder

Heat waves. Wildfires. Floods. Friederike Otto studies such extreme weather events to untangle what is natural and what is due to climate change. She and Geert Jan van Oldenborgh founded World Weather Attribution more than a decade ago. Today the initiative—powered by a handful of postdocs and a thousand-strong network of volunteers around the world—releases its attribution results within a couple of weeks of extreme weather events. (For more on extreme-weather-event attribution, see *PT*'s 2023 article "Connecting extreme weather events to climate change," by Michael Wehner.)

Friederike Otto (Photo by Peter Himsel.)

World Weather Attribution studies typically have multiple parts: What happened and what were the impacts? What was the role of climate change? And finally, looking forward, what adaptation actions would reduce the hazard for a future such event? The initiative, says Otto, has become much more professional over the past five years. "We have a team and some funding from the European Union and mostly from philanthropies."

Otto earned her first degree, in physics, at the University of Potsdam in 2007 and a PhD in philosophy at the Free University of Berlin in 2011. She joined the faculty at Imperial College London in 2021 and became a professor in the university's Centre for Environmental Policy last October. She also contributes to the Intergovernmental Panel on Climate Change (IPCC). She is motivated, she says, by wanting to show that "climate change is here and now and not something that happens somewhere else and sometime in the future."

Why did you study physics?
I would have loved to do history, but my grades from high school were not high enough. In Germany, the more popular a course is, the higher your grades have to be to get in. My options were engineering and physics. Physics turned out to be a good choice.

Was there something that hooked you on physics?
I really enjoyed quantum mechanics, which is also why I ended up doing a PhD in philosophy.

How did you get into climate studies?
I chose climate physics as one of the subjects for which I would do an exam for my diploma. I learned a lot about climate models and ended up focusing on them for my PhD.

Where did your path take you after the PhD?
I applied to lots of postdocs in Germany, and I never even got shortlisted. I applied to one postdoc out-

side Germany, at Oxford University. I ended up there, and I started studying extreme weather events.

How did you get into studying extreme weather?

Pretty much at the same time I started my postdoc, in 2011, two papers were published about the Russian heat wave of 2010. One of them concluded that climate change made the event five times more likely, and the other said it was mainly a natural event. My postdoc adviser, Myles Allen, who had pioneered one of the methods based on climate models to attribute extreme events, introduced me to Geert Jan van Oldenborgh, who had pioneered a different approach based on observations.

Geert Jan and I combined the two methods. We wrote a paper that basically reconciled the two papers. It showed that they were both right but were asking different questions. With that work, we started to establish the methodology that—with lots of variations and improvements—we are still using in World Weather Attribution.

Tell me how you started World Weather Attribution and how it works.

At the time, very few people were studying extreme weather. Usually, when an extreme event happened, scientists would not say anything in public about the role of climate change. When I was at the American Geophysical Union meeting in 2014, someone who worked for Climate Central, a US-based nonprofit, said to me, "Can you do this faster?" Geert Jan and I tried, and we decided yes, we could do it faster.

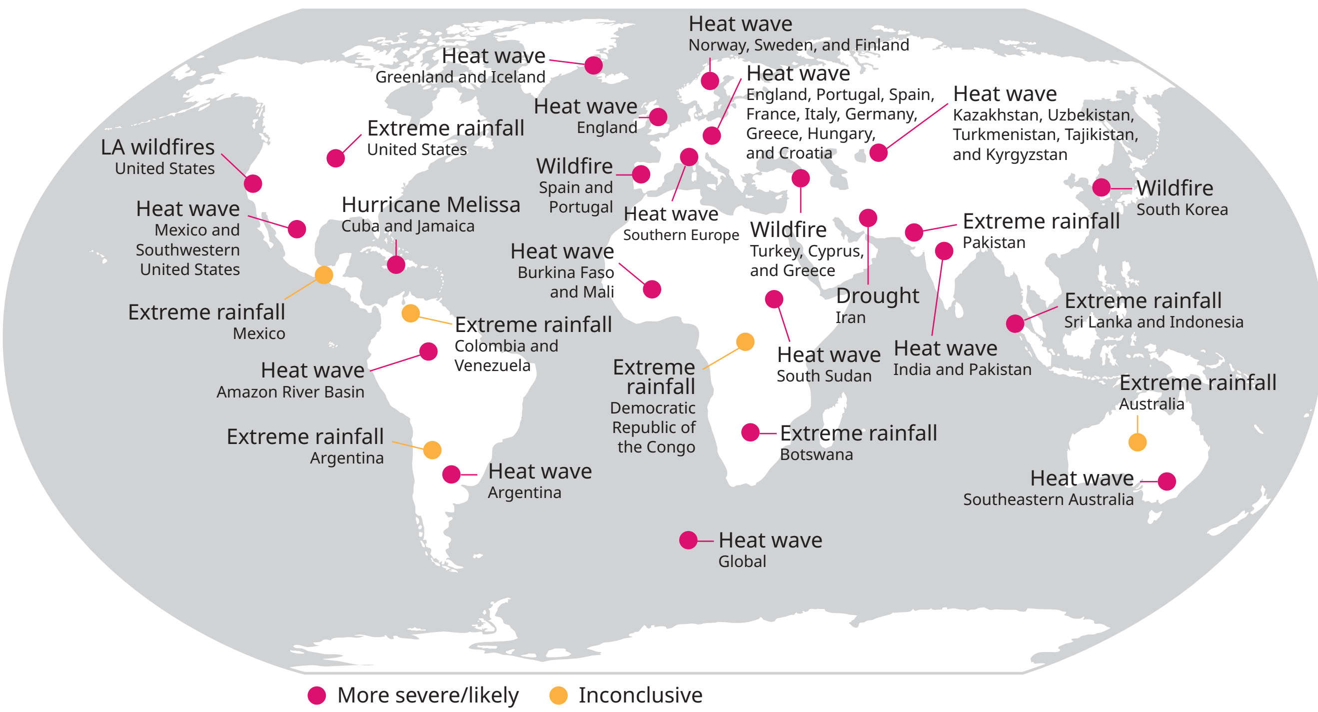
When you say faster, what time scales are you comparing?

We had worked on the normal peer-review time scale. A study may take six months, but by the time the results are published, a year and half or so later, people have long forgotten the particular event. Faster means within a week or two.

What makes it possible to be faster?

We have a large network of collaborators around the world who can quickly help us define an event. And we have a clear breakdown of the steps. First, you need to figure out what happened and how to define the event. For a heat wave, for example, what's the region? What variables should we look at? Over what time frame? And so on. That takes time and expertise. The next step is to look at the observational data and look for trends. Are the number or intensity of these events changing over time?

Then you do an attribution analysis. For that, you use climate models or statistical modeling to compare the events for the climate we live in today with an assumption of the



World Weather Attribution researchers found that climate change increased the severity and/or likelihood of most of the 28 extreme weather events it analyzed last year. (Image adapted from World Weather Attribution using a map by iStock.com/katykin.)

same events in a world that is, now, 1.4 degrees Celsius cooler. Would the occurrence frequency or intensity have changed? You might find that in today's climate, it's a 1 in 10-year event, but that in a world without climate change, it's a 1 in 100-year event. Because the only difference in the models is global warming or the increase in greenhouse gases, you can then say that the event has become 10 times more likely because of climate change.

How many events do you analyze a year, and how do you select them?
We have developed a trigger methodology, together with the Red Cross, that is based on humanitarian impact. For each type of hazard, we have different criteria. For flooding, for example, if more than 100 people lost their lives or more than a million people were affected, or a state of emergency was declared, then we consider the event.

With that method, 3 to 12 events trigger per week, and every Friday, the team discusses them and makes a decision. Do we have the people power available? If an event is in a region that has not been studied much, or if it's a type of hazard for which we don't have much evidence, we give it priority.

We aim to do 20 events a year. For most of them, climate change is a significant factor: In 2024, it was in 25 out of 30 events, and in 2025, it was 23 out of 28.

Have you had pushback?
Surprisingly little. Our results have been reported accurately by a broad spectrum of the media. There was some resistance in the scientific community when we started. People said we can't bypass peer review.

After announcing our findings quickly, we subsequently write papers that are peer reviewed so they will stand the test of time. And when we do something new method-wise, we write a paper and put it to peer review so that our methods have credibility.

Do you see impact?
Together with the Red Cross, we look at drivers of vulnerability and hazard and ask what those drivers mean for adaptation. For a recent wildfire study in Patagonia, for example, we said that to prevent wildfires, invasive pine trees need to be reduced. We try to be detailed, but it depends how fast we do things and how many local collaborators we have on the team.

Another good example of adaptation is the heat-wave action plans that Germany introduced in 2023. Our studies were used in a debate in parliament. But it's always hard to know what is because of our input versus other factors.

We always hold a press briefing so that the media can ask questions and we can explain the results. For some studies, we do policy briefings.

How do you juggle that work with your professor duties?
I probably teach less than some professors because my work on World Weather Attribution buys out some of my teaching time. I also work with legal scholars on how to translate scientific evidence into legal evidence and, with an expert in Kenya, I cosupervise a graduate student on heat and health. I have another graduate student who looks at climate change from an economics point of view.

What is your involvement in the IPCC?
For the sixth assessment, published in 2021, I was a lead author on the chapter on extreme events and I worked on the synthesis report. It's quite empowering to be able to bring your expertise to policymakers. And you get to know a lot of people from around the world. Now I'm coordinating lead author on regional climate change and extreme weather for the seventh assessment.

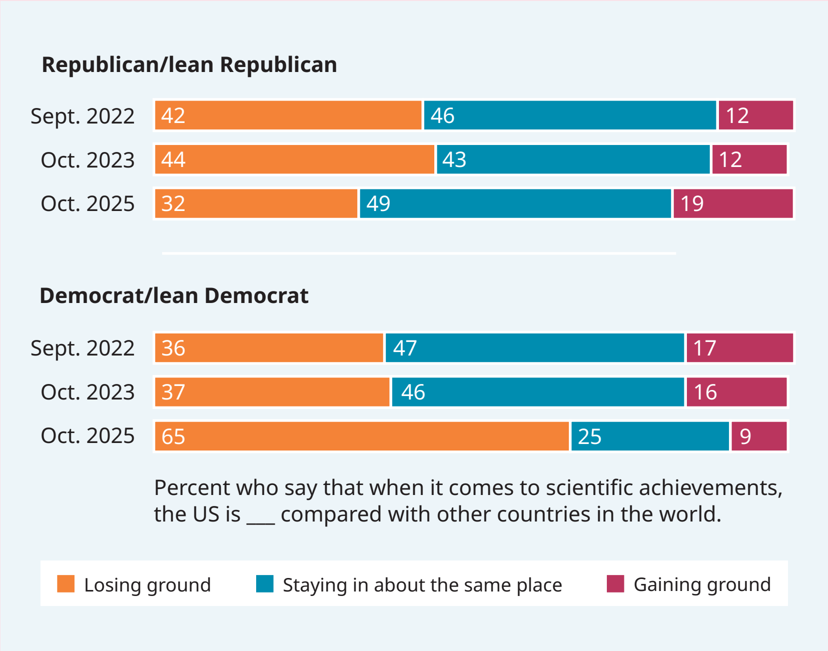
I would like to see people act on the evidence of global climate change. Working on the IPCC is one way to try to make that happen. World Weather Attribution is another. PT

Republicans and Democrats disagree on direction of US science

By Jenessa Duncombe

A survey last fall of US adults shows diverging public opinion on whether the US is gaining ground, losing ground, or staying in about the same place with respect to its scientific achievements relative to other countries. Overall among respondents, 13% said that the US is gaining ground, 38% said maintaining, and 47% said losing. Nearly two-thirds of Democrats and those who lean toward the Democratic party said that the US is losing ground. That's more than twice the share of Republicans and those who lean Republican who said the same.

The nonprofit Pew Research Center conducted the survey of more than 5000 US adults in October 2025 and published the results in a January report titled *Do Americans Think the Country Is Losing or Gaining Ground in Science?* Questions were given online and over the phone in both English and Spanish. The weights of different demographic groups were adjusted to be proportional to the US population.



(Figure adapted from B. Kennedy, E. Kikuchi, *Do Americans Think the Country Is Losing or Gaining Ground in Science?*, Pew Research Center, 15 January 2026.)

When Pew asked about the direction of US science in 2023, Republicans and Republican leaners were 7 percentage points more likely to say the US was losing ground. In 2025, Democrats were more likely to say that, and the difference between parties was larger (33 percentage points). The margin of sampling error was plus or minus 1.6 percentage points in 2023 and 1.7 percentage points in 2025. A small percentage of respondents both years chose not to answer.

Last year, the Trump administration made cuts to federal grant funding, laid off federal scientists, and retired federal databases. The introduction of tariffs, travel restrictions, and student visa disruptions altered the collaboration of US scientists with their global peers.

Nearly identical shares of both parties in the 2025 survey said that it is very or somewhat important that the US be a world leader in scientific achievements. Republicans and Republican leaners were more likely than Democrats and Democratic leaners to say private companies contribute a great deal or quite a bit to scientific achievement in the US. Democrats and Democratic leaners were more likely than Republicans and Republican leaners to say that colleges and universities and federal government agencies were key contributors. PT

Federal science workforce declines sharply under Trump

The last year was marked by turmoil at science agencies and the administration's stated desire to shrink the federal workforce.

By Clare Zhang

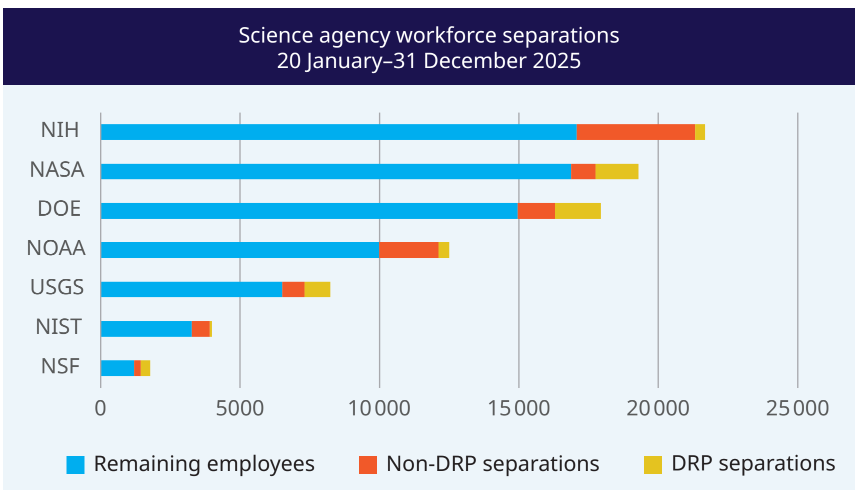
Federal science agencies shed more jobs in 2025 than they did over the previous two decades of steady decline, data from the US Office of Personnel Management (OPM) reveal. The number of federal employees in the physical sciences fell 12% from September 2024 to November 2025, compared with an 8% decline from 1998 to 2024.

In the first full year of the second Trump administration, the White House pushed for cuts to the federal workforce by incentivizing staff to leave through the deferred resignation program (DRP), cutting probationary staff, asking agencies to submit plans for significant reductions in force, and issuing RIF notices. The OPM's recent data release covering January to December 2025 provides insight into the effects of those efforts at the agency level.

Since Trump took office, agencies overseeing science have seen significant job losses, including reductions of more than 30% at NSF and around 20% at the US Geological Survey, NOAA, and the National Institutes of Health. The workforces of the Department of Energy and NIST shrank by 15% and 17% respectively, while NASA lost 12% of its staff. (In OPM data released just before press time, departures at NASA had risen to 24% by January 2026, likely as the agency processed additional deferred resignations.) In comparison, the total federal civilian workforce fell about 10% from January to December 2025.

Those science agencies saw the greatest losses in administration and program management and analysis. They also collectively lost thousands of employees across engineering, health science, and physical science.

Changes to scientific staff at the Department of Defense are less clear, but DOD as a whole shed about 75 000 positions in 2025, including in research offices. The Office of Naval Research, for example, shrank by more than 400 people, about 14%.



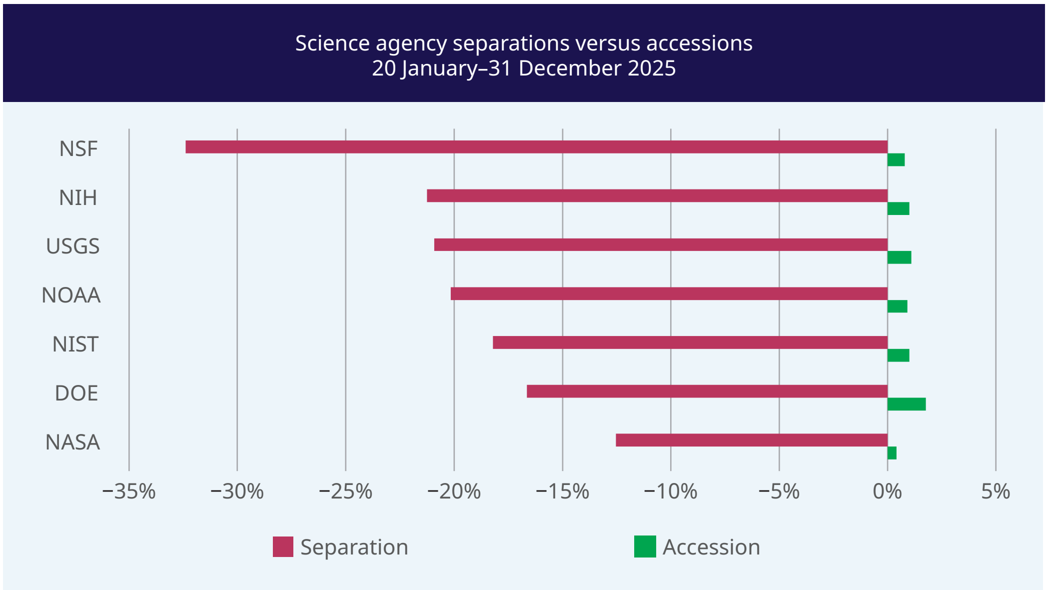
Federal science agencies experienced significant job losses in 2025, many of them through the deferred resignation program (DRP). (Image by *FYI*.)

Deferred resignations

More than 15 000 employees at science agencies left the federal workforce last year. Around 5000 of those staff accepted offers from the DRP, in which the administration offered to continue paying full salaries to resigning employees until 30 September or until their scheduled retirement date, if before 31 December.

The DRP affected science agencies unevenly. At NASA, 63% of the agency's total departures last year were through the program. The DRP also accounted for more than 50% of separations last year at DOE, NSF, and USGS. In comparison, about half of all federal workforce departures in 2025 came through the DRP.

At NOAA, NIST, and NIH, the



Federal science agencies saw much higher rates of employees exiting the workforce than entering in 2025. (Image by *FYI*.)

DRP accounted for less than 20% of separations last year. For instance, only about 80 of the more than 700 people who left NIST used the program. NOAA saw many non-DRP voluntary retirements, whereas many separations at NIH were due to non-DRP departures or RIFs.

Some agencies offered multiple rounds of deferred resignations, so the OPM data may not yet account for all employees who accepted offers last year.

Probationary firings

Early last year, the administration carried out mass firings of employees who had not completed their probation period—typically of one year—and thus were easier to fire than longer-term employees. A court eventually ruled that the firings were illegal but did not mandate reinstatement for many of the fired individuals. Some employees went through multiple rounds of being fired and reinstated. Others were put on leave following reinstatement and did not return to work until months later, some as recently as December 2025.

The number of probationary federal employees in the physical sciences in 2025 remains unclear because of redactions in the OPM data. In the unredacted data, the number of probationary federal employees in the physical sciences appears to fall sharply from 2024 to 2025. For instance, DOE had 116 physical sciences employees with less than one year of service in 2024, compared with 12 such employees in 2025. The length of service of more than 200 DOE employees in 2025 is redacted, however, so the number with less than one year of service could be much higher than 12.

Reductions in force

The OPM data do not reveal any completed RIFs at DOE, NOAA, NIST, or USGS. NIH was a notable exception among agencies that oversee science, with 807 employees lost due to RIFs, including 340 across contracting and program management, 71 in general health science, 62 in writing and editing positions, and 50 in public affairs. NASA lost 13 employees as part of RIFs across program management, engineering, and physical science. NSF lost four employees as part of RIFs across program management and other administrative functions.

Last year, the administration in February directed agencies to produce plans for "large-scale" RIFs and then asked for similar plans in advance of the government shutdown in October. The Departments of Energy, Commerce, and Health and Human Services collectively issued around 1600 RIF notices during the shutdown, which were temporarily blocked first by a court and later by the stopgap funding law.

Workforce additions

Both the high number of separations and the low number of new hires contributed to the federal workforce drop in 2025. The employees added at agencies overseeing science constituted no more than 2% of the total workforce of those agencies, whereas separation rates ranged from 7% to 30% at those same agencies. The administration froze federal hiring beginning in January last year, and the freeze is ongoing indefinitely, with exceptions. **PT**

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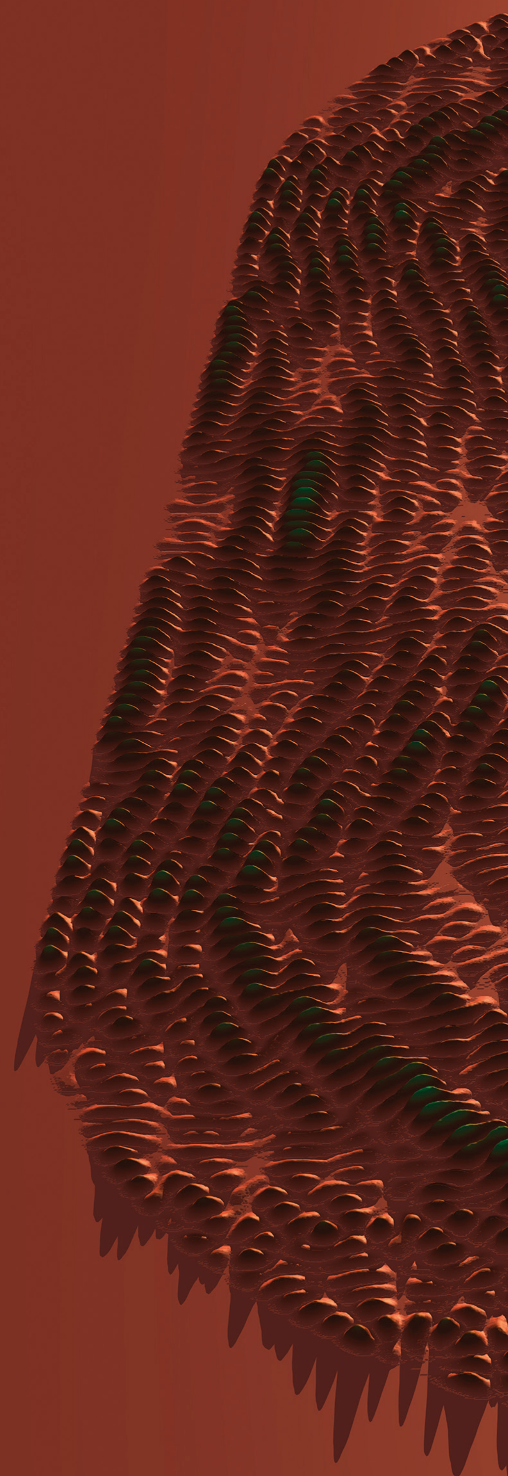
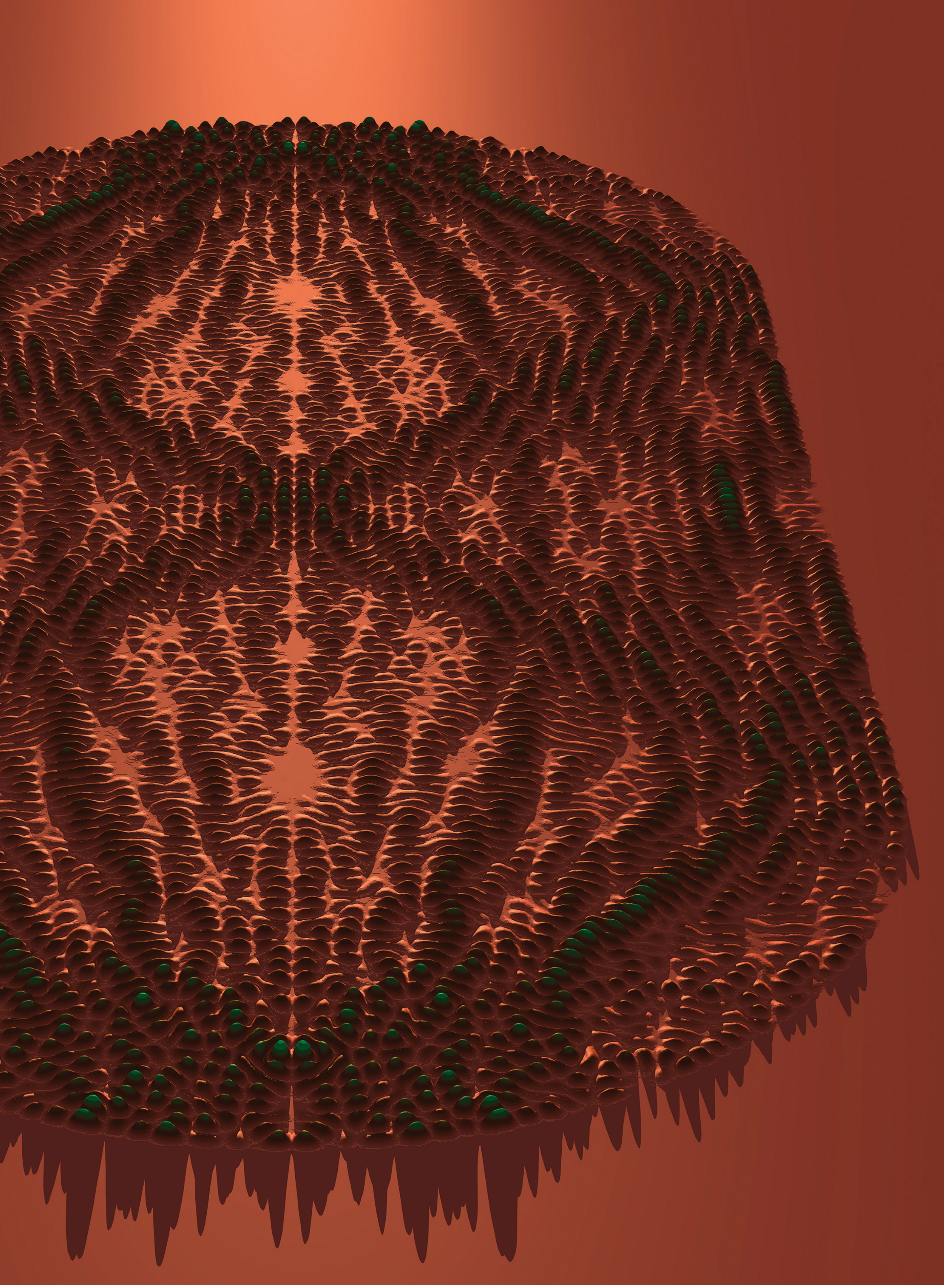
THE PARADOXICAL PHENOMENON OF QUANTUM SCARRING



By Lev Kaplan, Eric Heller, and Joonas Keski-Rahkonen

Inside certain quantum systems, where randomness was thought to lurk, researchers—after a 40-year journey—have found order and unique wave patterns that stubbornly survive.



In a classical chaotic system, tiny changes to its initial conditions produce exponentially large deviations in behavior. Think, for example, of a billiard table with curved ends, similar to the shape of a stadium. A ball that ricochets off one of the curved ends will have a vastly different trajectory than if it bounces off a point just a short distance away. (To learn more about the field of chaos and its development, see the 2013 *PT* article "Chaos at fifty," by Adilson Motter and David Campbell.)

Over time, after the ball bounces off the curved boundaries many times, the trajectories will spread uniformly over the entire stadium and go in every direction. Mathematically, the stadium is said to be ergodic.

Chaotic phenomena can also emerge in quantum systems, but they manifest differently than in a classical system. An example of a quantum chaotic phenomenon is the quantum scar. In 1984, one of us (Heller) made the striking theoretical discovery that some eigenstates of a quantum chaotic system must retain visible traces, called scars, of the unstable classical orbits that form in a classical chaotic system.[1] The scarred eigenstates have an enhanced probability density around the paths of the unstable orbits. Figure 1 shows a theoretical pattern of a quantum wavefunction that has been scarred by multiple classically unstable orbits in a stadium.

Because of experimental challenges and technical difficulties, quantum scars remained just a theoretical idea for decades until they were conclusively observed with scanning tunneling microscopy in a quantum dot system in 2024. Now more experiments and observations are underway, and researchers are examining potential applications. Beyond theoretical curiosity, quantum scarring could prove useful in the creation of new kinds of electronic circuits.

The path most traveled

The scar phenomenon is, at first glance, paradoxical because it has no analogous classical expectation. Before the early 1980s, researchers widely assumed that the quantum states of a chaotic system would look random, which reflects the long-term nature of classical chaos.

But in simulations published in a PhD thesis in 1983—one year before the discovery of quantum scars—Steven McDonald noticed anomalous eigenstate structures. They were associated with unstable classical orbits in a quantum chaotic system. He didn't know what to make of the "mystery" structures and didn't explain their origin.[2]

Before Heller's 1984 independent discovery and justification of them, quantum scars lacked any theoretical basis. Quantum ergodicity theorems, which were proven in the 1970s and 1980s, make precise the idea that in a quantum system whose classical limit is ergodic, most high-energy eigenstates spread out evenly over the available phase space.[3–5] Additional theoretical work by Michael Berry in 1977 led to the random-wave conjecture, which states that high-energy wavefunctions of quantum chaotic systems behave statistically as random superpositions of plane waves.[6]

Scarring implies that quantum mechanical systems retain a memory of short, unstable classical orbits, even at infinite times, whereas

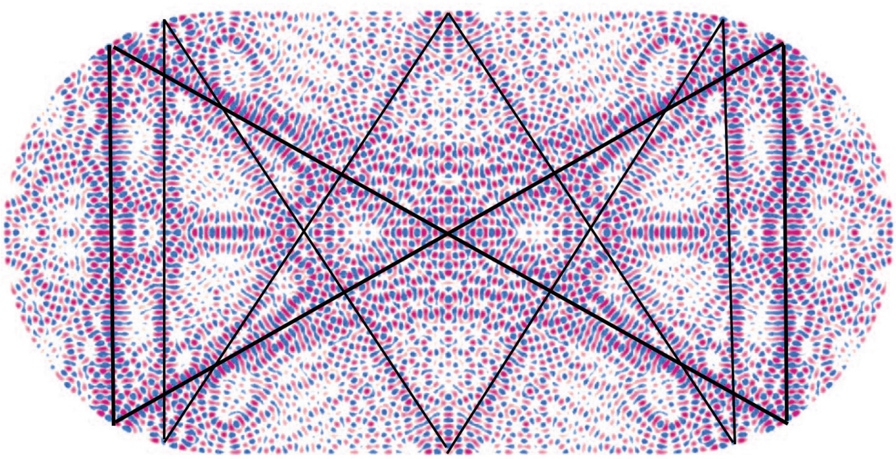


Figure 1. This quantum scar pattern is the result of a particle that is confined to bounce in a 2D stadium. In that quantum chaotic system, the scars form along two types of unstable periodic orbits, which resemble two variants of a bow-tie shape (black lines). The red–blue pattern accentuates the underlying wavelike structure of scars: Red corresponds to wave peaks; blue, to wave troughs.

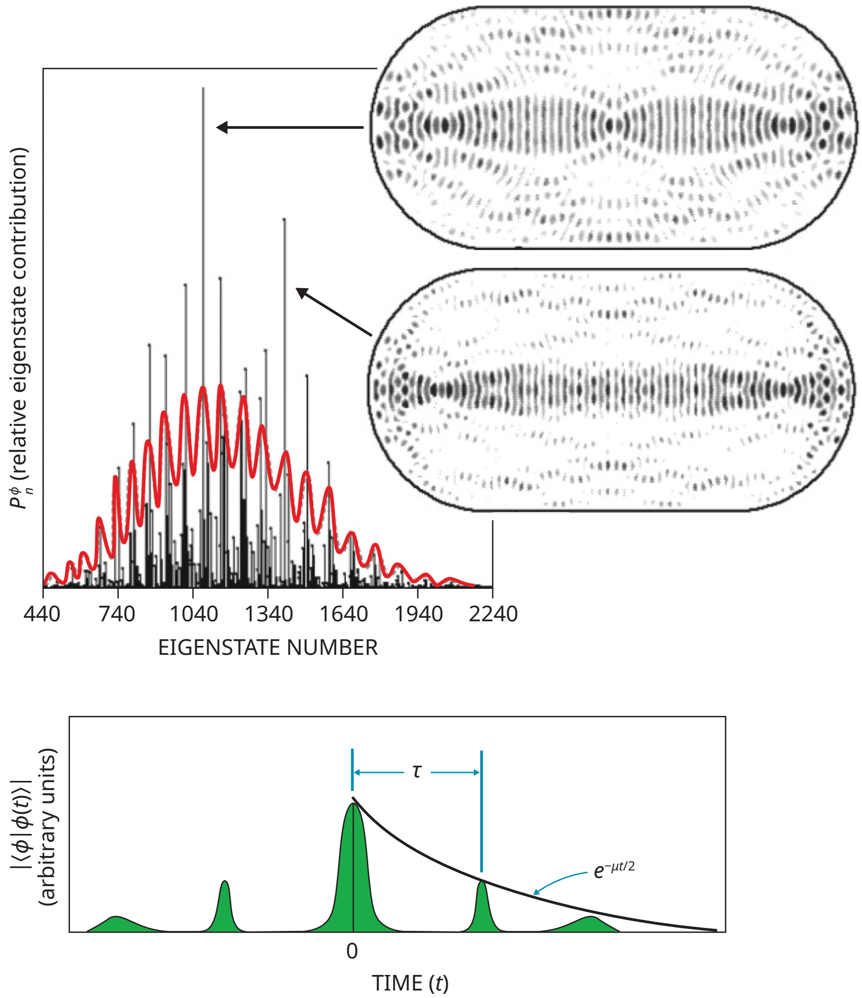


Figure 2. How unstable periodic orbits form quantum scars. When a Gaussian wavepacket $|\phi\rangle$ is launched along an orbit of a stadium (a rectangle with curved ends), it has, in the time domain, an autocorrelation function (shown at the bottom) that's characterized by a recurrence interval τ. The Fourier transform of the autocorrelation function yields, in the energy domain, the wavepacket's local density of states (LDOS). The constructive interference of the wavepacket with individual eigenstates $|\Psi_n\rangle$ of the quantum system produces scar patterns along the unstable periodic orbits, which have a period τ and instability exponent μ. The full LDOS (black dots and lines) shows the wavepacket's overlap with individual eigenstates: $p_n^{\phi}=|\langle\phi|\Psi_n\rangle|^2$. The smoothed LDOS (red curve) is associated with the short-term time evolution of the system. Two scarred eigenstate patterns are shown as examples. (Figures adapted from ref. 17.)

the corresponding classically dynamic systems, which are governed by those orbits, do not retain such a memory. So what's going on?

Constructive interference

A key insight is that a quantum wavepacket that's launched on an unstable periodic orbit will recur at regular intervals that are integer multiples of the orbital period. The recurrences are much more frequent than random overlaps of the wavepacket with its initial state. Over time, scars form as a result of propagating wavepackets constructively interfering with the original one.

The amplitudes of the recurrent wavepackets can be described with an autocorrelation function. To resolve all the eigenstates in the quantum system and to describe how much the wavepacket contributes to eigenstates at different energies, researchers calculate the autocorrelation function's Fourier transform. The result is the local density of states (LDOS), which describes the amplitude of the system's eigenstates in the energy domain.

Physically, the time–energy uncertainty principle relates a system's short-time behavior to the spectrum on large energy scales. Consequently, a smoothed version of the LDOS is computable so long as the short-time autocorrelation function is known. In energy windows in which the smoothed LDOS reaches a peak, the average eigenstate will have an above-average overlap with the wavepacket, and thus the eigenstate will be scarred along the periodic orbit under study. A curious phenomenon occurs for the opposite case: Eigenstates in energy windows in which the smoothed LDOS is at a minimum will be antiscarred.[7] That means that the eigenstates have a probability density that's below average along the periodic orbit.

After a long time, the wavepacket spreads out over the entire phase space, although not entirely uniformly, and the autocorrelation behavior becomes much more complicated and is no longer computable from properties of the periodic orbit alone. The long-time behavior adds fine-scale structure to the LDOS, which gives rise to additional LDOS fluctuations. But the wavefunction scarring, caused by the wave interference at particular energy windows, is not erased. Figure 2 plots

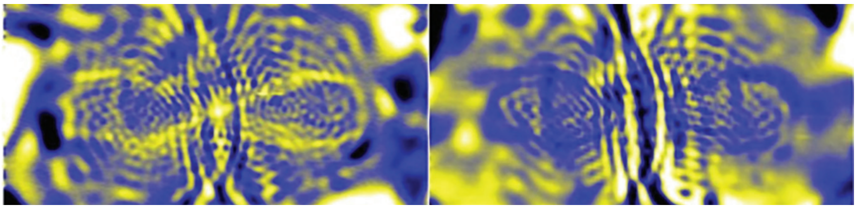


Figure 3. These scanning tunneling microscopy images are the first experimental verification of quantum scarring. The patterns are the result of a quantum system's eigenstates having an increased or decreased probability density around the paths of unstable orbits. The studied system is a soft-walled, stadium-shaped quantum dot on a graphene sheet and is modeled with a relativistic electron wavefunction. The state on the left is scarred by a lemniscate (∞-shaped) orbit, and the one on the right is antiscarred—the probability density around the orbit's path is decreased. Yellow indicates a high conductivity and is proportional to a high probability density of electrons; blue, to a low conductivity and a low probability density. (Images adapted from ref. 10.)

the LDOS, which shows the overlap of the wavepacket with particular eigenstates, and a sample autocorrelation function of a wavepacket.

How is the wavepacket analysis consistent with the quantum ergodicity theorems? Once again, it's useful to consider the wavepacket picture. A quantum wavepacket with minimal uncertainty has a width that's given by Planck's constant, which is fixed, but the size of the available phase space grows with the wavepacket's mean energy E. As the wavepacket's energy increases, the wavepacket probes an ever-tighter region of phase space that surrounds the periodic orbit. The fraction of the available phase space that's covered in the 2D case scales as $E^{-1/2}$. The quantum ergodicity theorems don't apply at the size scale at which scarring happens. Those theorems guarantee wavefunction uniformity on macroscopic, classical scales, but probability-density fluctuations from scarring occur at scales that are classically microscopic but still quantum mechanically significant.

Making predictions

Scar patterns may be visually striking, but the real test of the theory lies with its capability to make quantitative predictions.[8] Even though the random-wave conjecture lacks a formal proof, many theoreticians view it as a promising framework through which to understand quantum chaotic behavior. The random-wave conjecture predicts Gaussian random fluctuations in wavefunction amplitudes instead of perfect uniformity, which is forbidden by the uncertainty principle. (To the human eye, such random fluctuations may appear to look like patterns.) Any theory of quantum scarring, therefore, should predict the statistical distribution of wavefunction amplitudes.

Perhaps the simplest choice is to start with a Gaussian wavepacket $|\phi\rangle$ with minimal uncertainty and to consider the distribution of overlaps $\langle\phi|\Psi_n\rangle$ between the wavepacket and the eigenstates $|\Psi_n\rangle$ in some energy window. All that information is contained in the LDOS, which may be computed from the autocorrelation of the wavepacket in time. With the initial wavepacket aligned optimally along the stable and unstable directions that are perpendicular to the orbit, a simple expression can be obtained for the periodic recurrences, and a lower bound on wavefunction nonuniformity can be placed.[8]

Although important information is contained in the full probability distribution $P(\langle\phi|\Psi_n\rangle)$, it's convenient to have a single measure of deviation from ergodicity. The mean intensity $\overline{|\langle\phi|\Psi_n\rangle|^2}$ over a sufficiently large energy window is fixed by a sum rule. That is, the scarring of some eigenstates by a given orbit is balanced by the antiscarring of others. To measure nonuniformity, therefore, one can calculate the mean intensity amplitude, also called the inverse participation ratio: $\mathrm{IPR}=\overline{|\langle\phi|\Psi_n\rangle|^4}/\left(\overline{|\langle\phi|\Psi_n\rangle|^2}\right)^2$.

An IPR of 1 is indicative of a classical state, in which all eigenstates contribute equally to the system; for random waves, the IPR is 2 or 3. Quantum chaotic systems deviate even further from ergodicity because of the effect of periodic orbit recurrences at short times. In those systems, and if full randomness for new recurrences at large times is assumed, $\mathrm{IPR}=\pi\,\mathrm{IPR}_{\mathrm{rnd}}/\mu$ for a wavepacket placed optimally on a periodic orbit. The dimensionless instability exponent μ characterizes the periodic orbit and for a quantum chaotic system is often about 1.[9]

Experiments in graphene

In the 1990s, quantum scars were successfully imaged in various classical-wave systems, including microwave cavities in which the squared electric field plays the role of wavefunction intensity, acoustic cavities in which the pressure field may be imaged, and fluid systems that exhibit surface waves. Those types of experiments provided oblique experimental confirmation of scar theory in macroscopic systems and allowed researchers to quantitatively compare the results with semiclassical predictions of scar strength.

The first direct visualization of scars in a quantum system, however, was achieved only in 2024, four decades after scars were first identified theoretically. The researchers imaged electrons in

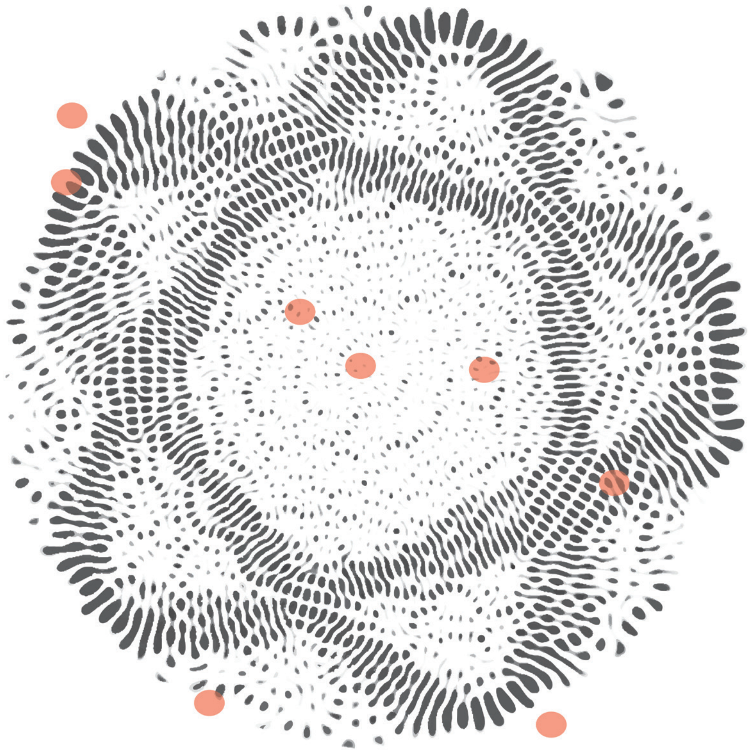


Figure 4. This variational scar pattern is formed after a rotationally symmetric potential well is perturbed with randomly placed Gaussian bumps (red spots). The constructive interference of the bumps with an eigenstate of the perturbed system produces scarring along a periodic orbit of the unperturbed system.

quantum dots using scanning tunneling microscopy with nanometer resolution.[10] Figure 3 shows an example of scarred and antiscarred wavefunctions in a soft-walled, stadium-shaped quantum dot on a graphene sheet. Because the electrons in the graphene system behave like they're massless and obey the relativistic Dirac equation, the patterns are called relativistic scars. (The 2021 *PT* article "Relativistic quantum chaos in graphene," by Hong-Ya Xu, Liang Huang, and Ying-Cheng Lai, discusses relativistic scars in more detail.)

Relativistic scars also satisfy an equation analogous to the nonrelativistic, time-independent Schrödinger equation, which is the equation obeyed by conventional scars that were introduced in 1984, so the basic physics of the two scar types is similar.[11] But the relativistic scars do have two novel features: They exhibit chiral behavior, like circularly polarized photons, and the maximally scarred energies, which correspond to the peaks of the smoothed LDOS, occur at equal energy intervals, unlike in systems described by the Schrödinger equation.

Diverse patterns

The theoretical scarred state shown in figure 4 visually resembles a traditional quantum scar, but it has a different origin.[12] First, a radially symmetric potential well is perturbed by introducing multiple randomly placed impurities, which in the figure are indicated with red spots. Resonances related to the motion in an unperturbed classical system result in near degeneracies in the unperturbed quantum well. When randomly placed bumps are added, specific linear combinations of the nearly degenerate basis states constructively interfere and form strongly scarred eigenstates.

Scars formed through that mechanism are called variational because the scarred state is a superposition that either maximizes or minimizes the expectation value of the impurity potential. Examples of both cases are shown in figure 5. In the time domain, variational scarring is linked to wavepacket recurrences in the perturbed system that are much stronger than the recurrences in the original symmetric well.

Researchers are working on experimental verifications of variational scarring in semiconductor nanostructures and in graphene-based quantum dots, which were used for the first direct visualization of conventional scarring. If variationally scarred eigenstates exist, they could be useful for certain applications, such as the efficient transport of electrons through a quantum system. Because the scar orientation depends on the position of the local perturbation, scars could possibly allow for electron steering by enhancing or suppressing electron transmission along certain entrance and exit channels.

Furthermore, the shape of the variational scar pattern could be tuned by an external magnetic field or by controlled deformation of the confining potential, which could be done with a nanotip.[13] Looking ahead, the capacity to selectively manipulate variational quantum scars and possibly other types of scars points toward the prospect of "scartronics," in which conductivity and other properties of a quantum device are engineered through the intentional generation and manipulation of scarred states.[13,14]

Recent developments

Of great interest for quantum-information-processing applications are many-body quantum scars—special many-body eigenstates in otherwise thermal systems that

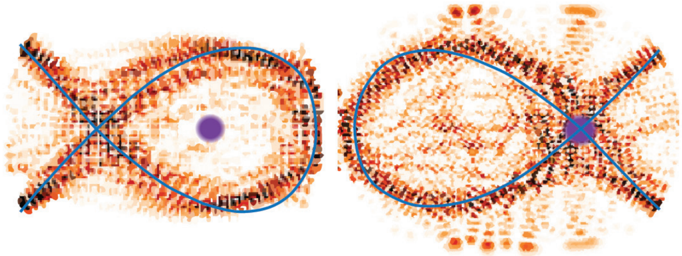


Figure 5. An elliptical oscillator perturbed by even a single Gaussian bump (purple dot) exhibits variational quantum scars. The scarred state is a superposition of the near-degenerate states of the unperturbed system and can either minimize **(left)** or maximize **(right)** the expectation value of the bump's potential. The resulting patterns resemble the periodic orbits (blue curve) of the unperturbed system.

display oscillatory behavior and slow thermalization. Their robustness against thermalization has piqued researchers' curiosity in using them for ultrasensitive measurements. A prototypical example occurs in a Rydberg-blockaded atom chain, in which nearest-neighbor sites are forbidden from simultaneously being in the excited state.[15] The initial configuration of Rydberg atoms exhibits persistent oscillations that are indicative of nonergodic dynamics. Unlike in the case of single-particle quantum scars, the oscillations are not associated with classical periodic orbits. Instead, the orbits in many-body Hilbert space are associated with kinematic constraints and hidden algebraic structures.[16]

Many-body scars reveal that even strongly interacting, nonintegrable quantum systems can host hidden, low-entropy trajectories that evade thermalization and sustain unexpectedly long-lived coherent dynamics. Despite significant progress in understanding that form of scarring, many questions remain, including its precise relationship to conventional and variational scars.

What began more than 40 years ago as a surprising imprint of unstable classical orbits on some quantum states has diversified into three main research directions: conventional, variational, and many-body quantum scarring. A central question concerns the underlying ontology of the different types of scars and whether periodic orbits are essential to each type. But all the scar types lead to distinct recurrences in wavepacket dynamics, which reflects their shared ergodicity-breaking nature. With theory and experiment advancing rapidly in tandem, the field is experiencing a renaissance period, which vividly illustrates how a long-standing concept can continue to evolve and surprise. **PT**

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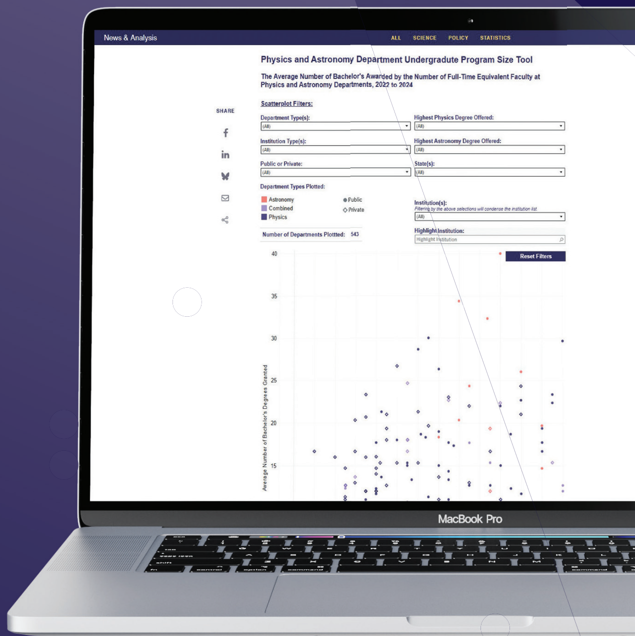
PHYSICS AND ASTRONOMY DEPARTMENT UNDERGRADUATE PROGRAM SIZE TOOL



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Building graduate programs that support mental well-being

Patrick Banner, Kellen O'Brien, and Chandra Turpen

Graduate students in physics and astronomy struggle with mental health. Support from peers and advisers is critical; so is institutional change.

(Design by Masie Chong with artwork adapted from iStock.com artists Visual Generation, Davyd Kopych, PeterSnow, and mspoint.)

Spring is a busy time for Alex and Will, two physics PhD students. Both have conferences and fellowship application deadlines approaching.

Alex is excited for the conference. The schedule he has built includes meals with colleagues and talks by speakers he hopes to meet. He still needs to collect data and make his talk slides, but he'll do that later this week. Last night, his friends reminded him of a neat application for his work, and he is using that inspiration to fuel the writing for the fellowship application. He was alerted to the fellowship opportunity by his adviser, who expressed confidence that he could get it.

Will is applying for a fellowship that he learned about in an email newsletter. His adviser agreed to write a recommendation letter but didn't offer any additional guidance. Will hasn't caught up with friends in a while because he's been trying to work hard, but he still feels behind in his research. Spending time on the application also means he's not taking data for his conference talk, which he is anxious to prepare for. Since he isn't sure he can get the fellowship anyway, he considers giving up on the application altogether.

Alex and Will aren't individual graduate students; they're composites based on our own experiences and those relayed by PhD students we've talked to. Obtaining a PhD is a demanding endeavor, and graduate students respond differently to the challenges. Like Alex, some find passion and inspiration, often with the help of supportive advisers and encouragement from friends and family. For others, like Will, the challenges lead to mental health struggles. Any challenge that isn't immediately overcome can make a student feel behind and cause them to overwork and self-isolate. From fear of failure, they might not pursue creative ideas and exciting opportunities. As a result, both the student and the research enterprise are affected.

We have observed firsthand the prevalence of grad students like Will who go through mental health challenges in physics and astronomy (P/A) PhD programs, and we wanted to find ways to help ameliorate those struggles. Studies generally agree that graduate students have higher rates of mental health conditions than the general population.[1,2] In one survey at the University of California, Berkeley, for example, more than 40% of graduate students in the biosciences reported symptoms of clinical levels of depression. There are minimal data, though, on P/A graduate students specifically. Physics and astronomy are fields with cultures that may present particular challenges to mental health (even more than other STEM fields), such as beliefs that innate brilliance is needed to be successful[3] or that the objectivity of the field makes it impervious to the influence of human biases.[4]

Given that context and our observations, we administered a survey that was designed to investigate two questions: How prevalent are mental health struggles in P/A grad students? And how are those struggles related to aspects of the graduate student experience and students' identities?

Community-driven survey design

We strove to not only gather and interpret data but also use that data to seed community action. To that end, we involved community voices by holding a codesign discussion with graduate students.[5] We used information from that discussion and data collected at the University of Maryland and from other published work to inform our survey design. The survey, given in summer 2024, had two major parts.

First, to assess the prevalence of mental health challenges in our sample cohort, we used clinical scales that measure symptoms of anxiety, depression, and impostor phenomenon. On all three scales, higher total scores indicate more frequent or severe symptoms. Each scale is used in clinical contexts: If a respondent scores in the moderate to severe range, the score could be used to recommend further diagnosis or treatment.

The second part of the survey investigated features of the graduate student experience that may contribute to mental health challenges. To determine which features were most important to capture, we sought input from students in the codesign session[5] and validation interviews.[6] We found a few common themes and developed sets of questions to probe them. In our analysis, we focused on five variables:

- Adviser support.
- Work–life balance.
- Sense of professional progress: a student's perception that they are progressing through the PhD program and will benefit professionally from the work they are doing.
- Authenticity at work: a student's sense that

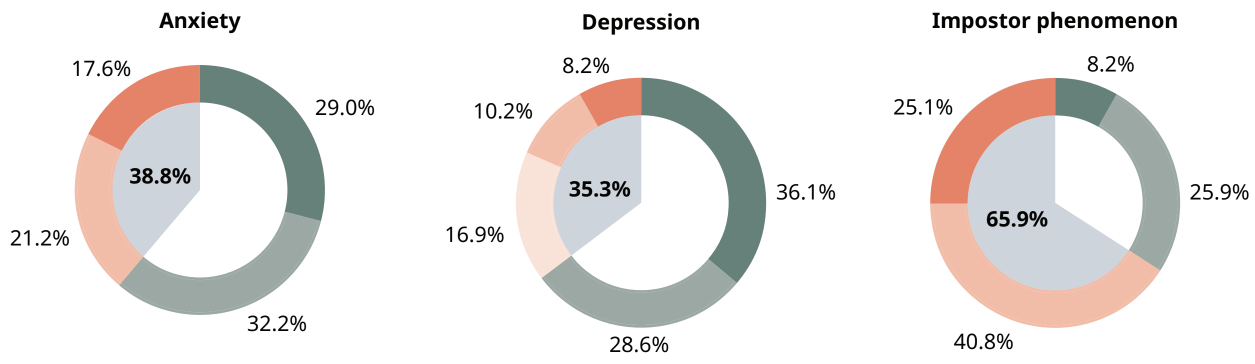


Figure 1. Our sample's distribution of scores on the severity of specific mental health challenges. Dark orange indicates the highest score category (most severe/frequent symptoms); dark green, the lowest score category (fewest symptoms). The percentage of respondents in the moderate to severe categories is indicated by the gray shaded regions.

they can be themself in the workplace, rather than having to hide parts of themself.

- Loneliness.

Samples of statements used to evaluate each variable are given in the table on page 38. When respondents were asked for feedback about the survey, responses included the following: "It felt like someone who knew me very well was asking the questions." "Good survey: 10/10." "I felt 'seen' by this study." We consider those comments, and a lack of comments to the contrary, as supporting evidence that we measured some aspects of the graduate experience that are salient to students.

We administered our survey to eight P/A graduate programs at seven US institutions. All are R1—very high research output—universities, and all but one are public institutions. At the time of the survey, each program had between 45 and 300 enrolled graduate students, totaling about 1000 students. The survey was given online. Participation was voluntary; after completing the survey, students could enter a raffle for $50 gift cards. Graduate students in each program were paid to promote the survey using departmental communication channels.

We received complete responses from 255 students. To preserve anonymity, we asked for minimal information about them. Regarding gender, 58% identified as men, 32% as women, and 8% as nonbinary; 2% chose not to self-identify. Regarding nationality, 61% of respondents were domestic students and 38% were international; one respondent chose not to self-identify. The sample slightly overrepresents women, nonbinary, and domestic students.[4] About 48% of our respondents were in their first two years of graduate school; 17% said they had completed more than four years of graduate school.

The scale of the problem

Our results regarding anxiety and depression are shown in figure 1. In our sample, 38.8% of P/A graduate students reported moderate to severe symptoms of anxiety, a rate roughly six times that of a nationally representative sample. Those scoring in the moderate to severe range are typically experiencing anxiety that is strong or persistent enough to interfere with day-to-day tasks. Additionally, 35.3% reported moderate to severe symptoms of depression, a rate roughly four times that of a nationally representative sample.[4] (Some respondents were in the moderate to severe range for both anxiety and depression.)

One survey item asks whether a respondent had, in the last two weeks, experienced "thoughts that you would be better off dead or of hurting yourself in some way." In our sample of 255 students, 49—nearly one in five—answered affirmatively. That is five times the rate of the general population.[4]

Lastly, we surveyed for impostor phenomenon. People experiencing impostor phenomenon believe they are less competent than others judge them to be.[7] Though generally objectively successful, they downplay their accomplishments to themselves and others, fear that any failure could "expose" them as impostors, and expend great effort to maintain the ruse that they believe they have created. In our sample, nearly two-thirds of graduate students experienced moderate to severe impostor phenomenon, as shown in figure 1.

The prevalence of anxiety, depression, and impostor phenomenon among P/A grad students is comparable to or higher than that among many other student populations that have been studied.[4]

Roughly 75% of the targeted population did not respond to the survey. It is unclear whether a potential respondent with serious mental health challenges would see the survey as a burden they choose not to engage with or as an anonymous opportunity to share their experiences. Similarly, a respondent who does not struggle significantly with such challenges might view the survey as a task with little burden or as something irrelevant to them. Though the results should not be unduly generalized to the entire P/A graduate student population, we recognize in our data a large number of P/A graduate students who are experiencing mental health challenges.

The mental health struggles of P/A graduate students are harmful not only to the students themselves but also to the research enterprise. A student who struggles with anxiety might procrastinate, which leads to last-minute, low-quality work.[8] A student who struggles with depression might lack the motivation to do the work or pursue new ideas.[9] And a student who struggles with impostor phenomenon might overprepare for tasks in ways that lead to burnout or might avoid trying high-risk, high-reward research directions.[10]

Our findings clearly demonstrate that P/A graduate students are experiencing high rates of mental health challenges. One way for institutions to tackle those struggles is to invest in greater access to mental health care, including offering health insurance plans with reasonably priced mental health care copays.

At the same time, since mental health challenges appear much more prevalent in graduate students than in the general population, we suspect that structural aspects of graduate education are exacerbating students' mental health struggles. The measured prevalences of mental health symptoms did not vary significantly by institution in our sam-

Variable	Sample statements
Adviser support	My adviser regularly shares professional development opportunities with me (e.g., conferences, workshops). My adviser encourages me to reflect on the work I'm doing. My adviser gives me feedback on skills I still need to work on.
Work–life balance	Because the job demands it, I usually work long hours. I delay making important appointments (e.g., to see a doctor) due to my workload.
Sense of professional progress	I know what I need to do in order to graduate. The work I am doing in grad school is making me a better scientist.
Authenticity at work	I feel like I fit in with other people in my workplace. I often feel like I hold back my real personality while working.
Loneliness	There are plenty of people I can rely on when I have problems. There are enough people I feel close to.

▲ Samples of the statements used to assess independent mental health variables. For each variable, survey respondents were asked to rate how much they agree or disagree with each statement. For the statements under the first four variables, respondents could select one of six options, from "strongly agree" to "strongly disagree." For the loneliness scale,[18] respondents could choose one of five options, from "[I feel like this] none of the time" to "[I feel like this] all the time."

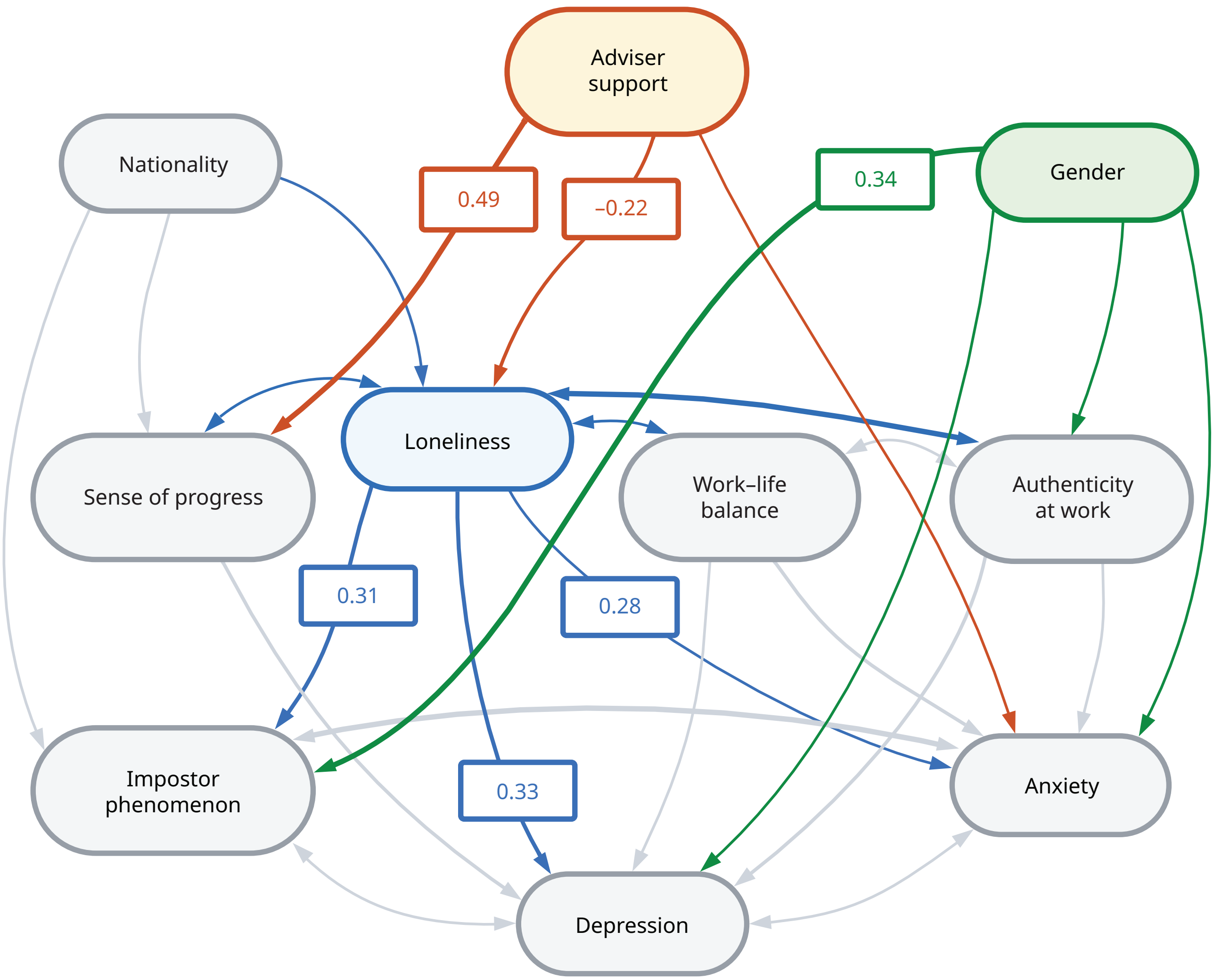


Figure 2. A map of the connections between mental health metrics and facets of identity and experience among physics and astronomy graduate students, generated from a structural equation model. Arrows indicate a statistically significant relationship ($p < 0.05$); numbers in boxes indicate strengths for the strongest relationships ($p < 0.001$). One-directional arrows signify causal relationships. For example, in our model, an increase in loneliness predicts an increase in depression. Bidirectional arrows indicate correlations. A negative sign in a relationship indicates anticorrelation. To represent gender in the model, men are assigned a value of 0 and women and nonbinary people are assigned a value of 1; the positive correlation indicates that men had a lower average score than women and nonbinary people for impostor phenomenon.

ple, which indicates a systemic problem. As an analogy, a person with asthma benefits from an affordable rescue inhaler, but they also benefit from policies that reduce pollutants in the air. What are the "pollutants in the air" of the graduate student experience, and how can the P/A community respond with care and support?

To answer those questions, we assessed the surveyed students' perceptions of various aspects of the graduate student experience and used structural equation modeling (SEM) to relate those experiences to specific mental health struggles.

Analyzing the graduate student experience

SEM is a statistical tool that uses the correlations in a dataset to model complex causal relationships between variables.[11] A researcher provides an initial causal model, informed by previous studies and theoretical arguments, and then uses SEM to estimate the strength of the causal relationships specified in the model.

After positing an initial model, we eliminated insignificant relationships one at a time to reach a final model, represented visually in figure 2, that captures the significant relationships in the data. The analysis produced three principal conclusions, which are color coded in the figure:

- Loneliness (blue) is important; it has connections to almost every other variable measured.
- Support from advisers (orange) influences all three mental health metrics.
- Regarding gender (green), women and nonbinary students experience higher rates of mental health struggles.

Colors in figure 2 highlight different chains of influence that, according to our model, facets of graduate education or student identity have on mental health outcomes. We interpret those chains of influence as guides for where to pursue change in graduate education. In the sections below, we describe the model results in more detail and our ideas for intervention. In future work, it would be worthwhile to empirically explore how such interventions may improve mental health outcomes.

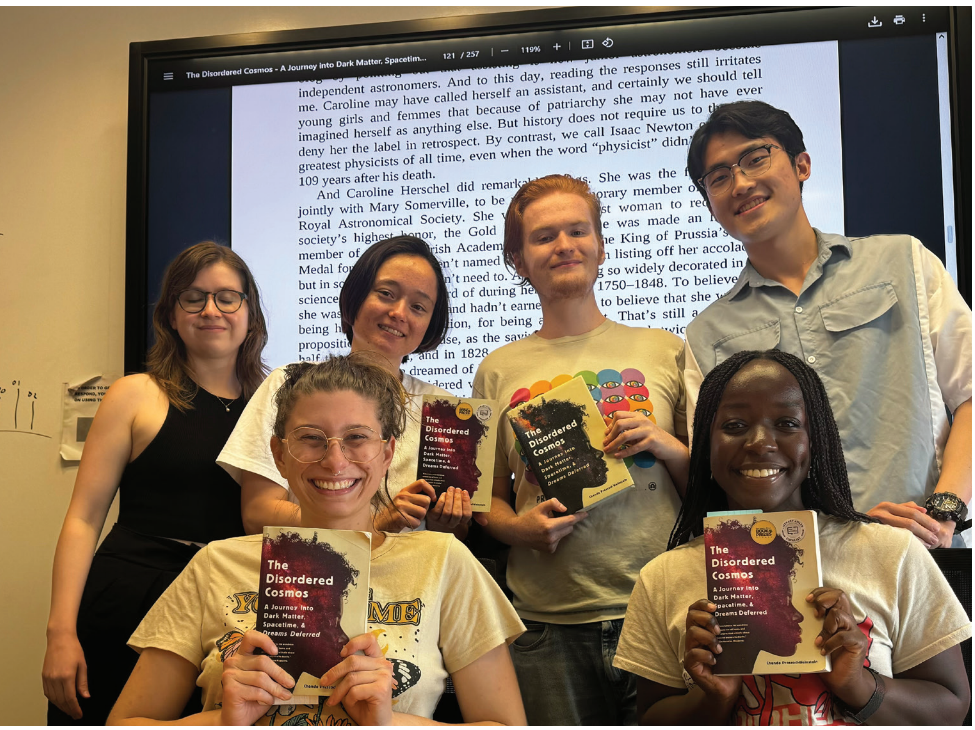
Social support is critical

Model results. Loneliness is deeply embedded in the final model (see the blue arrows in figure 2). Greater loneliness predicts increased rates of impostor phenomenon, depression, and anxiety (indicated by single-headed arrows). Loneliness also has significant correlations (indicated by double-headed arrows) with work–life balance, authenticity at work, and sense of progress. Lower adviser support predicts greater loneliness, and international students report more loneliness than domestic students.

What can be done? To foster feelings of social support in graduate students, interventions will have to go against two broad cultural trends. First, academic culture is often focused on attaining high research output, and some academics view socializing as a distraction from research rather than an aid to it. Second, in the US, broader society is increasingly experiencing a loneliness epidemic, which is driven by various economic, cultural, and technological trends.[12]

To combat those cultural pressures, all members of a graduate program can be intentional about providing social support. Graduate students themselves can play a significant role through such actions as gathering colleagues for lunch. For activities that require more work to organize, graduate student organizations can help. Two successful examples at the University of Maryland are the Noether Physics Society's book club and the Mental Health Task Force's game nights. Graduate students may also find support from friends and family and by engaging in activities outside their academic department.

Advisers can help shape the culture of their research groups by organizing group social activities and encouraging work–life balance. Departments can con-



The Noether Physics Society's book club at the University of Maryland in College Park. (Photo courtesy of the Noether Physics Society.)

An annual talent show, Wanton Mechanics, is held by the University of Oregon department of physics. (Photo courtesy of Richard Taylor.)

tribute financial resources, physical space, and staff to sustain student- and faculty-led events. Finally, students have often moved away from a network of family and friends to attend graduate school; advisers and departments can find ways to involve those networks, even virtually, in celebrating students' accomplishments.

Student–adviser relationships

Model results. The SEM model supports the idea that research advisers have an outsize effect on a PhD student's experience. In the model, adviser support has statistically significant total effects on all three mental health outcomes—anxiety, depression, and impostor phenomenon. Those total effects are almost entirely attributable to the impact of adviser support on two variables: a student's loneliness and sense of professional progress, as shown in figure 2. In our initial model, we postulated that adviser support would have direct effects on work–life balance and a student's feeling of authenticity at work, but we found those effects to be insignificant in the final model.

What can be done? The results of the model suggest that advisers generally can support their graduate students' mental health in two ways: by fostering students' perceived social support and by helping students feel a sense of professional progress and growth during their graduate education.

To help students feel a sense of social support, advisers can encourage, organize, or sponsor social outings with their group, connect their students with colleagues to expand their professional network, and encourage students to seek social connection outside the group and department. To help students maintain a sense of professional progress in the face of inevitable setbacks, advisers can reframe struggles and setbacks as part of the research experience and opportunities for learning.[13] Other studies of PhD students suggest that such emotional support from advisers is at least as important to graduate student well-being as technical expertise.[14]

P/A researchers rarely receive formal mentorship training at any stage in their careers. Institutions should provide and mandate such formal training for their faculty and graduate students. Mentorship training can cover a wide variety of topics, including how to support students in thinking about their professional goals, provide regular constructive feedback to students, have conversations around mutual expectations, encourage a growth mindset, and unpack biases.

Through appropriate institutional policies, the community can avoid placing responsibility for so much of a graduate student's well-being on the adviser. For example, some programs require regular meetings with a dissertation committee that is formed early in the graduate student's education rather than shortly before the defense. Having multiple contacts with a wide array of experiences and advising styles can give students additional mentorship and support.

Gender and mental health

Model results. Our model indicates that gender identity has significant direct effects on anxiety, depression, and especially impostor phenomenon, as shown in figure 3. Women and nonbinary students both reported statistically significant higher average scores than men on all three clinical scales.

Of the five aspects of the graduate school experience we surveyed, gender identity was significantly related only to authenticity at work. In our sample, women and nonbinary students did not report feeling lonelier than men, did not report worse work–life balance or less sense of professional progress than men, and did not report lower feelings of adviser support than men. Those were all connections postulated in our initial model that were insignificant in the final one. Thus, women and nonbinary P/A graduate students in our sample reported more symptoms of mental health challenges, but that finding was not well explained by the factors that we measured.

What can be done? It is likely that other aspects of the STEM graduate education experience, beyond those surveyed, contribute to the disparities. As an example, some qualitative studies have shared powerful stories of women graduate students encountering rigid program structures that conflict with other family care responsibilities.[15]

Some meta-analyses have suggested that gender differences in impostor phenomenon are more common in education than in professional settings;[16] others have

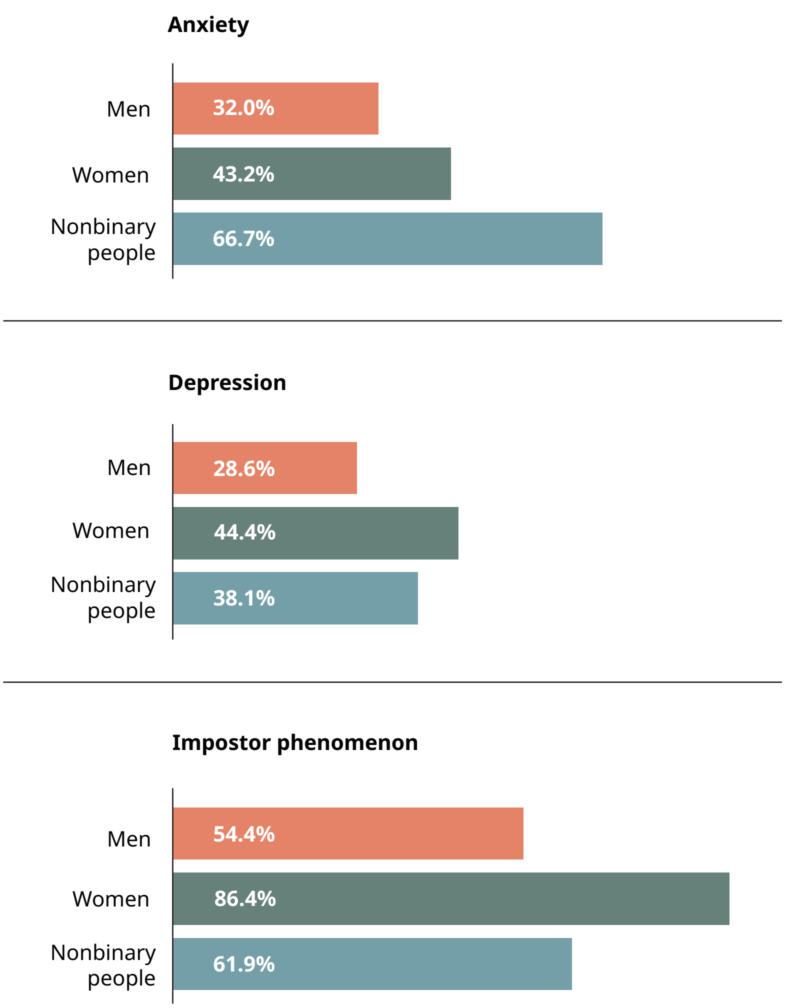


Figure 3. The percentage of men, women, and nonbinary students in our sample that scored in the moderate to severe categories for anxiety, depression, and impostor phenomenon. Women and nonbinary students do not differ statistically significantly; both report statistically significantly more symptoms of mental health challenges than men in our sample, even when controlling for the other variables in our model.

The Physics Graduate Student Association at the University of Illinois Urbana-Champaign holds a gathering, called Fast-a-thon, for students to participate in fasting during Ramadan. (Photo courtesy of Layla Ahmed.)

suggested that the prevalence of impostor phenomenon in a population may be connected to whether that population is underrepresented in a given domain and may therefore be more likely to encounter specific cultural stereotypes.[17] For example, physics is a field in which many practitioners believe innate brilliance is needed to succeed;[3] such a belief could be particularly harmful to gender minorities, who are often perceived as not having such innate ability.

Mental health struggles could also be exacerbated by other challenges, including systemic bias, microaggressions, discrimination, high-stakes testing, competitive cultures, and exclusionary practices in graduate programs, none of which were measured in our study. More in-depth research on those phenomena could help to further develop informed interventions for P/A graduate programs.

Advancing the conversation

The data in our survey reveal some troubling results. Our sample of P/A graduate students reported challenges with anxiety and depression at six and four times the rates of the general population, respectively, and two-thirds of our sample reported moderate to severe impostor phenomenon. Women and nonbinary students in our sample reported worse mental health than men on all three scales.

Our study also sheds light on possible ways that graduate education helps or harms students' mental health. When students feel that they are not well supported by their advisers and do not have social support, they are more likely to struggle with anxiety, depression, and impostor phenomenon. And when students feel that they have the emotional support of both peers and their advisers, they are less likely to struggle with mental health issues. Our study enumerated two ways that advisers support graduate student mental health: cultivating social support and fostering a sense of professional progress.

In graduate programs, students have agency in their own mental health. We encourage P/A community members to make use of counseling and other resources when necessary and to advocate for expanded access to those resources. To support mental well-being more generally, students can seek out peer connections, communicate openly with advisers about challenges, and learn to approach setbacks as learning opportunities.

At the same time, a graduate student should not bear the responsibility of their mental health alone. A culture of well-being emerges through daily interactions and systemic choices made by graduate programs, and all members of a program contribute to those factors. Thus, advisers and departments must work to foster connection, adopt student-centered teaching and advising practices, bring empathy and care to department culture, and remember that graduate education is, fundamentally, for graduate students. With our study, we hope to start conversations about how to build supportive cultures, reduce mental health struggles among P/A graduate students, and make all members of our community not only more productive but also healthier and happier. **PT**

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OPINION

Lessons from Stuart Freedman: Six scientists share their stories

Freedman performed crucial work as an experimentalist. But his mentorship was an equally important contribution.

By Jill Marshall and Jim Napolitano

Stuart Freedman has been mentioned in *Physics Today* several times in recent years for his efforts, with John Clauser, on the first experimental Bell test.[1] Done as Freedman's thesis, it provided evidence that local hidden-variable theories, proposed as alternatives to quantum mechanics, were incorrect. His paper was referenced in several 2025 *PT* pieces: the feature "Hippies, Bell tests, and a career studying quantum entanglement," by David Kaiser; a letter from Robert Cahn responding to the feature "Chien-Shiung Wu's trailblazing experiments in particle physics," by Chon-Fai Kam, Cheng-Ning Zhang, and Da Hsuan Feng; and the republished story "Magic moments with John Bell," by Reinhold Bertlmann. In 2022, it was referenced in *PT*'s coverage of that year's Nobel Prize in Physics, awarded for experiments with entangled photons. Seeing those recent references has prompted us to bring to light Freedman's contributions in another area: his mentorship and inspiration to students and younger colleagues.

Before his sudden death in 2012, Freedman lived an extraordinary physicist's life. His experimental acumen left its imprint on many areas, including fundamental nuclear physics, quantum entanglement, and neutrino oscillations. He performed world-class research and held positions at Princeton University, Stanford University, Argonne National Laboratory, the University of Chicago, Lawrence Berkeley National Laboratory, and the University of California, Berkeley. We present the case here that his contributions to developing human capital in physics were as profound as his contributions in advancing its research agenda.

We believe that Freedman has had an inordinately undervalued reputation, which possibly was because he had a self-effacing manner and neither the time nor the inclination for self-promotion.

Here we've compiled, from the two of us and four other scientists, stories that exemplify the value Freedman provided to the human side of science. We all went on to complete PhDs in physics (although none directly supervised by Freedman). Rather than simply extending his own research agenda through those he mentored, Freedman supported them in pursuing their own paths.

These stories illustrate core aspects of Freedman's mentorship at critical stages of a scientist's development: as an undergraduate student, as a graduate student making career choices, and as a young experimental physicist forming their own professional foundation.

Let physics drive you

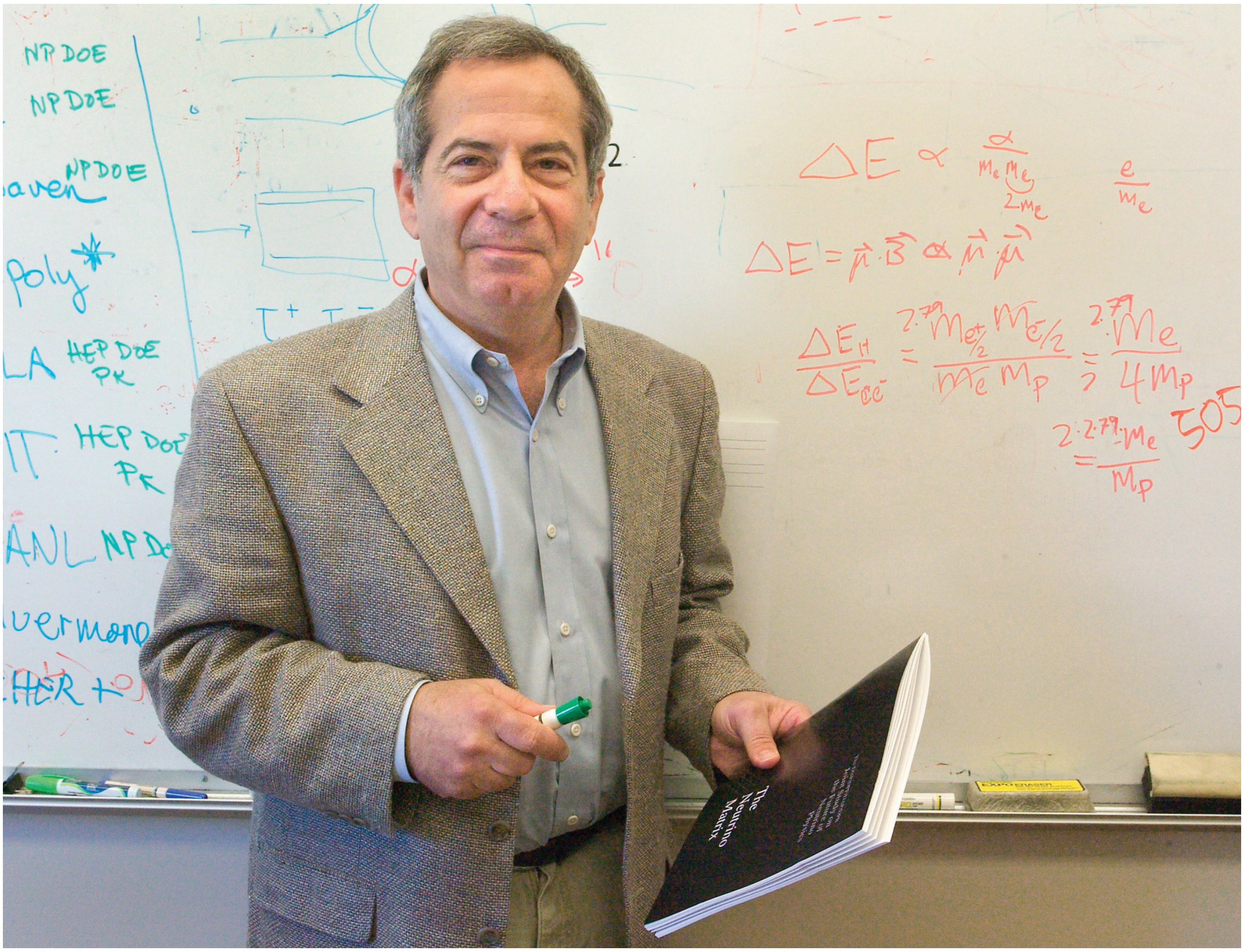
Jim Napolitano

Jim Napolitano met Stuart on the first day Napolitano arrived at Stanford in 1977 to begin graduate school. The nuclear-physics experiments that they conducted together at Stanford were only the beginning of a decade of collaboration. Stuart worked with Napolitano on his PhD thesis experiment at SLAC, and Napolitano was a postdoc and then scientific staff member in Stuart's group at Argonne.

Stuart's manner, Napolitano says, was approachable and welcoming. In addition to the wealth of physics knowledge he imparted, Stuart provided lessons in technical writing, flying sailplanes, keeping things in perspective, and exercising good judgment in interactions with research groups and the scientific community.

Napolitano recalls that one of those lessons was "Beware of becoming too attached to a 'program.'" In other words, Stuart urged Napolitano and others to always let physics drive their efforts and to not get pigeonholed by a specific field or technology.

Indeed, Napolitano's career has involved many fields, including nuclear physics, high-energy physics, and advanced computing. He has taught in the classroom and instructional laboratory. A tribute to Stuart appears in the preface of a textbook that Napolitano coauthored.[2]



▲ Stuart Freedman in 2005 with a copy of *The Neutrino Matrix*, which summarized a neutrino-physics study he co-chaired with Boris Kayser. (Photo by Roy Kaltschmidt, courtesy of Lawrence Berkeley National Laboratory.)

He continues to realize that so much of what he teaches his students are lessons that Stuart taught him, which is about as close as one can get to immortality.

Be a guide, not a guard

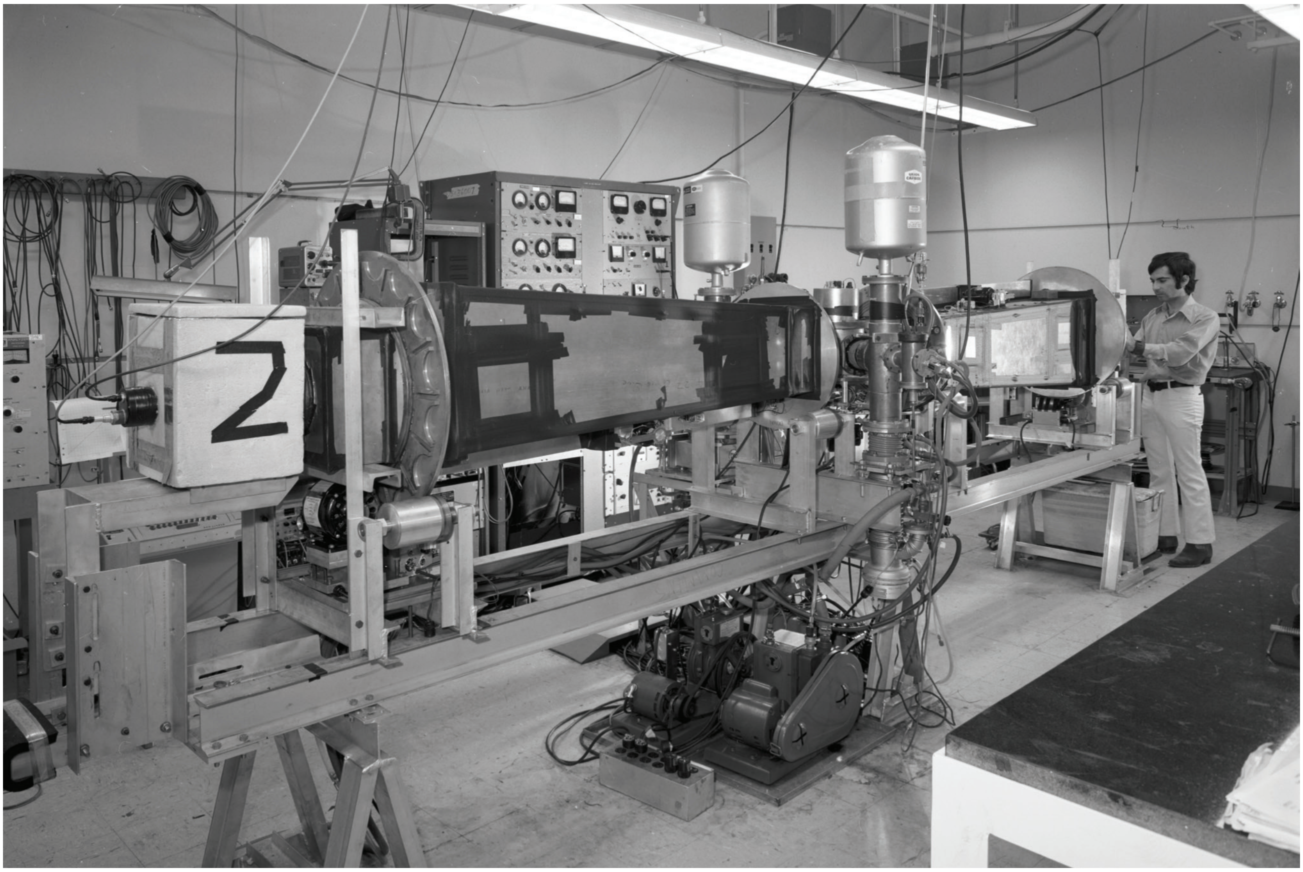
Jill Marshall

Jill Marshall met Stuart when he was the instructor of her undergraduate mechanics class at Stanford. She vividly recalls a casual hallway conversation during her senior year when Stuart, dressed as always in blue jeans, asked about her plans. The inquiry itself was memorable. Stuart was the only physics department faculty member who she remembers ever asking about her plans as if they mattered.

Marshall told Stuart that she was applying to graduate school at Stanford, although she thought it unlikely that she would be admitted there, and that she was also applying to several other schools, including the University of Texas at Austin. Stuart offered a profound response: “Well, would you rather go to a school like Texas where they build people up or one like Stanford where they don’t want you unless you already have a Nobel Prize?” It seemed to her that his advice was based on his own experience.

Stuart’s candor about what might (and what should) be valued by a physics department left a strong impression on Marshall. His practice of being the “guide on the side,” helping students identify their interests and abilities, rather than the “guard at the gate,” deciding who was worthy of being a physicist on the basis of their prior achievement, became a hallmark of her teaching philosophy and a theoretical underpinning of her research in physics education.

After PhD work focused on nuclear particles, Marshall went into space science and physics-education research. She has served as a codirector of UTeach, a teacher preparation program at UT Austin, and the 2012 president of the American Association of Physics Teachers.



Freedman making adjustments to his PhD apparatus at Lawrence Berkeley National Laboratory in 1971. (Photo courtesy of Lawrence Berkeley National Laboratory.)

Embrace your role, whether leading or assisting

Robert Cousins and John Greenhalgh

As a freshman at Princeton, Robert Cousins was placed into an honors discussion section that was led by Stuart, fresh from earning his PhD from Berkeley. "Several times a week, about 15 of us spent an hour with Stuart, digging deep into physics concepts and problems, and also discussing cultural differences between California, Kentucky (my home), and the Northeast," Cousins says. "We learned to appreciate Stuart's quirky, ironic sense of humor, as well as his warmth and patience with us."

Stuart and fellow Princeton faculty member Gerry Garvey planned to collaborate on experiments using the cyclotron, which provided senior thesis opportunities for Cousins and classmate John Greenhalgh. Cousins reports, "It turned out to be an amazing experience, as John and I became completely immersed in the cyclotron group, reinforcing my decision to become an experimentalist, while meeting and discussing physics and techniques with superb grad students and visiting faculty." Cousins also remembers that Stuart was "incredibly patient" while he dealt with students making "various blunders in the lab." A consummate experimentalist, Stuart was able to see their mistakes as growth opportunities.

Cousins remembers how Stuart handled a situation in the cyclotron lab when he and Greenhalgh were "bickering" about details of the execution of their joint senior thesis experiment. Stuart told them that it really didn't matter who was right because they were bickering about things that did not really matter. He gave them sticky notes and eventually T-shirts with "THE BOSS" written on one and "THE FLUNKY" on the other and instructed them to trade roles each day.

In 1976, Cousins and Greenhalgh both began grad school at Stanford, while coincidently, Stuart became an assistant professor there. Although enrolled in Stuart's graduate seminar on nuclear physics, they both leaned toward research in high-energy physics and explored opportunities at SLAC. "Then, in the fall of 1977, Mel Schwartz gave a colloquium about his forthcoming experiment at Fermilab (studying pi–mu atoms). Afterward, Stuart told us that we should talk to Mel about working with him," Cousins says. That changed the course of their careers. By January, Cousins and Greenhalgh were on their way to Fermilab, for another "wonderful experience" completing their dissertation work.

Greenhalgh feels fortunate to have been mentored by Stuart, whose approach to physics (and life) has served him well in his career. He notes, "He impressed upon me the beauty of experiments that touched upon the most fundamental questions ... If there is such a thing as having taste in physics, he had it."

Following Stuart's advice, Cousins moved into high-energy physics. He is now a professor emeritus at UCLA. After a postdoc at Princeton, Greenhalgh went on to a career in MRI. He is now vice president of R&D at FONAR and a consulting medical physicist for West Physics.

See potential, despite errors

David B. Kaplan

David Kaplan recalls sitting in the office of Schwartz, who was his undergraduate adviser at Stanford, when Stuart came in and announced that "Helen [Quinn] and Roberto [Peccei] have a theory that predicts a new light particle [now known as the axion] in the standard model." Stuart described the particle to Schwartz, "who snorted and said it would have been seen already." Stuart convinced Schwartz otherwise, and then "the two of them went at it on the blackboard, going through various existing experiments and designing new ones to test the theory." Says Kaplan, "I sat on Mel's couch like a fly on the wall, very excited by what I was seeing, although not at the prospect of being an experimentalist like them but by the idea that as a theorist I could predict new particles!" Kaplan credits the interaction with strengthening his belief in the power of theory and solidifying his career trajectory.

Kaplan remembers an interaction in which Stuart guided him and Ann Nelson in their senior project, for which they were to design, build, and conduct an experiment. Stuart suggested that they repeat Richard Cox's precocious 1928 discovery of parity violation in the weak interactions. Kaplan describes the experience as "an ambitious and exciting project which Stuart supervised with a light touch, allowing me to mess it up by flooding the box with helium to reduce background counts, in the process destroying six phototubes on loan from SLAC." Kaplan recalls, "We both agreed—he with his usual understated sardonic wit—I was not experimentalist material, but I was nevertheless allowed to graduate from Stanford and took with me a profound respect for Stuart's intelligence and passion for physics." Stuart saw Kaplan's potential despite his blunder in the lab.

▲ Robert Cousins and John Greenhalgh (left and right, respectively, in the top photo) in shirts that Stuart Freedman gave them in spring 1976. After the seniors were arguing about a joint experiment, Freedman instructed them to switch roles every day. (Photos by Princeton University physics department, courtesy of Robert Cousins.)

Kaplan followed his commitment to theory. He is

Freedman in a sailplane. (Photo courtesy of Joyce Freedman.)

now a senior fellow at the Institute for Nuclear Theory at the University of Washington.

Own up to your mistakes

Jane "Xan" Alexander

Jane "Xan" Alexander, one of Stuart's undergraduate students at Stanford, remembers a time when he modeled a capacity for self-reflection and growth rarely observed in physics faculty. Stuart made a teasing remark in class about her having left "an article of clothing" (a jacket) in the TA's office, and the male students laughed. At the time, Alexander and Marshall shared an office. On a large strip of paper taped to the wall, they recorded things said to them by faculty (for example, "You obviously should be in the liberal arts" and "Gentlemen, let's begin class"), statistics they came across (for example, that the Stanford physics department awarded more BS degrees to women in 1949 than it would be awarding in 1980), and so on, to help them process what it meant to be female physics majors in a department that did not uniformly welcome them. Alexander wrote "an article of clothing" on the paper. Later, she came into the office and found Stuart staring in silence at what she had written. She braced for an angry defense, to be told she should recognize a joke, but he turned to her and simply, sadly said, "I'm sorry."

Alexander valued her interactions with Stuart. She says, "I remember him as one of the few professors who didn't care that I was female, only that I was a student to mentor and to respect as a junior colleague."

Alexander pursued research policy and administration. She has served as deputy director of the Defense Advanced Research Projects Agency, executive director for science and technology at the Office of Naval Research, and deputy director of the Homeland Security Advanced Research Projects Agency.

A human legacy

As these recollections show, Freedman made a lasting impact on those around him. He mentored by example, in how he interacted with students and other more junior members of the physics community. He taught the importance of building a rewarding career and of seeing and valuing the potential in other people.

To recognize Freedman's legacy as a mentor, the American Physical Society in 2016 established the Stuart Jay Freedman Award in Experimental Nuclear Physics, awarded annually to an early-career experimentalist. Shortly after his death, the American Physical Society April Meeting featured a talk on his scientific legacy, and UC Berkeley hosted a symposium, called Measuring Nothing and Getting It Right, to honor him. Freedman indeed worked on many groundbreaking experiments, but his guidance as a mentor had an equally lasting impact. PT

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Jill Marshall is a former STEM education professor at the University of Texas at Austin. She has served as a codirector of UTeach, the university's secondary STEM teacher preparation program. Her research interests include high-energy nuclear physics, space particle physics, and physics education. **Jim Napolitano** is a physics professor at Temple University in Philadelphia. He conducts research in experimental nuclear and particle physics, is passionate about developing experiments for undergraduates, and has authored several advanced physics textbooks.

WHAT CAN PHYSICISTS DO?

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

Alexandra Loubeau
studies how sonic booms affect people on the ground

By Toni Feder

Acoustics engineer, NASA

BM, music engineering technology, University of Miami, 1998
PhD, acoustics, Pennsylvania State University, 2006

What was your research focus?

As a graduate student, the acoustics work I did was related to understanding how noise travels through air. I looked at how nonlinear effects changed sound, especially at high frequencies. The point was to understand if loud noises were affecting the hearing of bats.

(Photo courtesy of NASA.)

What were you looking for in a job?

I wanted a research position but not necessarily a teaching position. I was open to what was out there. I got a postdoc in Paris, where I worked on sonic-boom prediction modeling. The postdoc research led to my position at NASA. I came here in 2008.

What do you do at NASA?

My project has changed over time, but it's all geared to understanding sonic booms. Early on, I studied the human response to sonic booms using simulators. Now I'm involved with *X-59*, an experimental airplane to demonstrate a quieter sound at supersonic speeds. [See *PT*'s 2024 article "NASA unveils a supersonic plane with a quiet boom."]

I'm involved in the predictions and measurements aspects and how to combine those with community survey results. The point is to see how people's reactions change as a function of some range of noise levels and to provide domestic and international regulators with data for developing a new sound standard for commercial supersonic travel over land.

How do you spend your time?

My day-to-day changes. For flight testing, I set up microphones and gather data, which I later analyze. I lead a team, and I'm a technical point of contact for our external partners. I also communicate NASA's research in papers and at conferences.

How do you use physics in your work?

Physics is important for understanding how sound travels from an airplane to the ground and how the atmosphere affects the sound.

What new skills did you need?

One technical skill that I needed to brush up on was statistics. I have also learned how to lead a team and how to create presentations for different audiences.

What do you like about your job?

I like working with people from across NASA and learning from partners—researchers and regulators—from around the world. It's exciting to be part of a project that will change how we all fly. PT

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

QUICK STUDY

Physical properties of a perfect pasta sauce

Understanding how ingredients interact can help cooks consistently achieve delicious results.

By Daniel Maria Busiello, Vincenzo Maria Schimmenti, and Ivan Di Terlizzi

Cooking tasty food requires more than culinary intuition; it's a science. A principal actor in cooking is heat, which drives the transformation of ingredients and their molecular components into a delicious dish. In an Italian kitchen, the protagonists are often pasta and a sauce. To create a sauce that is smooth and clings well to the pasta, a cook must rely on a combination of factors, including texture, viscosity, and the wetting properties that govern how the sauce spreads and adheres to the pasta surface.

At heart, sauces are soft-matter dispersions: Many components coexist in a metastable state in which fat, water, proteins, and carbohydrates share space without separating. In the sauce for spaghetti aglio e olio, a dish made with generous amounts of garlic and olive oil, starch-enriched pasta water helps stabilize the oil–water dispersion by coating oil droplets and thickening the surrounding liquid, preventing large oil globules from forming. Tomato-based sauces benefit in a similar way: Without the viscosity-enhancing effects of both starch from the pasta and pectin from the tomatoes, the sauces would stay too fluid to remain on the pasta and drain away.

Stabilizing starches and other thickening ingredients appear in not only Italian food but many other cuisines as well, including Chinese cornstarch-based sauces, Indian gravies, and Mexican moles. Understanding the scientific process behind those beloved dishes can help cooks to both better appreciate them and learn science-backed techniques to make a sauce that is velvety and clings to pasta.

How sauces stay together

Whether a dispersion separates or becomes stable and uniform is set by the physics of the interfaces between the sauce's components, such as fat droplets and the surrounding water. The pressure difference between the interior and exterior of a curved droplet interface is proportional to the surface tension, which reflects the tendency of the interface to minimize its area, and is inversely proportional to the droplet radius. Small droplets with high pressure differences are unstable and tend to merge into larger ones, which pushes the sauce's components to separate.

Two strategies can counter the component separation effect and stabilize the dispersion. The first is to introduce ingredients such as emulsifiers, which hinder droplet merging and adsorb at oil–water interfaces to lower surface tension. The second is to vigorously mix the sauce to maintain a small droplet radius. Starch, such as that released into water by boiled pasta, helps stabilize the dispersion through a complementary mechanism. Once heated above their gelatinization temperature, starch granules swell and release sugars, which form a loose network that slows the drainage of thin liquid films between droplets and reduces their likelihood of merging. Gelatinization takes place when dry pasta becomes soft after boiling.

Rheology is another factor that helps explain the texture and viscosity of sauces. When a sauce is stirred or poured, the key quantity is the effective viscosity, which is a measure of a fluid's resistance to deformation under shear. In many sauces, it is beneficial for viscosity to decrease as the shear rate increases. That behavior allows the sauce to spread easily during mixing, when shear rates are high, yet cling to the pasta at rest, when shear rates are low. In the kitchen, starch and pectin are practical ingredients that change a sauce's effective viscosity.

Many of the interfacial and rheological effects are strongly influenced by temperature. Heat drives nearly every transformation in a sauce: It reduces viscosity, promotes mixing, swells and gelatinizes starch, melts fats, and unfolds proteins. Yet it also increases the risk of destabilization through aggregation, a process in which unfolded proteins come together to form clumps.

The strategy for a cook, then, is to move through different temperature windows rather than rely on a single one. Higher temperatures are essential at the onset of sauce preparation, as they allow fats to melt and starches to gelatinize, enabling the thickening and mixing of components that stabilize the sauce. But finishing the sauce off the heat allows it to reach its final texture and coat the pasta evenly. A classic example is the technique of mantecatura, used in pasta dishes and risotto, in which the dish is rapidly stirred off heat while fats from cheese and butter are incorporated to create a creamy consistency. At that stage, emulsifiers and stabilizing particles coat dispersed droplets without triggering protein aggregation, while tossing and stirring help both reduce droplet size and incorporate air to enhance the sauce's texture. Managing temperature in deliberate stages is therefore one of the most reliable ways to achieve a cohesive, well-balanced sauce.

Into the kitchen

Depending on its ingredients, every sauce will have its own challenges. Protein-rich sauces can experience denaturation, a process in which proteins lose their functional structure and aggregate. A prime example is cacio e pepe, a classic Italian dish made with pecorino cheese and black pepper, in which the smooth cheese-based sauce evenly coats the pasta. Pecorino cheese contains whey proteins and casein, which at low to moderate temperatures can adsorb at the interfaces between fat and water droplets and thereby stabilize dispersions.

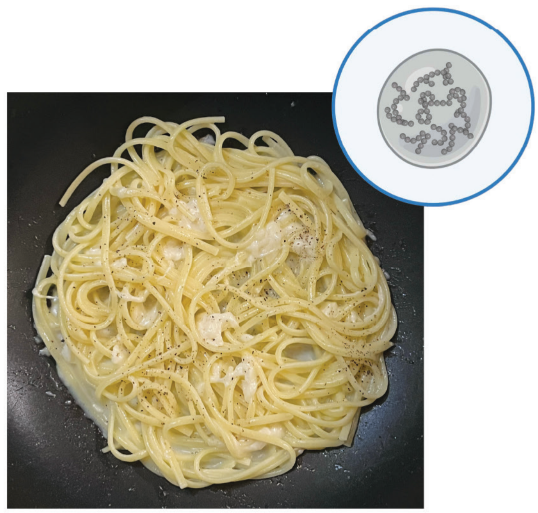
If present in sufficient amounts, gelatinized starch increases effective viscosity and helps confine fat- and protein-rich droplets; those effects suppress collisions and phase separation. As a result, the sauce remains smooth and cohesive as it coats the pasta, even at elevated temperatures. Panel (a) of the figure shows a cacio e pepe with a velvety sauce clinging to the pasta. Casein is relatively heat stable, but temperatures above about 65 °C can promote protein aggregation and the loss of emulsifying action in cheese-rich mixtures. If the sauce encounters nearly 100 °C pasta without enough starch to provide stabilization, the result can be visible clumping and a stringy sauce, such as the one shown in panel (b) of the figure.

Another famous pasta dish, carbonara, is traditionally prepared with egg yolks, pecorino, and guanciale (cured pork jowl). The sauce's stability relies on molecular emulsifiers, primarily lecithin and yolk proteins, that lower interfacial tension and coat dispersed fat droplets. (The same mechanism is responsible for stabilizing mayonnaise.) The mechanism is rapid and efficient but sensitive to heat. Above 65 °C, yolk proteins coagulate as a result of the yolk's lecithin losing its emulsifying properties, and the emulsion can fail. Failures tend to result in a grainy or greasy texture rather than the dramatic curdling seen in cacio e pepe.

Interfacial and rheological principles also extend to sauces with garden-grown ingredients. Tomato sauces, for example, are polymer-rich dispersions in which pectin, sugar, and other dissolved solids increase viscosity. Evaporation during the cooking process and the addition of starchy pasta water can enhance coating by further increasing effective viscosity. Pesto, on the other hand, behaves as a particle-stabilized dispersion, where nut fragments, herbs, and grated cheese accumulate at oil–water interfaces during mixing and

a)

b)



▲ Visualizing stabilization in cacio e pepe, a traditional Italian sauce made with pecorino cheese and black pepper. **(a)** A velvety sauce has gelatinized starch, which forms a viscoelastic network that traps dispersed fat and protein (as depicted in the inset) and maintains a smooth, cohesive texture. **(b)** A separated sauce has clumping caused by protein aggregation (visualized in the inset) at high temperature. (Panel (a) photo by Simone Frau; insets created using BioRender.)

form a weak network that slows the growth of large oil drops.

Perfecting, not by accident

Even for cooks who understand the science behind an expertly executed sauce, things can go wrong. Knowing how to identify problems in a sauce can make it possible to deploy targeted fixes. Loss of gloss indicates inadequate interfacial coverage—in other words, the effective surface tension is too high to prevent oil droplets from merging into visible oil beads. A cook can remedy that problem by applying moderate shear through mixing the sauce with a spoon and adding small amounts of an emulsifier, such as a knob of butter, or a gelatinized starch. Grainy clumps are a signature of protein aggregation caused by excessive heat. To fix that, a cook should return the sauce to a lower temperature window, gently dilute it with starchy water to separate the aggregates, and mix it again to restore a smooth dispersion. When those adjustments fail, a blender can provide the needed shear.

Bound together, the ideas in this article provide a compact guide for making perfect sauces. Whether cooking aglio e olio, pesto, or another sauce, cooks can achieve the desired consistency by following scientifically reproducible cooking techniques.

We thank the coauthors of and contributors to our 2025 Physics of Fluids *paper on cacio e pepe phase behavior for their help and support.* **PT**

Additional resources

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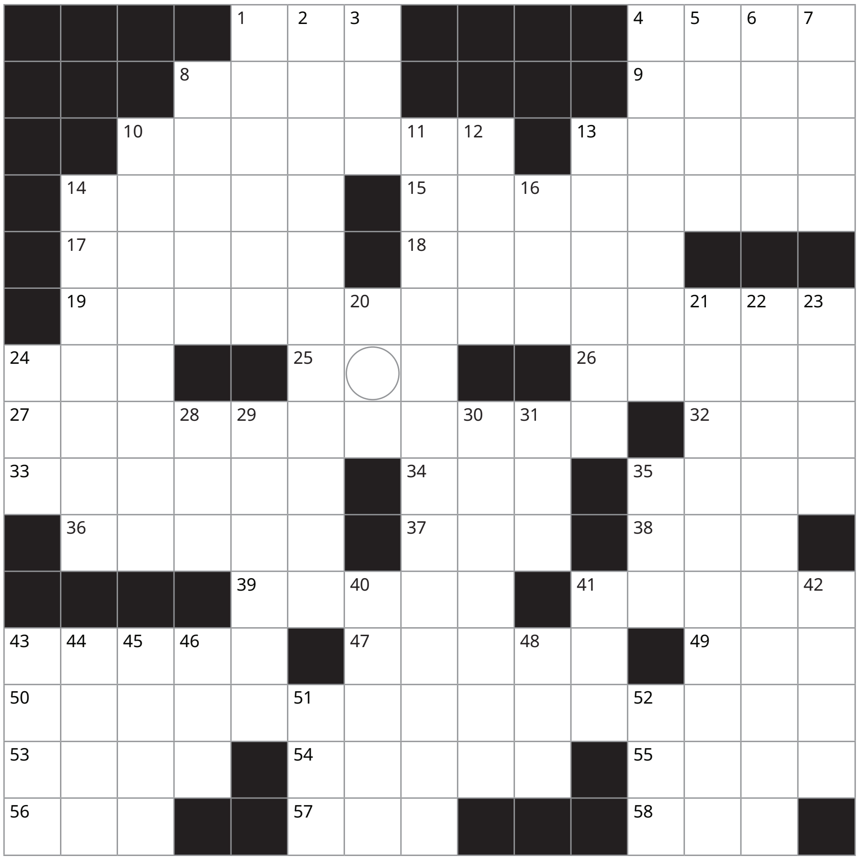
CROSSWORD



X marks the spot

By Doug Mar

ACROSS

1 Mil. command centers
4 Two-masted sailboat
8 Spell (such as of the flu)
9 Et ___ (and others)
10 Dishes steamed in corn husks
13 Steep slope
14 Made a mistake
15 Location where a rogue wave (over 25 meters high) was first confirmed with scientific evidence
17 Country whose flag features an orange Sun in the center
18 Hail
19 Techniques for creating illusions
24 Tour de France mo.
25 Super Bowl that will be played in 2027
26 The *A* in radio astronomy's VLA
27 An aspiring actor might receive one
32 Freshly squeezed drinks, for short
33 Martial arts teacher
34 Amateur radio operator
35 ___ were
36 Fashionably old fashioned
37 Coffee cup
38 Sound of disapproval
39 MacGyver's first name on *MacGyver*
41 Indian honorific
43 Circa
47 Old enough
49 Sch. in Tempe
50 What the circled square marks, vis-à-vis this puzzle's dark squares
53 Tease
54 Most common Wordle starting word, according to *The New York Times*
55 Investment options, for short
56 Barely manage, with "out"
57 Web portal with a butterfly logo
58 ID on an IRS form

DOWN

1 Skills class rebranded as "family and consumer sciences," familiarly
2 Number whose log base 10 is equal to 15
3 Letters on a Cardinals cap
4 America's Cup participant
5 Sorry to say
6 Filament
7 Grammy-winning Dua
8 Vessel used by the US Navy in World War II for production and delivery of ice cream
10 Aircraft for the Red Baron
11 Component in eggs Benedict
12 Peeved
13 One of two physicists associated with a T^4 blackbody radiation law
14 Guarantor
16 Sports official, informally
20 Weapon associated with the King of Diamonds
21 What some squares nearest the circled one resemble
22 Its largest city is Dushanbe, meaning "Monday"
23 Part of GPS (abbr.)
24 Law degs.
28 Clock setting for ETAs at PHX
29 Make fizzy
30 Pizza topping
31 Texter's "Wow!"
35 One thing ___ time
40 Merchandise
41 First verse's last word in "America the Beautiful"
42 Is willing to believe
43 Area unit equal to $\frac{1}{640}$ of a square mile
44 Bill
45 Six + cinq
46 Snack food brand
48 Dad to Margo, Edith, and Agnes
51 Farm butter?
52 Word that appears twice in one of this puzzle's clues

Trees can glow during thunderstorms

By Alex Lopatka

The purple light emanating from these spruce needles is emitted by weak electric discharges. Patrick McFarland of the Pennsylvania State University and colleagues placed a branch of a spruce tree below a charged aluminum plate and grounded it with a metal wire. The electric field formed by the two metals' attraction has a strength that is about 1/5 of that of fields required for lightning. In response to the field, an electric charge travels up the branch to the tips of the leaves, where it is released into the air.

The glow of the branch's leaves is a laboratory demonstration of Saint Elmo's fire, a phenomenon that has long been seen, for example, during thunderstorms by sailors on ship masts and pilots on aircraft. Yet despite decades-old discussions in the scientific literature, researchers did not confirm that electric discharges can form on tree leaves during thunderstorms until 2024. That summer, McFarland his adviser, William Brune, drove a minivan retrofitted with monitoring equipment into the path of a thunderstorm in North Carolina. They observed with a telescope UV radiation emitted from the canopies of two trees and then focused the radiation on a UV-sensitive camera.

The discharges measured in North Carolina lasted one to three seconds and corresponded to currents of about 1 μA. The phenomenon, if widespread in forests during thunderstorms, could affect atmospheric chemistry. McFarland and colleagues are interested in studying the discharges' production of hydroxyl radicals, which oxidize greenhouse gases and thus decrease how long the atmospheric-warming gases reside in the air. (P. J. McFarland et al., "Corona discharges glow on trees under thunderstorms," *Geophys. Res. Lett.* **53**, e2025GL119591, 2026; image courtesy of William Brune.) PT

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