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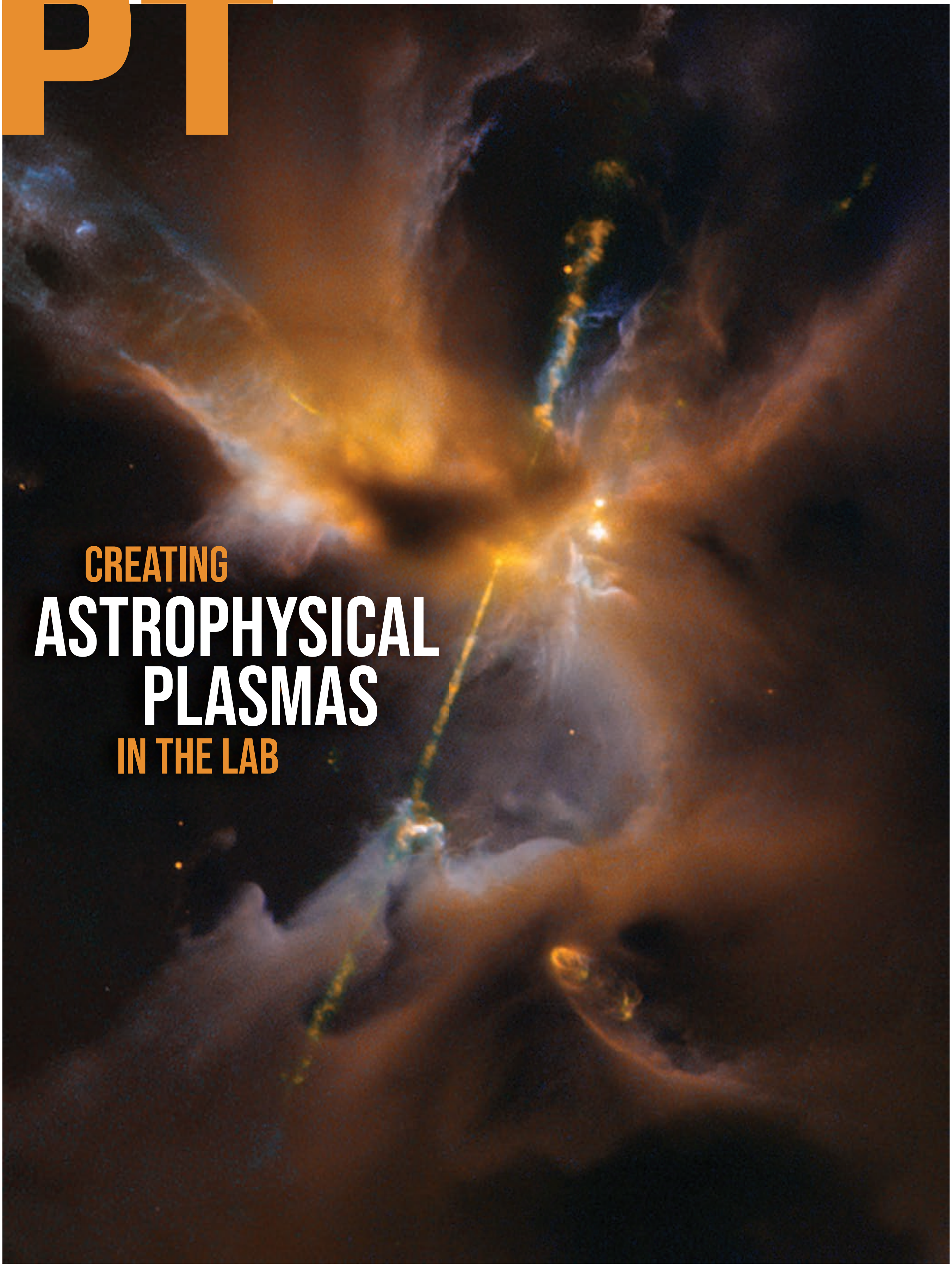

CREATING ASTROPHYSICAL PLASMAS IN THE LAB

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FEATURES

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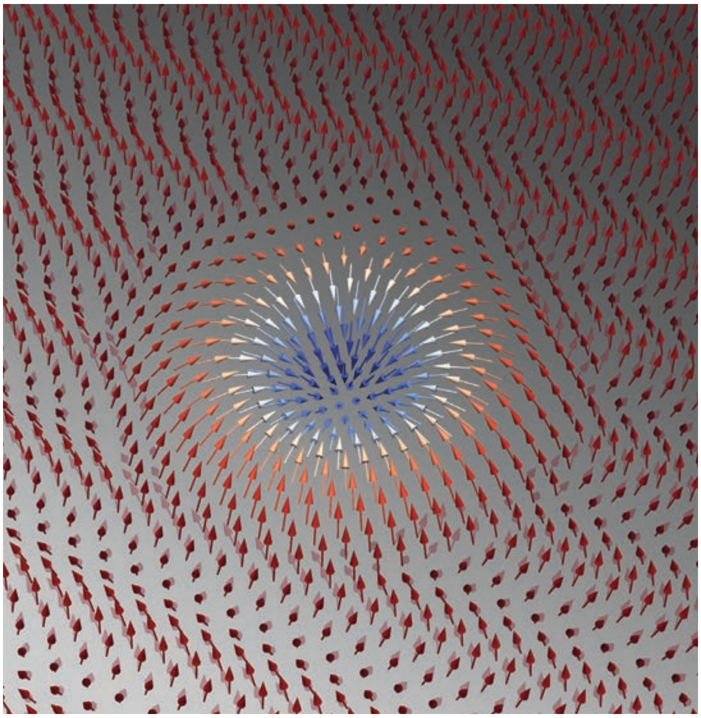

DEPARTMENTS

ON THE COVER

Two narrow jets of plasma erupt from a newborn star found in the constellation Orion in this *Hubble Space Telescope* image. The jets together are 10^{13} m long and may form when matter in the star's accretion disk interacts with the strong stellar magnetic field. One approach to studying the essential physics of the jets is for researchers to create millimeter-sized versions in the lab. The making of energetic, magnetized plasmas in the lab is discussed in the article by Jack Hare on **page 30**.

(Image from NASA, ESA, *Hubble* Heritage/*Hubble*-Europe Collaboration, D. Padgett, T. Megeath, and B. Reipurth.)

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TO READ ABOUT NCAR'S ROLE IN THE ATMOSPHERIC SCIENCES, TURN TO PAGE 18

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Coherent x rays generate equally spaced ultrafast pulses

The adaptation of Nobel Prize–winning optics work to the x-ray regime brings new capabilities to the free-electron laser.

By Alex Lopatka

One of the most effective tools that researchers have to study small and fast particles and processes is the x-ray free-electron laser (XFEL). The extremely bright, ultrashort pulses of light resolve phenomena such as the folding of proteins, the motion of electrons, and the progression of chemical reactions at the attosecond time scale—a billionth of a billionth of a second. (To learn more about XFELs and their applications, see the 2015 *PT* article "Brighter and faster: The promise and challenge of the x-ray free-electron laser," by Phil Bucksbaum and Nora Berrah.)

Despite the many capabilities of XFELs, their light pulses are only partially coherent. The limitation means that individual pulses are randomly distributed in time and in their energies. (Some XFELs use seeding techniques to improve the coherence but not in the ultrafast time domain.) If XFEL light could be mode locked, periodic

Figure 1. Undulator modules (blue) of the x-ray free-electron laser facility at the Paul Scherrer Institute in Villigen, Switzerland, generate magnetic fields. They slightly deflect the incoming x-ray electron beam to generate partially coherent femtosecond light pulses. Between each of the modules, researchers added a chicane—a group of four dipole magnets—to further deflect the electrons. The additional delay created by the longer path the electrons had to take increased the coherence of the laser output. In combination with a modulating external laser, the setup resulted in trains of periodic, phase-correlated attosecond x-ray pulses. (Photo courtesy of the Paul Scherrer Institute PSI/Markus Fischer.)

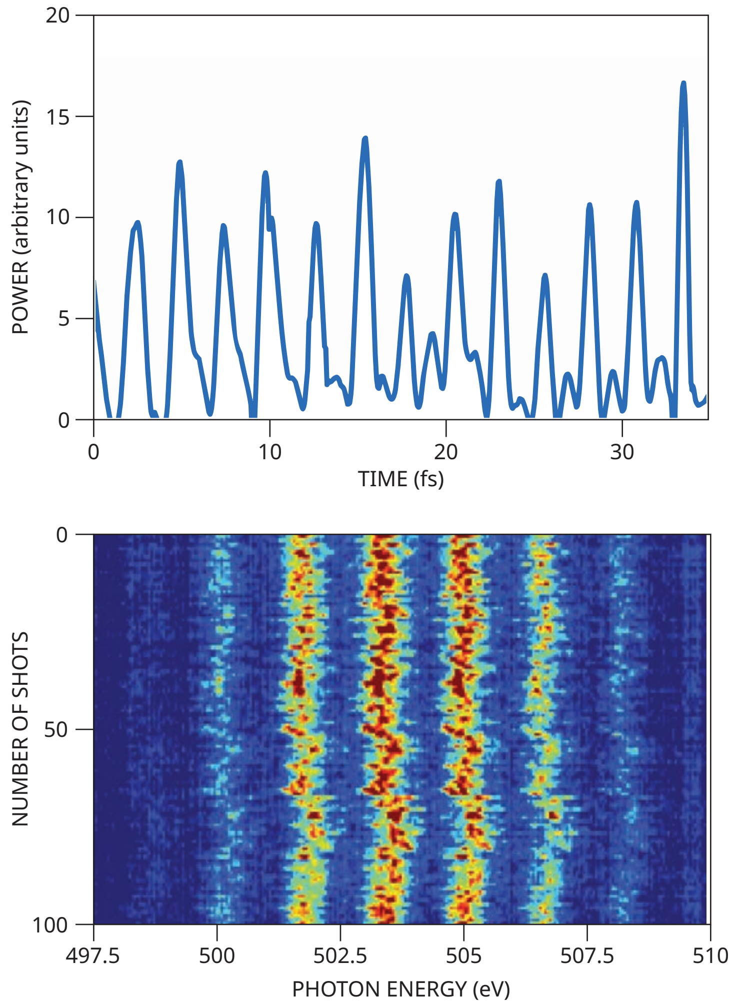

Figure 2. Periodic, phase-locked attosecond pulses were recently generated at the x-ray free-electron laser at the Paul Scherrer Institute in Villigen, Switzerland. The reconstructed temporal profile **(top)** shows that the attosecond pulses are equally spaced a few femtoseconds apart from one another. The frequency comb **(bottom)** is produced from 100 consecutive single laser shots. The normalized spectral intensity ranges from low (blue) to high (red). The demonstration at x-ray wavelengths is analogous to the optical frequency comb, which was first developed at visible to IR wavelengths in 1999. (Plots adapted from ref. 1 and courtesy of Wenxiang Hu.)

trains of ultrashort pulses could be generated. That would provide researchers with a tool analogous to the optical frequency comb, which is critical for experiments with optical clocks, high-precision spectroscopy, and other applications.

Now Eduard Prat of the Paul Scherrer Institute in Villigen, Switzerland, and colleagues have achieved that goal for XFELs by coaxing the x-ray light to generate equally spaced periodic pulses in time.[1] The mode-locked scheme, which was accomplished at the institute's SwissFEL user facility, is the first demonstration of its kind. The new result expands the capabilities of XFELs and may make them useful in new ultrafast applications.

Finding signals in the noise

A regular laser emits light by first stimulating emission from atomic or molecular excitations and then forcing the emission to bounce back and forth through a gain medium to become amplified. A free-electron laser operates similarly but uses relativistic electrons as the gain medium instead of atoms or molecules.

As the electron beam is driven though a linear accelerator and an undulator structure of alternating dipole magnets, the electrons wiggle and interact with the radiation they produce. The constructive interference causes electrons to group into microbunches that emit coherent light.

The method works well with optical cavities for free-electron laser facilities that operate in the far-IR to visible wavelength range. For x rays, however, suitably reflective mirrors are hard to come by, so constructing an optical cavity is extremely challenging. High-power, tunable x-ray laser light can be generated with a single-pass approach. Self-amplified spontaneous emission (SASE) was first studied in the early 1980s,[2,3] and it's what most of the handful of XFEL facilities in the world have settled on.

In SASE, the electron beam initially emits photons in a haphazard, incoherent cluster. As the electrons travel through the undulator structure, they gain or lose velocity as they interact with emitted photons that are in or out of phase with them. If the undulator structure is long enough, at least dozens of meters, the electrons can form microbunches and generate intense pulses on the femtosecond time scale. Figure 1 shows several of the undulator modules at the SwissFEL.

Borrowing from laser optics

In 1999, Theodor Hänsch and colleagues demonstrated that a mode-locked laser can generate a train of equally spaced femtosecond pulses in the visible to IR wavelength range.[4] The advance was achieved by stabilizing the relative phases in the train of pulses. During stabilization, the light waves that form in an optical cavity remain in phase with one another and constructively interfere in time.

In the frequency domain, the narrow, well-defined spectral peaks of the laser output resemble the teeth of a hair comb. (For more on how optical frequency combs were first produced, see the *PT* story "Glauber, Hall, and Hänsch share the 2005 Nobel Prize in Physics.")

Frequency combs are critical for synchronizing large astronomical radio-telescope arrays, better understanding quantum communications, and other applications. Frequency combs are also related to high-harmonic generation, which is the idea that underlies the creation of attosecond pulses of light from tabletop sources. (For more about that research, see the 2023 *PT* story "Attosecond pioneers win physics Nobel.")

By 2008, researchers proposed that the mode-locking technique from laser optics could be implemented in free-electron lasers.[5] The technique starts with a series of magnetic chicanes. Each chicane is a group of four dipole magnets that slow the electrons with respect to the photons; the delay allows for the production of the axial laser modes that are needed to generate a frequency comb.

Next, the photon emission is periodically modulated by an external laser with a wavelength tuned to 263 nm or 790 nm, both of which match the mode spacing set by the chicanes. The laser, therefore, effectively organizes the random SASE noise into a train of equally spaced pulses of just a few hundred attoseconds each.

Generating coherent light

When the mode-locking theory paper was published in 2008, XFELs weren't yet operational. "Many people thought SASE would not work," says Prat, "because you need a very high brightness electron beam and a very precise control of the undulator." A year later, the first XFEL facility—Stanford University's Linac Coherent Light Source—began operation. After that, researchers spent years focused on generating light pulses on the femtosecond time scale by tweaking the SASE technique to be more effective and increasing the brightness of the x rays.

The goal of creating a mode-locked XFEL proved challenging. In 2024, Prat and colleagues published a paper describing the implementation of magnetic chicanes at the SwissFEL. The chicanes induced equal, periodic delays of a few femtoseconds between the electrons and their radiation. Although the result was encouraging—the researchers succeeded in generating a frequency comb—the structure of the light in the time domain was still random.[6]

For the 2025 paper, Prat and colleagues added an external laser to stabilize the x-ray emission and generate a periodic train of attosecond pulses in the time domain. Prat says that "the true challenge was the temporal measurement." To prove that the frequency comb exists and measure the train of attosecond pulses, the researchers needed a device capable of resolving the ultrafast time structure of the x-ray beam. Typically, that's done with an RF deflector, which bends the electron beam in the transverse direction and allows for the time profile of the bunch to be measured. But almost all RF deflectors have been limited in resolution to about 1 fs.

To make measurements at subfemtosecond resolution, Prat and colleagues maximized the power of their RF deflector and almost doubled the width of the electron beam at the deflector. With those upgrades and the modulating laser, Prat and colleagues demonstrated at the SwissFEL a mode-locked frequency comb with a periodic time structure.

For the first time, ultrafast x rays had equally spaced light pulses. Figure 2 shows plots of the controlled x-ray light in the time and frequency domains.

Coauthor Sergio Carbajo of UCLA says that "we're in the nascent stage of what we can do with mode-locked XFELs." One possibility is the ultrafast detection of atomic and subatomic particles and their configurations, which could reveal new isotopes.

Another application is measuring inner-core electrons and their dynamics at subangstrom spatial and attosecond temporal resolution. The observations, Carbajo says, could be critical to the study of several research areas, including cellular aging, surface catalysis, and quantum electrodynamics. **PT**

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The new math of network optimization, courtesy of string theory

Modeling the shapes of tree branches, neurons, and blood vessels is a thorny problem, but researchers have just discovered that much of the math has already been done.

By Johanna L. Miller

Social networks, neural networks, computer networks: So many of the things we mean when we talk about networks are abstract or virtual structures, characterized by the mathematical connections among nodes rather than their physical arrangement in space. When physicists have joined the interdisciplinary field of network science, those are the types of systems they've tended to focus on. But in the past few years, some have turned their attention to physical networks, such as real neurons (depicted in figure 1) and blood vessels, and researchers have asked, Why do those structures have the shapes that they do?

Some possible answers can be ruled out. For example, one might guess that networks grow in a way that minimizes the total length of the links needed to connect a set of points in space. But it can be proved that, if that were true, network links would always join at

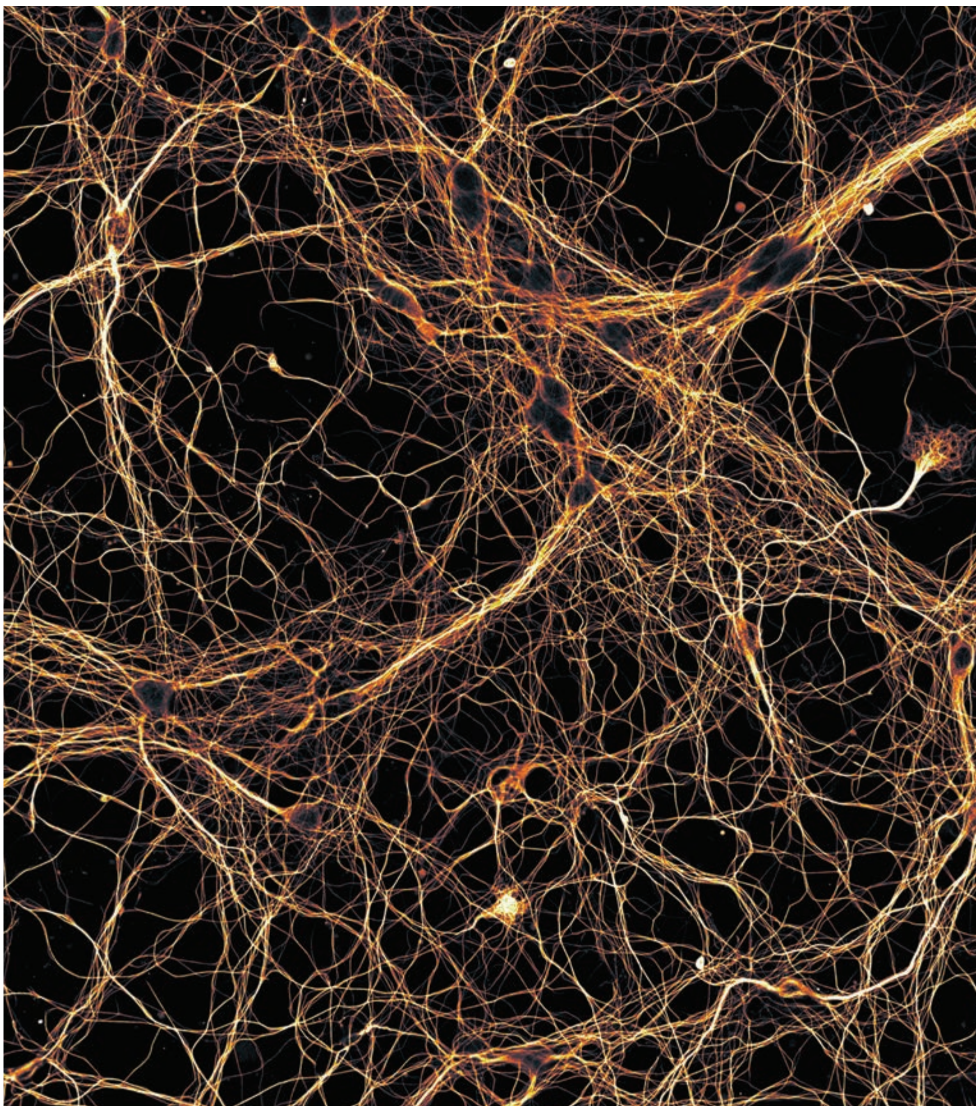

Figure 1. Real neurons, such as the ones shown here from a rat's hippocampus, are an example of a physical network whose structure is constrained by material resources. Examining the constraints can lead to insights into network geometry. (Image by MikeRoscopy/Wikimedia Commons/CC BY 4.0.)

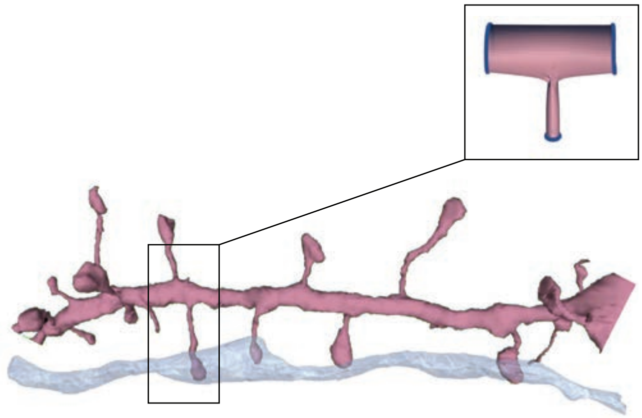

Figure 2. Orthogonal sprouts—thin network branches that emerge from a much thicker straight spine—are predicted by the surface-minimization hypothesis, and they appear in many real physical networks. (Image adapted from ref. 1.)

planar, 120° junctions—and they don't. Now Albert-László Barabási, of the Network Science Institute at Northeastern University in Boston, and colleagues have found that physical network structures can be better explained by a different hypothesis: The networks seek to minimize not their length but their surface area.[1]

It's easy to see why surface area should be the most relevant quantity for networks of blood vessels and other tubelike structures that are nothing but surface area. For other systems, such as tree branches and nerve cells, the outer surface of a network link is often the most biologically expensive to construct. In testing the hypothesis, however, the researchers hit a wall: Calculating the surface-area-minimizing network structure is a computationally intractable problem. There are too many possibilities for the thickness and position of all the network branches, and it's too difficult to exactly model the junctions where branches smoothly join together.

But then Xiangyi Meng—Barabási's collaborator and former postdoc, now on the faculty at Rensselaer Polytechnic Institute—made a critical discovery: String theory, he realized, had already grappled with a mathematically equivalent problem. In string theory, reactions among elementary particles are represented as continuous branched manifolds called worldsheets, which evolve in a way that minimizes their surface area. Exactly solving the surface-minimization problem is just as intractable for string theorists as it is for network theorists. But the string theorists had a decades-long head start, and they developed mathematical tools to find useful approximate solutions.

By piggybacking on the string-theory solution, Barabási and colleagues calculated what the surface-minimizing physical networks should look like, and the features they found agreed well with observations. For example, they found that networks under a wide variety of conditions should contain the structures in figure 2, which they call orthogonal sprouts: thin tubes that emerge at a 90° angle from a straight, much wider tube. Orthogonal sprouts don't show up in most other network models. But they appear in many real-life networks, including corals, fungi, blood vessels, and tree roots. PT

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Data reanalysis throws existence of an ocean on Titan into question

The finding that the Saturnian moon may host layers of icy slush instead of a global ocean could change how planetary scientists think about other icy moons as well.

By Sarah Wells

Saturn's largest moon, Titan, boasts mountains carved from ice and meandering rivers filled with liquid ethane and methane. During its visit to the Saturn system between 2004 and 2017, the *Cassini* spacecraft collected not only that data (see figure 1) but also other information that many researchers interpreted as evidence for a buried global ocean. As Titan orbits Saturn, the moon is stretched in a process called tidal flexing, which is the result of the planet's strong gravitational field and the moon's changing distance from its host. Researchers analyzed the Doppler shifts in *Cassini*'s radio signals from when the probe orbited the moon and concluded that the push and pull that Titan experiences is possible only if the moon has a liquid interior, as opposed to an inflexible solid one. That conclusion put Titan in good company with other suspected ocean moons, like Jupiter's satellite Europa, and supported the idea that oceans on icy moons may be common.

But not all the Titan data fit that picture. The push and pull on Titan from Saturn's gravitational field can be quantified by the tidal Love number. Some analyses of the data have found that number to have high values, which would support a global ocean; others have found low values. None of the analyses could isolate an imaginary component of the Love number that describes the shear energy dissipation in Titan's interior. Flavio Petricca and colleagues at NASA's Jet Propulsion Laboratory and other institutions in the US and Europe set out to conclusively measure Titan's Love number by reanalyzing *Cassini*'s data with modern data-processing techniques, including phase-averaging algorithms that had been used to remove noise from Mars's rotation data collected by NASA's *InSight* lander.

Petricca and colleagues found that the data supported a large Love number. But they also showed a value for the moon's shear energy dissipation that was much larger than they would expect for a body with a liquid ocean.[1] After refining a model, the researchers inferred that what's under Titan's more than 150-km-thick ice shell is not an ocean but rather a churning, slushy mix of hydrated rock, semi-melted ice, and pockets of meltwater, as shown in figure 2. The convection of heat generated by tidal flexing circulates pockets of meltwater and potentially moves materials like silicates or even organics to the moon's surface. Although Titan may lack a global ocean, the volume of all the liquid water trapped in the ice could be equivalent in volume

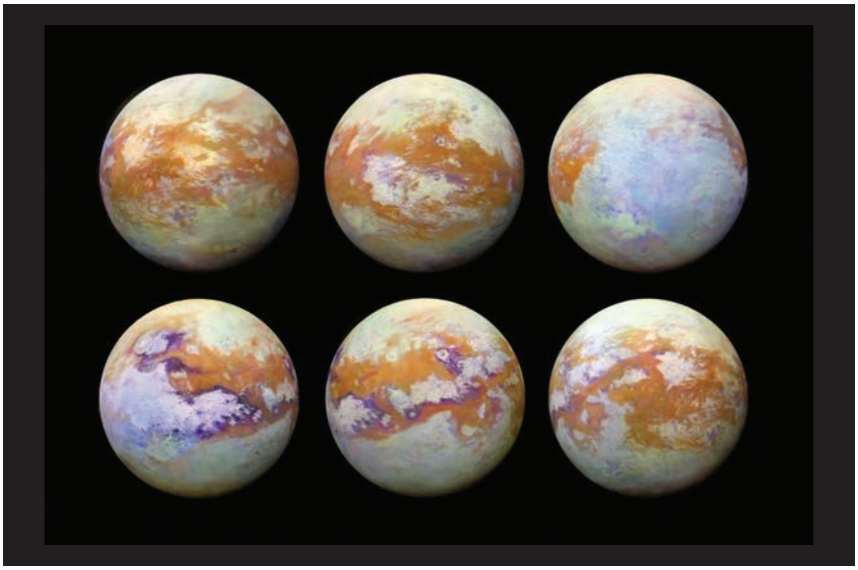

Figure 1. These detailed photos of Saturn's moon Titan were created from data collected by the *Cassini* probe, which started observing the moon in the early 2000s. (Photos by NASA/JPL-Caltech/University of Nantes/University of Arizona.)

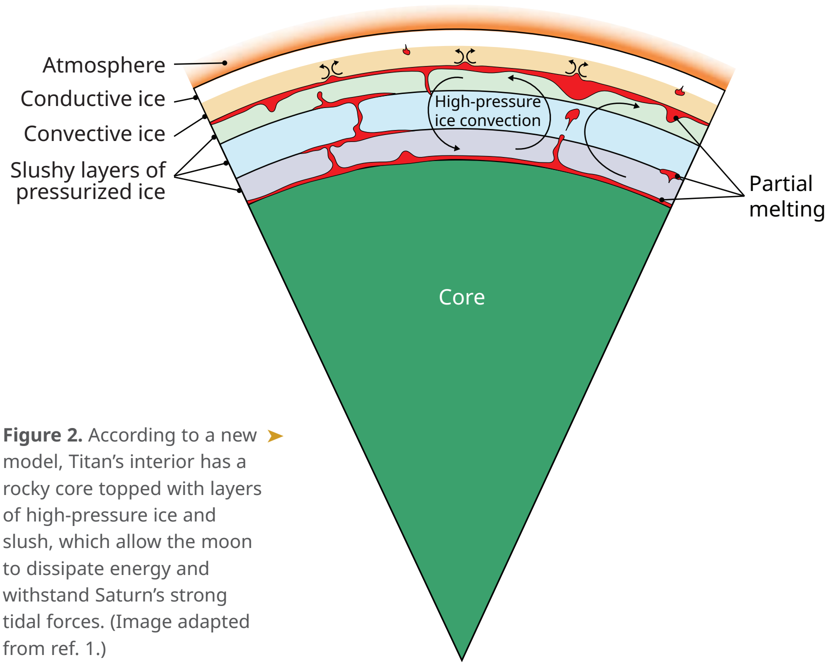

Figure 2. According to a new model, Titan's interior has a rocky core topped with layers of high-pressure ice and slush, which allow the moon to dissipate energy and withstand Saturn's strong tidal forces. (Image adapted from ref. 1.)

to the Atlantic Ocean. The researchers say a slushy environment may be better for the prospect of life than a global ocean.

The research team doesn't yet understand how Titan's hydrosphere could have become slushy. One possibility is that a collision or other perturbing event in the Saturn system in the past 100 million years shifted Titan's orbit and potentially the moon's ability to support a subsurface ocean. Understanding Titan's hydrospheric history could also provide insight into what it takes for oceans to develop or be maintained on icy moons.

Researchers do not have the wealth of gravitational data for other moons that they do for Titan, but that will be changing in the 2030s. The European Space Agency's *Juice* and NASA's *Europa Clipper* are on their way to study Jupiter's icy moons. As for Titan, NASA's *Dragonfly*, a first-of-its-kind rotorcraft mission, is slated to explore multiple locations on Titan's surface and, as part of its objective, try to detect icequakes, whose seismic activity would be dampened if an ocean exists. **PT**

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Philanthropies selectively mitigate damage from lost federal science funding

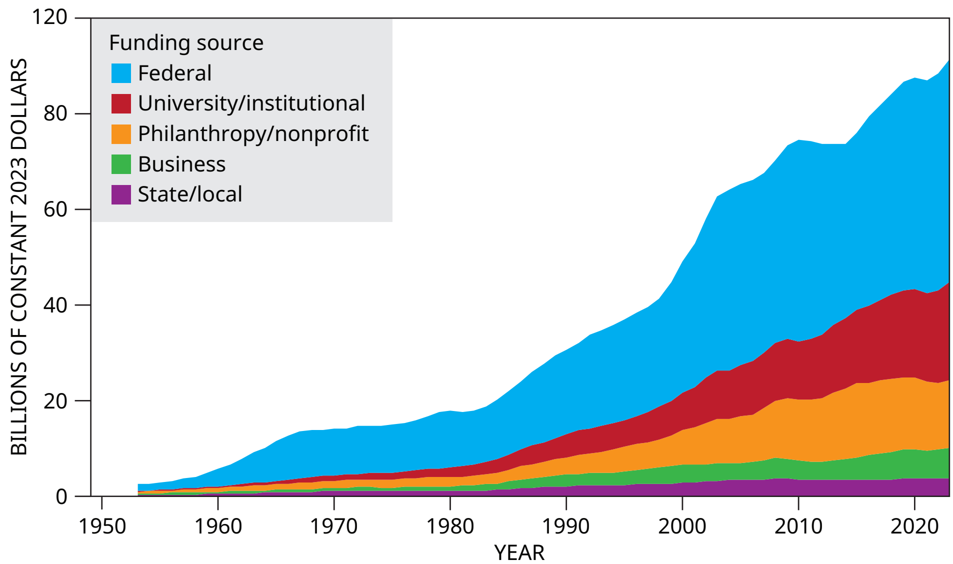
They are focusing on early-career scientists and on vulnerable areas like climate.

By Toni Feder

Since President Trump regained the White House in January 2025, cuts to and uncertainty about federal science funding have led to reductions in hiring for research; panic about paying students, postdocs, and technicians; the dissolution of projects; and scrambling for funds. As a result, science philanthropies are seeing increased demand for their resources. In response, they are creating programs to retain early-career researchers, continue threatened projects, and keep research directions open. But philanthropies caution that they can "fill gaps, not gulfs," as Harvey Fineberg, retired president of the Gordon and Betty Moore Foundation, puts it.

What philanthropies can do best is "de-risk" research by funding ideas that may not work or that might not be funded by government or industry, says Cynthia Friend, president of the Kavli Foundation. "Researchers need a proof of principle before their work is viable for federal funding," she says. At the Kavli Foundation, "we try to strategically fund research that has a potential for transformative impact."

Philanthropic giving from foundations and other nonprofits accounted for about 15% of funding for US basic and applied research at universities and nonprofit research organizations in 2023, according to the most recent figures from the Science Philanthropy Al-



Funding for basic and applied research at US universities and research institutions reached nearly $115 billion in 2023, the most recent year for which data are available. About 15% of that was directly from philanthropic foundations and nonprofits; including legacy philanthropy, such as from university endowments, that number goes up to about 21%. Those and related data are available in an interactive format in the 2025 *Science Philanthropy Indicators Report.* (Data from NSF's National Center for Science and Engineering Statistics; figure adapted from the 2025 *Science Philanthropy Indicators Report*.)

Researchers convene at the University of Chicago in summer 2025 to work on ultraquantum matter, in a collaboration funded by the Simons Foundation and the Simons Foundation International. Applications to such philanthropy-funded activities are rising as US federal funding has become rockier. (Photo by Ashvin Vishwanath, Harvard University.)

liance. In a survey it conducted last year, says Kate Lowry, the alliance's strategy director, nearly 80% of the respondents said they were changing or considering changes to their grant making in response to shifts in federal science funding. For example, some philanthropies awarded extensions for current postdocs and graduate-student grant recipients.

"Philanthropies have always been in the business of funding areas that others are not supporting," says Fineberg. Typically, he says, they look for niche areas, specific needs, and frontier science. "In light of the current funding environment," he continues, "every philanthropy that is involved in science has had to ask itself, Where do we invest?"

Helping younger generations

The biggest impact of the uncertainty in federal funding so far "is nervousness in the scientific community," says Gregory Gabadadze, a professor at New York University and the Simons Foundation's senior vice president for physics. The foundation, he says, saw a huge increase last fall in applications to all its programs in math and the physical sciences. "It's not clear how to deal with that situation," he says. "But the foundation leadership will allocate more funds than usual to support the best of them."

In its new Simons Empire Faculty Fellowship program, the foundation is awarding research institutions in New York state a total of $45 million to hire 55 junior faculty into tenure-track positions in mathematics, physics, neuroscience, and ecology and evolution. The foundation will pay the new hires' salaries for three years. The program is intended to thaw the hiring freezes adopted by many institutions. "That will help younger generations," says Gabadadze. The foundation is also increasing the number of awards to collaborations and to well-established institutions that reach out to researchers from less-supported places. Those two programs are getting funding bumps of $30 million and $3.7 million, respectively. The Simons Foundation and the Simons Foundation International have a combined annual budget for math and physical sciences that fluctuates around $100 million, Gabadadze says.

For its part, the Moore Foundation has boosted funding for early-career researchers. "We thought the postdoc period was important and vulnerable," says Fineberg. The foundation set aside $55 million—of more than $210 million it spent on science in 2025—for some 400 postdoctoral researchers across 25 fields.

The University of Washington is among the 30 universities that are benefiting from the Moore Foundation's support for postdocs. With a $2.5 million gift, "we ended up being able to provide funding for 16 postdoctoral fellows for periods of 9 to 24 months," says Cecilia Giachelli, an associate vice provost at the university. "What is huge is that people can complete their projects. The postdoc is a key time for a researcher's career stability. The money will help us retain them."

Being catalytic

Smaller foundations are also adjusting their giving. Some are specifically funding areas, such as climate-change research and underrepresentation in science, that have been targeted by the Trump administration.

The Kavli Foundation is expanding a program it created in 2022 to help scientists whose research has been disrupted. For example, it has supported scientists from Ukraine who were displaced by Russia's invasion of their country. Now, says Friend, the program is helping several US-based scientists whose work has been disrupted by funding interruptions. The number of fellowships, she says, is increasing from 5 to up to 20. The program, she adds, focuses on early-career scientists and "can help bridge to the future."

The Research Corporation for Science Advancement tries to be "catalytic" with the $11 million it distributes annually, says Andrew Feig, a senior program director at the organization. In December, it gave a total of $800 000 to 11 current and past awardees who had lost funding or whose funding had been delayed. "We couldn't put a finger in the dike for all of the need," he says. "We triaged the applicants to see who had the most critical need and was experiencing meaningful disruption. We looked to see that they were making longer-term changes to meet the new funding norm."

In mid-January, Congress passed a budget that is nearly flat—a far brighter outlook than Trump's proposed budget, which would have cut funding for basic and applied research by 37%, according to estimates by the Science Philanthropy Alliance. Even so, research funding will change, says Feig. "If you are not in the pillars that the administration is interested in—critical materials, quantum information, AI—you had better be ready to pivot if you want to maintain funding," he says. "Federal funding may be more tied to translational work that can quickly move into applications."

"The goodwill of rich people"

"We are in a tight situation," says Mark Raizen, an experimental physicist at the University of Texas at Austin, "and it's clear that private foundations cannot pick up the slack." Applying for federal money has become very frustrating in recent years, says Raizen, whose work on production and applications of isotopes is mostly funded by philanthropies. "Researchers write proposals and get rejections. It's discouraging for young scientists." Still, he notes, federal agencies will renew funding for good work, whereas "foundations don't fund continuously: Once you have proven something, it's not high risk anymore."

"Researchers are looking more desperately for opportunities," says David Kaplan, a theoretical physicist at Johns Hopkins University. He notes that he and his colleagues are lucky to have funding from Michael Bloomberg. But philanthropies and individual donors can be "idiosyncratic," he says. Giorgio Gratta, an experimental physicist at Stanford University, says he appreciates the contributions of philanthropies and individual donors to science, but "going back to rely on the goodwill of rich people—like before World War II—seems like a step backwards for a nation that has been a trendsetter in funding fundamental science." PT

What the National Center for Atmospheric Research means to the atmospheric sciences

Born out of a time of great need for the federal government, NCAR plays a role with few analogues.

By Jenessa Duncombe

News that the National Center for Atmospheric Research (NCAR) may be dismantled broke in December. A senior White House official told *USA Today* that the administration wanted to eliminate the center's climate-related work and transfer some functions elsewhere. It was the first that NCAR's parent organization, the University Corporation for Atmospheric Research (UCAR), had heard of the plans.

NCAR's main sponsor, NSF, confirmed the news and announced that it would evaluate how to "redefine the scope" of NCAR's modeling and forecasting to concentrate on areas like weather prediction, severe storms, and space weather. The agency also said it would explore options to transfer the stewardship of NCAR's supercomputer, two research aircraft, and Mesa Laboratory.

The outcry was immediate. The American Meteorological Society, along with the American Astronomical Society, American Physical Society, and 11 other scientific societies, sent a letter to the White House and another to members of Congress expressing their concern. (AMS, AAS, and APS are member societies of the American Institute of Physics, publisher of *Physics*

The National Center for Atmospheric Research's Mesa Lab in Boulder, Colorado. (Photo by C. Calvin, © University Corporation for Atmospheric Research, CC BY-NC 4.0, via OpenSky.)

Today.) A congressional outreach campaign led by the American Geophysical Union has so far tallied 37 000 emails and phone calls. Supporters of NCAR gathered in protest in Boulder, Colorado, where NCAR is based.

Many of the news stories that followed highlighted NCAR's scientific contributions. Other coverage emphasized the center's climate research. At times, news articles implied that NCAR was a stand-alone climate lab, even though only about 100 of the center's 800-some employees work in the climate division. (For more on NCAR's programs, see the 2017 *PT* article "Atmospheric research in the Rocky Mountain foothills.")

Despite all the attention that has been given to what NCAR does, there has been little discussion of what NCAR is. NCAR is an oddity in the scientific ecosystem: It's not a government lab, nor is it a university. It's a federally funded R&D center (FFRDC). NCAR is managed by a nonprofit consortium of universities, which sets it apart from many of the nation's FFRDCs. NCAR has been continuously funded by NSF since its beginnings, and it represents a Big Science mode of support that is envied by researchers in other fields.

NSF is in the process of deciding how to transform NCAR, and the community can weigh in by responding to NSF's Dear Colleague letter through 13 March. During this time of transition, it is worth exploring why NCAR is the way it is and what makes its role in its field unique. This picture came together via historical records, interviews with past NCAR and UCAR employees, and conversations with past and present collaborators with the center.

The backwaters of science

Atmospheric science in the US was not in a good place after World War II. About 90% of meteorologists were employed by the federal government, and few worked at universities. Meteorology was thought of as more of a trade than a science, and many people interested in science looked elsewhere. Between 1953 and 1957, an average of 10 meteorologists were awarded PhDs per year nationwide, according to a paper in the *Bulletin of the American Meteorological Society* by George Mazuzan, a former NSF historian.

Officials at the National Weather Service's predecessor, the US Weather Bureau, worried about an impending workforce shortage. A special committee of

A meteorologist adjusts an anemometer on a weather station, on a 1945 cover of the Army Air Forces *Weather Service Bulletin*. (Image from Headquarters Weather Wing Army Air Forces; courtesy of the family of Nels Johnson, US Weather Bureau [dec.].)

meteorologists convened in 1956 by the National Academy of Sciences considered solutions. The committee concluded that the lack of both academic departments and money to support them was preventing the realization of the discipline's potential. Simply awarding more small grants to university scientists or setting up localized research centers would not be adequate.

The committee argued instead for what NSF calls Big Science—large-scale research programs or centers funded by the agency. It recommended in 1958 that NSF sponsor a new, independent institute where internal interdisciplinary scientists would join those from academia and government to tackle global problems. It was a lofty goal, and NSF signed a contract with UCAR to start NCAR in 1960. NSF has been its main sponsor ever since.

Over time, meteorology was broadened into the atmospheric sciences, which synthesizes meteorology with many other disciplines, including engineering, physics, chemistry, math, and astronomy. Smaller-scale funding grew too. The number of universities receiving grants for meteorology or atmospheric sciences increased sixfold from 1958 to 1962, according to Mazuzan. From 1959 to 1963, the total money awarded shot up more than 150%.

Science is the customer

The center's first director, Walter Orr Roberts, insisted that NCAR "must be, first and foremost, an intellectual center." It would have its own staff and a central lab. There was, however, an inherent tension in NCAR's formation. Principal investigators at universities and at NCAR would be competing for the same talent and pots of federal money. The solution was to make the university community NCAR's primary customer. Anything that individual institutions would be hard pressed to pursue by themselves, NCAR could take on.

Of the country's current 41 FFRDCs, many are run by a corporation or a university. For example, the not-for-profit Mitre Corp runs six FFRDCs, including the Center for Advanced Aviation System Development in McLean, Virginia; Caltech manages the Jet Propulsion Laboratory. A subset of FFRDCs are run by university consortia, like UCAR. The nonprofit is made up of 129 North American colleges and universities in the Earth system sciences. UCAR's close collaboration with the geosciences community sets NCAR apart from other FFRDCs.

Multiple researchers expressed concern about breaking apart NCAR and therefore potentially fragmenting the university-led, Big Science vehicle. "NCAR truly has been and remains a singular institution," says Daniel Swain, a research partner at NCAR and a climate scientist at the University of California Agriculture and Natural Resources. "To break it up would be to greatly diminish it. It's more than the sum of its parts."

Modeling the fundamentals

One important example of Big Science at NCAR is in its research in atmospheric modeling. In the dawn of weather modeling in the 1960s, NCAR was one of the US innovators of general circulation models to mathematically represent Earth's atmosphere and related components. Powerful computers run simulations by solving fundamental physics equations to account for constraints like mass and energy conservation.

NCAR focused on reducing the errors in its models' numerical schemes. Led by NCAR scientists Akira Kasahara and Warren Washington, NCAR's modeling group was one of the first to build a global model and to build a model that used a height-based z-coordinate system, which improved the simulation of mountain ranges.

Along with NCAR, UCLA and the US Weather Bureau's Geophysical Fluid Dynamics Laboratory were the hotbeds for computational modeling at the time. That was an ideal situation for NSF: Rather than funding half a dozen or more university labs across the country to build fundamental models, the agency could concentrate its money in a few places. The consolidation was all the more important because computer technology was progressing so quickly that institutions were purchasing new equipment and recoding their models every three to five years.

The work paid off: NCAR had released three major general circulation models by 1980. Crucially, it made its user manuals and code for its Community Climate Model freely available. As computing facilities at university departments became more widespread, academics used NCAR's model to test their ideas. There was no need for a university lab to have a software engineer—NCAR had them. Among NCAR's popular models is one of its prediction systems, the Weather Research and Forecasting Model. UCAR says it has 39 000 registered users worldwide. All software is public. (See Ryder Fox's 2016 *PT* article, "Dissecting the rapid intensification of Hurricane Patricia," which discusses the model.)

NCAR's fundamental research informs not only users but also public models. Today, the Department of Energy hosts the world's fastest supercomputers, and the agency decided a decade ago that it wanted to build a climate model on one of them. It used the architecture from NCAR's Community Earth System Model to build it. The Energy Exascale Earth System Model won the Gordon Bell Prize in 2023 when it succeeded at modeling cloud formations over decades. (For some history about DOE building its exascale model, see *PT*'s 2014 article.)

Private-sector scientists use NCAR's tools too. Mary Glackin was the senior vice president for science and forecast operations at the Weather Company until 2019. NCAR had recently rolled out the Model for Prediction Across Scales (MPAS), and the Weather Company became an early adopter of it. NCAR's work was first class, Glackin says, and it packaged the model in

Learn more about NCAR history

- P. N. Edwards, "History of climate modeling," *WIREs Clim. Change* **2**, 128 (2011).
- G. T. Mazuzan, "Up, up, and away: The reinvigoration of meteorology in the United States, 1958 to 1962," *Bull. Am. Meteorol. Soc.* **69**, 1152 (1988).
- C. A. Jacobs, in *Leadership in Science and Technology: A Reference Handbook*, vol. 2, W. S. Bainbridge, ed., Sage (2012), chap. 77.

From left: Sara Paull, Mary Hayden, and Savannah Ciardelli-Mullis collect mosquito samples in Colorado. As part of NCAR's interdisciplinary work, researchers study vector-borne diseases like Zika. (Photo by C. Calvin, © University Corporation for Atmospheric Research, CC BY-NC 4.0, via OpenSky.)

a way that was easy for the company's researchers to use. In January, the National Weather Service announced plans to adopt MPAS for the mathematical core of its next-generation flagship US weather forecasting model.

Although serving the private sector and other government agencies was not in the original design for NCAR, the center has grown to have "many, many collaborations," says UCAR spokesperson David Hosansky. Navigating those collaborations has posed a challenge for some scientists, including climate scientist and NCAR distinguished scholar Kevin Trenberth. As his work grew in scope beyond the funding that NCAR could provide, he had to write proposals to NOAA, NASA, and DOE. "Then, we were subject to their missions as well as NCAR's missions," says Trenberth.

"The glue and the oil"

Multiple people who spoke with *PT* emphasized that NCAR serves as a central hub in the atmospheric sciences. More than 600 visitors traveled to NCAR in fiscal year 2025 from 165 institutions across 37 states and 23 countries, according to Hosansky. Others come for graduate and postdoc fellowships or internships.

When the news broke that NCAR might be dismantled, the words that scientists used to describe NCAR were telling. They called it the "beating heart," "global mother ship," and "the glue and the oil of atmospheric science." The broad reach is illustrated in the diversity of scientific societies—including ones in oceanography, entomology, microbiology, astronomy, and geology—that signed the letter protesting the rescoping of NCAR.

NCAR is a community social activity, says former NSF program director Clifford Jacobs. Even the layout of the Mesa Lab, one of NCAR's many buildings in Boulder, was designed to encourage small groups of people to stop and chat. (See the 2010 *PT* feature by Stuart Leslie, who takes a deep dive into laboratory architecture, including Mesa Lab's.) "We so often forget that science has a strong social component to it. We always just talk about the formulas and this and that. But I'm a very big believer in the social aspects of science," says Jacobs. "NCAR has that community sense of them. Everybody feels that they have ownership in NCAR." PT

Q&A: Trity Pourbahrami helps scientists communicate their work

After a foray into international health and social welfare, she returned to the physical sciences. She is currently at the Moore Foundation.

By Toni Feder

In college, Trity Pourbahrami wanted to "think like a physicist" to better understand the human body. At the University of British Columbia, she double majored in physics and physiology. After graduating, she took a job in international health that took her to Armenia, Azerbaijan, and Georgia.

Some years later, and with a graduate degree in social welfare and public administration, Pourbahrami circled back to physics. Starting in 2009, she spent a decade at Caltech as director of communications in the Division of Engineering and Applied Science. And since late 2019, she has been a communications officer at the Gordon and Betty Moore Foundation.

Pourbahrami says that her career path has been guided by her "superpower" to connect with people and by the nexus of "preparation and opportunity."

How did you get into physics? And physiology?

I was in the first official class of Science One at the University of British Columbia. The approach was to select a few of us who were good at math and science in high school to spend our first year as undergraduates studying the sciences combined. So, for example, we studied waves from the perspectives of physics, math, and biology. We thought about how the sciences come together. [For more

Trity Pourbahrami (Photo by Tupou Tongilava.)

on Science One and similar programs, see *PT*'s October 2021 article "Undergraduate integrated science programs foster interdisciplinary and personal connections."]

After that incredible training, I got a summer fellowship working in an NMR lab studying how creams would be absorbed by the skin. That's what spurred me to want to think like a physicist but apply the thinking to the human body.

What did you do after college?
I was excited about science, but I wanted to know why it mattered. I took a job in Ottawa with the Canadian Society for International Health, where I helped build relationships and manage a project that involved the World Health Organization, the Canadian International Development Agency, and the Ministries of Health of Armenia, Georgia, and Azerbaijan. It opened my eyes to how what I considered to be accurate health information was seen differently by different cultures. For example, in those South Caucasus nations, before they became independent, they were told by authorities that they could have *X* cases of tuberculosis in their region, and if they reported more, they would get in trouble. I realized that to change that takes more than science and engineering. It's a cultural change. It's conflict resolution. It was totally outside of what I had studied. The experience really shaped me.

My personal experience turned out to be really helpful too.

What about your experience was helpful?
My family is from Iran. I was three years old in 1979 when the Islamic Revolution happened. I lived through the Iran–Iraq War. My father is an open-minded man who did not want his daughters growing up in a nation that valued them less than boys. We are Zoroastrian, and it was hard being a religious minority in Iran. My parents decided it would be best to find a way out. I was 11 when we moved to Canada.

In Armenia, Azerbaijan, and Georgia, not only was my language a plus—I speak Farsi, English, and French—but my background as a Zoroastrian was also a plus. It was a point of connection with people there. My cultural experience opened doors that would not otherwise have opened.

What did you do next?
I could have continued an international health path. But I had already met the love of my life, Peter Capak. He was working on his PhD in astrophysics in Hawaii. I left Ottawa for Honolulu, where I planned to get a graduate degree in public health from the University of Hawaii. But when I landed in Honolulu, the school had lost its accreditation for public health.

At first, I was lost. But I ended up meeting people, including Susan Chandler, the director of human services in Hawaii. She was starting a new program that would expose heads of finance, heads of police and fire, and others to what social services mean. To me, it was a way to understand the true holes and barriers to building community. I got my master's degree in the new program, social welfare and public administration.

At that point, Susan was on me to get a PhD. But this was a decision point. Peter was finishing his PhD. If I stayed to get a PhD, we would be apart. And I was worried about the two-body problem: How would we get two jobs in the same

Trity Pourbahrami (left) with anthropologist Andrea Buitrago (walking, front) and Moore Foundation program officer Maria DiGiano (walking, back) in the Colombian Amazon to learn about locally led efforts to protect freshwater ecosystems. The visit was part of the foundation's Andes–Amazon Initiative. (Photo by Trity Pourbahrami.)

location for two PhDs? In 2004, he got a postdoc at Caltech, and I moved with him.

I started consulting. For about five years, I worked with different groups, including the Western Justice Center Foundation, Women at Work, and UCLA. I trained the Pasadena school district's athletic programs in conflict resolution. Then I walked into my next decade at Caltech. The things I got to do there were incredible.

Was it a conscious decision to pivot back to science after about 10 years working in international health and social welfare?
It was preparation meeting opportunity. I was prepared for a lot of things. I was working with leaders in a lot of fields, and the incredible opportunity to be director of communications for the largest division of Caltech presented itself.

Tell me about your job at Caltech.
I did a lot of the standard work in internal and external communications. I was also the editor of *ENGenious*, a Caltech in-house publication. My team built faculty members' first websites. That led to many of the faculty understanding the value of communicating their work to a broader audience, which in turn opened the door to my coaching them. I helped them figure out how to connect to a broader audience and to explain why what they did mattered. Eventually, I started training teams, and I developed a curriculum to teach graduate courses on effective science and engineering communications. I was interacting with faculty, postdocs, and students.

What about the Moore Foundation was appealing enough to take you away from a job you loved?
A recruiter said, "The Moore Foundation is looking for someone like you. What would it take to get you?" They helped Peter find a job, and the Moore Foundation was supportive of me guest lecturing and continuing my international work, serving as the communications consultant to an interdisciplinary research team studying the dawn of the universe. The team meets at the Niels Bohr Institute in Copenhagen about once a year, and I provide one-on-one coaching and teach effective communications.

The job itself opened a world to me that I didn't have at Caltech. The Moore Foundation had been a big funder of Caltech for many years. Even though I am not a grant maker, I got to sit on the other side of the table and see communications from a different perspective. I also got a broader portfolio. I am involved in communicating not only the foundation's physical science work but also that of the Andes–Amazon Initiative, which is trying to preserve the land, water, and way of life of the Amazon. I'm also working on a new green chemistry initiative.

How do you spend your time?
Physics is a central part of what I do now. I partner with our grant makers to provide communications counsel to them. I do external communications. I get to work with scientists and advise them, which is a really fun aspect of my job.

I think about how I can have the most impact as a human on this planet. My superpower is connecting with people and winning people over. Part of my job is to help other people discover their superpowers. My work at Moore and at Caltech is the same in some ways: I hold the hand of experts and walk with them until we discover the points of connection, the points that really matter to make the world a better place. PT

Multiple science agencies escape Trump's proposed cuts

By Clare Zhang

In January, President Trump signed into law a package that funds many federal science agencies through September. Overall, Congress rejected the deep cuts that the White House proposed in its fiscal year 2026 budget request. NASA, NSF, and the US Geological Survey received cuts compared with FY 2025, but the Department of Energy's Office of Science and NIST received slight increases. NOAA's funding stayed roughly flat.

In addition to allocating agency funding, the law has numerous provisions that affect science policy. The report accompanying the law requests a briefing on whether the White House Office of Science and Technology Policy is in the process of repealing a Biden-era policy that mandates immediate open access to federally funded research by this year. The law also prevents the Commerce Department, NSF, NASA, and DOE from changing reimbursement rates for indirect costs, which include research-related expenses such as equipment and facilities maintenance. DOE and NSF were among the agencies that attempted to cap indirect cost rates last year. Thus far, courts have rejected the agencies' attempts at implementing the caps.

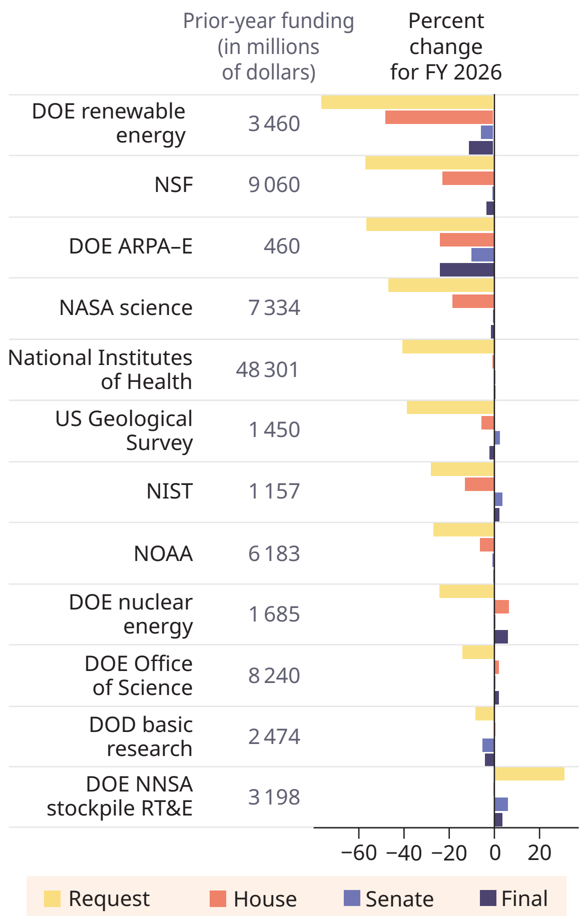
Funding for the National Institutes of Health and the Department of Defense passed in early February after being held up by a dispute over funding for the Department of Homeland Security. NIH received nearly level funding, whereas basic research funding at DOD was cut by about 4%.

Here are selected agency highlights:

- **NSF's** budget was cut by 3.4% to about $8.75 billion. The research account was flat-funded, and NSF is prohibited from cutting any directorate by more than 5% of what its budget was in FY 2024. Funding for NSF's STEM education programs was reduced to $938 million, a 20% cut from FY 2024 but far less than the 75% cut proposed by the White House.

  Funding for NSF's major construction projects rose to $251 million, up 7.3% from FY 2024. The funds provide for Antarctic infrastructure upgrades, a research supercomputer facility in Texas, and mid-scale infrastructure projects. The White House canceled the major construction funding for FY 2025, saying it was "improperly designated by the Congress as emergency."

  The report also directs NSF to submit a report on its management plan for the R&D centers and

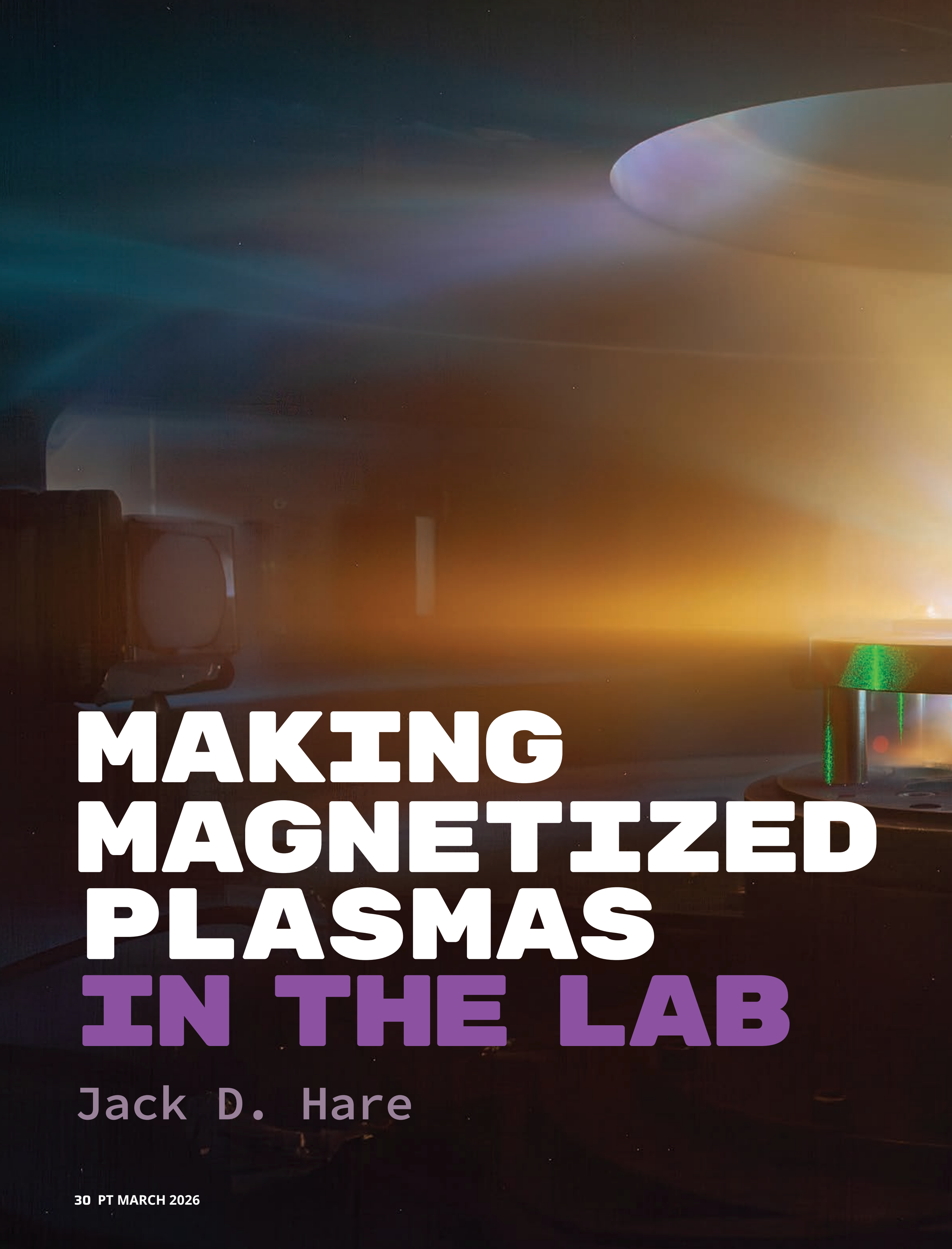


For detailed numbers, see *FYI*'s Federal Science Budget Tracker at https://aip.org/fyi/budget-tracker.

major scientific facilities it funds, including the National Center for Atmospheric Research, which the White House has said it plans on "breaking up" (see the story on page 18).

- **DOE's Office of Science** received a 1.9% increase to $8.4 billion. The program with the largest percentage increase, 7.7%, was Advanced Scientific Computing Research. Language in the report limits DOE from carrying out grant terminations on the grounds that the funding "no longer effectuates program goals or agency priorities." DOE cited that reasoning in the cancellations of hundreds of clean-energy grants last year.
- **NOAA** received essentially flat funding at $6.17 billion. The law adopts the president's proposal to move most weather research programs in the Office of Oceanic and Atmospheric Research to the National Weather Service. But lawmakers rejected the administration's request to zero out the office's remaining climate and ocean research programs.
- **NASA's** budget was cut by 1.6% and its Science Mission Directorate by 1.1%. The breakdown by discipline reveals reshuffling of funds across the directorate compared with FY 2024. The appropriation maintains level funding for the STEM engagement office, which the White House proposed eliminating. The law withdraws support for the Mars Sample Return mission but sustains $110 million for some of its components.
- **NIST's** budget increased by 2.3% to $1.18 billion, excluding the $663 million in earmarks that fund external projects. The research facilities construction budget received a 45% increase, and the report directs NIST to deliver quarterly updates on efforts to address its "maintenance backlog." Reports in 2023 and 2024 detailed decaying infrastructure across NIST's campuses in Maryland and Colorado (see *PT*'s 2023 article "Urgent measures are needed to shore up NIST's crumbling facilities"). NIST research funding received a 1.5% cut. **PT**

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



MAKING MAGNETIZED PLASMAS IN THE LAB

Jack D. Hare

With strong magnetic fields and intense lasers or pulsed electric currents, physicists can reconstruct the conditions inside astrophysical objects and create nuclear-fusion reactors.

A hot, dense plasma illuminates a laboratory in this long-exposure photograph. (Photo courtesy of Thomas Varnish.)

If matter is continually heated, its constituent neutral atoms will eventually break apart into a soup of charged particles known as plasma. Plasmas exist over a vast range of densities, from less than a single particle per cubic centimeter in the void between stars to a million times as dense as liquid water in the core of a white dwarf star.

An extremely dense plasma also has an extreme high energy density (HED), which causes the plasma to expand. The expansion is opposed by gravity in astrophysical objects such as stars. But in the lab, an HED plasma can exist only briefly and must be confined by strong magnetic fields or inertia.

Pressure is used to measure the energy density of a plasma. Earth's atmosphere exerts a pressure of 1 bar (10^5 N/m^2), and the pressure at Earth's center is 3 million times as large. HED plasmas are usually defined as having a pressure of at least 1 million bars, although in reality, HED-relevant effects can occur under less extreme conditions.

Even at such high pressures, the charged particles in a plasma are significantly influenced by magnetic fields. Studying the rich interplay between magnetic fields and the dynamics of HED plasmas in the lab offers a window into some of the most energetic astrophysical processes in the universe. Such studies are also relevant for carbon-free power from self-sustaining nuclear fusion reactors. Using the approach of inertial confinement fusion at Lawrence Livermore's National Ignition Facility (NIF), researchers demonstrated in 2022 for the first time that a laser-driven controlled fusion reaction could produce more energy than the energy put into it. Some plasma physicists aim to improve on that result with the help of magnetized HED plasmas.

Magnetic fields and plasmas

The charged particles of a plasma respond to electric and magnetic fields through the Lorentz force. In response to electric fields, the particles rapidly rearrange until their charges cancel out the electric fields. That phenomenon, known as Debye shielding, is similar to how the nuclear charge in an atom is reduced by the electrons that are closest to the nucleus.

In contrast, magnetic fields in plasmas are not shielded. Instead, particles follow tight orbits along magnetic field lines, as seen in the rightmost image in figure 1. The orbital motion has significant consequences: It ties the magnetic field to the plasma through the frozen-in flux, affects the plasma's magnetic pressure, and suppresses thermal conduction perpendicular to the magnetic field.

The frozen-in flux law states that the magnetic flux through part of a plasma is conserved, and the magnetic field lines are effectively pinned to the plasma. In other words, any time a force moves the plasma, the magnetic field moves too. The magnetic field exerts an opposing force because of gradients in the magnetic pressure $P_B = B^2 / 2\mu_0$, where B is the magnetic field strength and μ_0 is the permeability of free space.

In addition to magnetic pressure, plasmas also have thermal pressure. It's the same pressure in the context of regular liquids and gases, although in HED plasmas the thermal pressure often has a more complex functional form. The dimensionless plasma beta is the ratio of the thermal pressure to the magnetic pressure.

The magnetic field, in addition to the magnetic pressure, restricts heat transport in a plasma. That's critically important for nuclear fusion in stars and in a reactor because the fuel must stay hot to undergo fusion. In the absence of a magnetic field, the plasma's charged particles are free to move in any direction. When they collide, they transfer kinetic energy and therefore heat.

But in the presence of a strong magnetic field, the particles tightly orbit the field lines and cannot move far in the direction perpendicular to the magnetic field. The limitation in movement leads to anisotropic thermal conduction—heat can still be transported rapidly along the magnetic field lines, but conduction is significantly suppressed in the perpendicular direction. Magnetic fields,

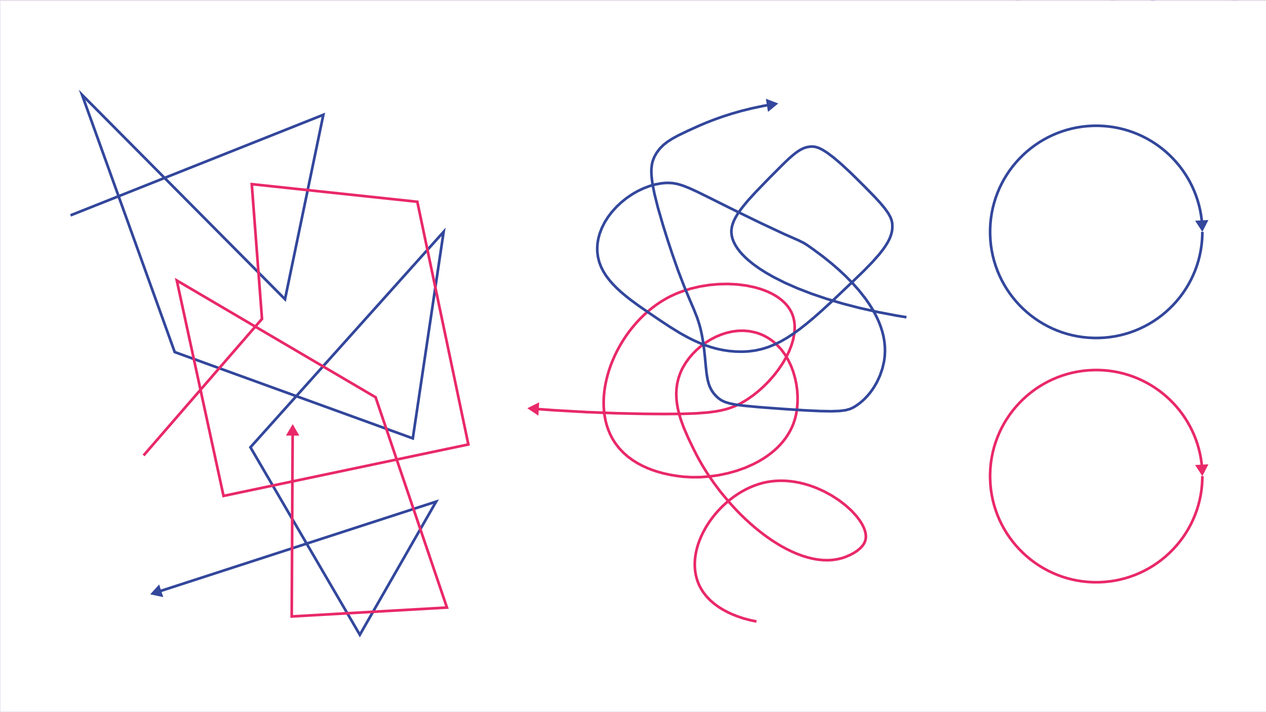


Figure 1. The orbits and collisions of particles in plasma. On the left, the magnetic field is minimal, so two particles follow a random-walk pattern, represented by the blue and pink lines. In the middle, the magnetic field is strong enough to deflect the particle trajectories between collisions. On the right, the particles tightly orbit the magnetic field lines and rarely collide, and the magnetic field is so strong that it suppresses the transport of heat and particles.

therefore, can insulate hot plasmas and maintain them at the conditions necessary for nuclear fusion.

For an HED plasma, the magnetic field has a significant effect only when it is strong. Creating magnetized HED plasmas in the laboratory, therefore, requires not only a method to provide them with high-energy densities but also a method to generate strong magnetic fields. Although that's difficult, researchers are taking on the challenge using intense pulses of either laser light or electric current. Both approaches to producing magnetized HED plasmas in the lab are being used to better understand how to harness nuclear fusion for power and to create scaled replicas of extreme astrophysical objects.

Magneto-inertial fusion

Research on controlled nuclear fusion aims to bring the energy source of the stars to Earth for carbon-free electricity, and magnetized HED plasmas are critical to that effort. Many controlled thermonuclear fusion schemes use magnetic fields to confine plasmas and to suppress the transport of heat through them. In magnetic confinement devices—including the ITER tokamak in development in France, the Experimental Advanced Superconducting Tokamak in China, and the Wendelstein 7-X stellarator in Germany—the plasma's magnetic pressure is much larger than its thermal pressure. The low-beta regime keeps the plasma stable, but the magnetic pressure has to be generated by running current through strong magnets. Such a large up-front energy cost can be justified only if the plasma produces fusion power in a steady state.

An alternative to a steady-state approach is a pulsed approach, in which the plasma is rapidly brought to fusion conditions and then explosively disassembles as the fusion reaction ignites the fuel. To generate steady power, the pulsed process must repeat on a cycle, analogous to an internal combustion engine, in which one pulse after another translates to a steady power output. The advantage of the pulsed approach is that many plasma instabilities do not have time to fully develop. But the disadvantage is that the plasma generates fusion power for only a short time, often no longer than a nanosecond.

To avoid the need to recoup the initial magnetic energy cost, designers of pulsed approaches often minimize the plasma's magnetic energy by having the systems operate at a high beta; that is, with a relatively low magnetic pressure. Although a low magnetic pressure alone cannot confine the fuel, research demonstrations have shown that it is strong enough to suppress heat transport, keep the plasma fuel hot, and significantly boost the fusion energy produced.

One of the most well-known pulsed approaches is the laser-driven scheme of inertial confinement fusion at NIF. In those experiments, lasers heat the surface of a spherical capsule, which causes material to ablate outward, and the remaining part of the capsule is launched inward like a spherical rocket. The center of the capsule is filled with low-density gas, which reaches fusion conditions at peak compression and then initiates a thermonuclear burn wave that travels out through the solid, dense fuel surrounding it. (For more on the NIF results, see the 2024 *PT* feature article "Harnessing energy from laser fusion," by Stefano Atzeni and Debra Callahan.)

Because of the steep temperature gradient between the hot spot and the cold fuel, the fusion yield is reduced by the significant amount of heat that's transported away from the hot spot. Recent lab experiments have added an externally driven magnetic field, as shown on the left in figure 2. The field suppresses heat transport perpendicular to the field lines, although some heat still escapes at the poles of the cylindrical hohlraum that holds the fuel capsule.[1] Simulations predict increased yields from magnetized inertial confinement fusion.

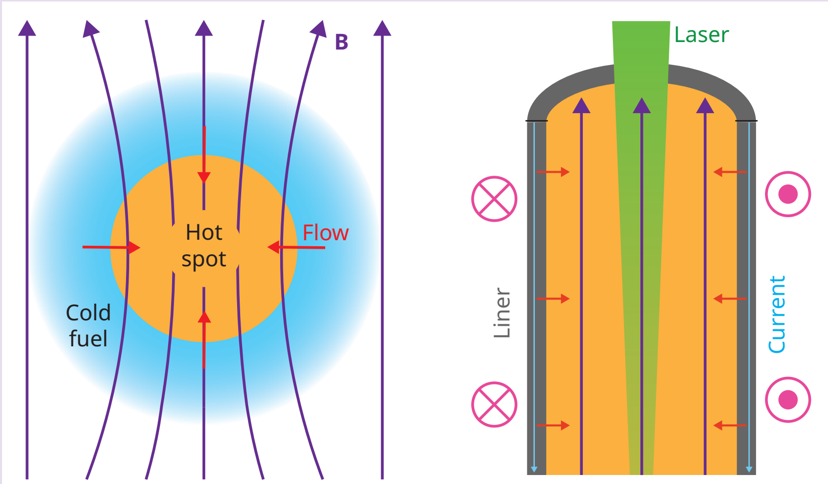


Figure 2. Two fusion energy schemes use magnetized high-energy-density plasmas. On the left, in magnetized laser-driven inertial confinement fusion, an externally applied magnetic field (purple) is compressed and amplified during the implosion of a laser-heated, spherical fuel capsule. The field suppresses thermal conduction from the central hot spot to the surrounding cold fuel, which improves the fusion gain. On the right, in magnetized liner inertial fusion, a hollow metal cylinder, or liner (gray), is initially filled with highly pressurized gaseous fuel (orange) and preheated with a laser (green). An externally applied magnetic field (purple) parallel to the cylinder's axis insulates the hot fuel from the cold metal liner. At the same time, a large electric current (light blue) is driven through the outside of the liner. The strong magnetic field (magenta) that's generated in response causes the liner to implode and compress the fuel inside to fusion conditions.

The increased yields are a consequence of the frozen-in flux law, which conserves the magnetic flux. As the capsule implodes, the area through which the magnetic flux moves decreases, and the magnetic field strength amplifies. The thermal insulation of the plasma, therefore, increases as it compresses, and the associated magnetic fields may reach many thousands of teslas. (For comparison, the magnet in a typical MRI machine has a field strength of 1.5–3 T.)

Instead of using lasers to compress the fusion fuel, researchers can use large electric currents in a technique called magnetized liner inertial fusion (MagLIF), shown on the right in figure 2. First proposed by researchers at Sandia National Laboratories, it uses a hollow metal cylinder, or liner, initially filled with gaseous fuel at high pressure.[2] An external magnetic field is applied parallel to the cylinder's axis, and a laser preheats the fuel to the plasma state. The external field suppresses thermal conduction between the plasma fuel and the cold liner, and a large electric current is driven through the outside of the metal liner, which causes it to implode and compress the fuel inside to fusion conditions. The implosion amplifies the externally applied field because of the frozen-in flux condition and increases the thermal insulation.

Because the current flows on the outside of the metal liner rather than through the plasma inside, many current-driven plasma instabilities are avoided, and the external magnetic field is necessary to insulate the hot fuel from the cold metal liner. MagLIF experiments at Sandia have produced encouraging fusion yields.[3]

Scaled laboratory analogues

The propagation of a thermonuclear burn wave in a magnetized plasma is relevant for not just fusion power but also for plasma jets, supernovae, and other astrophysical phenomena. Many jets are launched from young, compact stars and accretion disks around black holes. The jets of plasma are stunning structures but are challenging to observe, in part because of how far away they are, and their exact mechanism remains unclear.

One approach to studying them and other HED plasmas is to create analogues in the laboratory.[4] The dimensionless scaling approach enables experiments to mimic astrophysical objects on much shorter length and time scales.[5] In practice, matching all the dimensionless parameters and the initial boundary conditions is impossible. But researchers have used laser- and pulser-driven approaches to generate scaled HED plasmas in the lab to better understand the mechanisms by which jets are launched and stabilized.

Figure 3 shows the results of one experiment.[6] The researchers drove an intense pulse of electric current, which peaked at 1 million A and lasted for around 500 ns, through an array of thin wires. The current rapidly heated the wires and created a plasma that surrounded each one. The current flowing through the plasma generated a large magnetic field on the order of tens to hundreds of teslas. The magnetic pressure accelerated the plasma and swept it up to form a dense jet of plasma. The two images in figure 3 reproduce critical features of one prevailing model that explains the launching mechanism of astrophysical jets.

That experiment also offers insight into astrophysical observations of jets and plasmas. A jet made in the lab carries a significant fraction of the driving current, which in turn produces a strong magnetic field that confines the jet. The current, however, leads to fast-growing instabilities that twist and deform the jet. The deformation leads to a clumpy structure with substantial density variations, which has been observed in astrophysical jets, such as Herbig–Haro 46/47 by the *Hubble Space Telescope*.

The Biermann battery

Although most of the visible universe is made from magnetized plasma, the origin of the magnetic fields is an open question. Most plasma processes only amplify existing fields, and so an initial seed field is still required. One possible explanation occurs in plasmas with nonparallel density and temperature gradients, which create an effective electric current that can grow a magnetic field from nothing. The Biermann battery effect occurs in many astrophysical phenomena, including supernova explosions, and may be the seed for the naturally occurring magnetic fields in the universe.

Laser-driven experiments in the lab can be used to study how efficiently, how rapidly, and over what length scales the Biermann battery creates magnetic fields and how strong the fields can grow. A focused laser rapidly heats a target to create a hot, dense, and expanding bubble of plasma. Inside the hemispherical bubble, the strong, nonparallel temperature and density gradients make an intense magnetic field that encircles the bubble. The

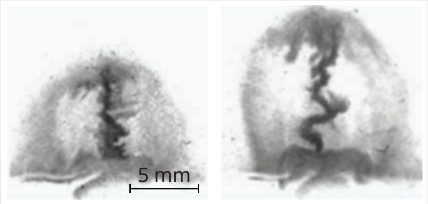


Figure 3. The x-ray emission shown in both images is from an astrophysical jet of plasma that was created in the lab. The jet is surrounded by a magnetic bubble, whose magnetic pressure causes the jet to form on the axis and propagate vertically. The intense pulse of electric current that forms the plasma also creates instabilities, which a mere 10 ns later cause the jet to kink and deform as it propagates. (Images adapted from ref. 6.)

magnetic field can then be measured using proton imaging, in which a high-energy beam of protons that passes through the plasma is deflected by the magnetic field.

Modeling a Biermann battery is difficult because the fine spatial and temporal resolutions that are necessary to simulate the steep gradients and complex physics are computationally prohibitive. Recent experiments have challenged results from simulations and show that magnetic fields can be generated much farther away from the plasma bubble than previously predicted.[7] The results are important not only because they help researchers understand self-generated magnetic fields in laser-driven experiments but also because of their implications for the generation of magnetic fields in the wider universe.

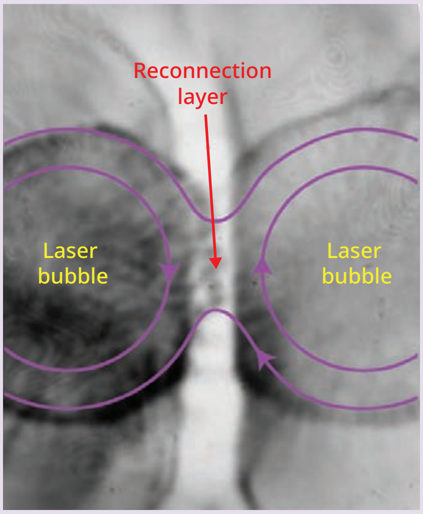


Figure 4. Hot, dense, and expanding bubbles of plasma (dark regions) can be made in the lab by a focused laser that rapidly heats a target. Because the plasma has nonparallel density and temperature gradients, the thermoelectric effect called the Biermann battery generates a magnetic field. Shown schematically in purple, the field is capable of deflecting a beam of high-energy protons, which researchers used to image a laser-driven magnetic reconnection event. The reconnection layer is a sheet of intense electric current, which rapidly heats and accelerates the plasma and changes the topology of the magnetic field. (Image adapted from ref. 10.)

Magnetic reconnection in the lab

The use of lasers and pulsed electric currents to study new HED regimes has also been critical for the study of magnetic reconnection. That explosive process changes a magnetic field's topology and rapidly converts magnetic energy to both accelerate and heat the plasma. Magnetic reconnection occurs when oppositely directed magnetic fields are brought together inside a plasma. The magnetic fields result in the creation of an intense sheet of electric current called a reconnection layer, which breaks and reforms the field lines. Magnetic reconnection is found in the dramatic eruptions of solar flares, around Earth's magnetosphere (where it causes the aurora), and in some of the brightest, most extreme astrophysical objects, including the swirling plasma that surrounds black holes. (To learn more, see the June 2010 *PT* article "Magnetic field reconnection: A first-principles perspective," by Forrest Mozer and Philip Pritchett.)

Researchers have conducted numerous experiments over the years to understand which features of reconnection are ubiquitous and which ones depend on certain plasma parameters. Laser-driven experiments often use magnetic fields generated by the Biermann battery effect, and reconnection takes place between two adjacent expanding plasma bubbles. The magnetic energy density is typically smaller than the thermal energy density, so reconnection does not significantly heat the plasma.

Proton images, such as the one in figure 4, clearly show the change in magnetic field geometry. Some work has shown evidence of small-scale magnetic perturbations that are caused by plasmoid instabilities, which tear the current sheet into many smaller ones and dramatically increase the rate at which reconnection occurs.

Magnetic reconnection has also been studied in plasma generated from heating thin wires with pulsed electric currents. The currents also produce magnetic fields embedded in the plasma. When two plasma flows from two exploding arrays of wires collide, the oppositely directed magnetic fields that the plasmas carry drive the formation of a reconnection layer. Inside, researchers have observed significant heating and the development of plasmoid instabilities, which are features of reconnection on fast time scales.

In some experiments with very dense plasmas, the plasmoids are characterized by localized hot spots of x-ray emission, and the hot spots—indicated by the bright spots in figure 5—move rapidly in the reconnection layer while quickly cooling and dimming. Astrophysical objects in which reconnection occurs have similarly

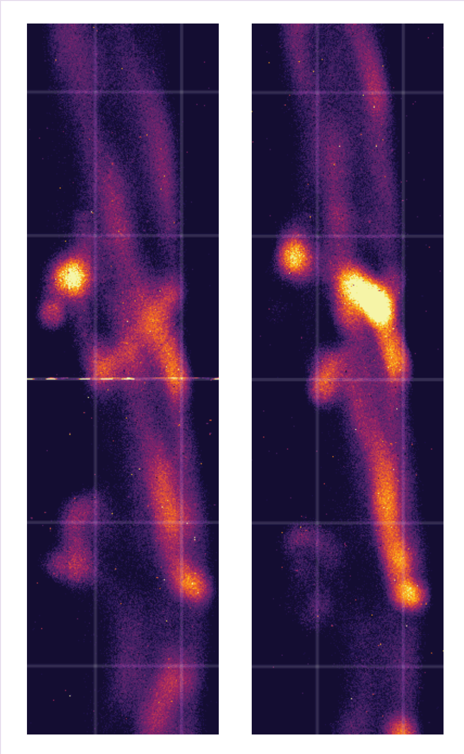


Figure 5. The localized, fast-moving hot spots of x-ray emission are shown as bright regions in the two images, each of which is 5 mm wide, and correspond to plasmoids. They're instabilities that are created in a magnetic reconnection layer—an intense sheet of electric current. Magnetic reconnection layers develop in Earth's magnetosphere, solar flares, and other astrophysical objects when oppositely directed magnetic fields are brought together inside a plasma. Then, the field lines break and reconnect. (Images adapted from ref. 11.)

strong, variable emissions in space and time. Such laboratory experiments, therefore, suggest that the cause of reconnection may be the plasmoid instabilities coupled with strong cooling of the plasma by x-ray emission.

Magnetic fields profoundly affect HED plasmas in many ways, including suppressing heat transport and providing huge pressures. By studying the plasmas in the lab, researchers can enhance existing nuclear fusion concepts or drive entirely new ones. Laboratory plasma research has reproduced some of the fundamental processes of astrophysical plasmas, including the launch of jets from young stars and the generation and reconfiguration of magnetic fields.[8,9] The difficulty of producing HED plasmas, combined with the richness of the physics involved, means that magnetized HED physics remains an exciting frontier for research. PT

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SPEAK EASY

The educational benefits of a three-minute research talk

The ability to communicate a key message clearly and concisely to a nonspecialized audience is a critical skill to develop at all educational levels.

Gavrielle R. Untracht and Matthew E. Anderson

(Design by Masie Chong; silhouettes adapted from photos by Robert C. Bain, © 2025 SJSU, and artwork adapted from iStock.com artists Maxim Basinski, arcady_31, paseven, and imnoom.)

At the family table over the holidays, how many of you were grilled by a relative who wanted to know exactly what you're doing in graduate school: "What are you working on again? Why is this so important? Pass the yams." What do you say to quickly explain your research before they get bored and go off to play with your baby cousin? It needs to be concise, short, and impactful.

That scenario, in which you have a very short time to get your idea across to someone who's not familiar with your field, is termed an elevator pitch. There are constraints you need to recognize: Who is my audience? What is their level of understanding? And how much time do I have for my pitch? At the family dinner table, you might have 90 seconds. If you run into your favorite researcher at a conference, you might have two minutes. If you're invited to pitch venture capitalists, you might have three minutes.

You want your relatives to remember your story so they can brag about you to their friends. You want that famous scientist at the conference to remember you when you apply for a postdoctoral position in their lab. And you want those venture capitalists to provide seed funding for your startup. What can you say to convince them that your idea is the one to remember?

The ability to explain complex concepts concisely to a nonspecialist audience is a critical skill at all academic levels. It can offer tremendous career benefits, especially in physics, in which cutting-edge topics may require years of study to fully comprehend. It can also help increase scientific awareness among the broader public. The two of us believe that physics educators owe it to the community and the profession to help students develop those skills, which can be honed with practice. In this article, we describe how campus competitions and classroom exercises can do just that: When students can develop proficient elevator pitches about their research, they are able to strengthen their physics communication skills.

The Three Minute Thesis competition

Originally developed in 2008 at the University of Queensland in Australia, the Three Minute Thesis (3MT) competition has taken hold in academic institutions across the globe. Students have a maximum of three minutes to explain their graduate research to a lay audience, and they can use only one background image. Competitions are judged by a panel of professionals recruited from all fields and professions. They typically include one or two preliminary rounds and finals.

The 3MT competition has been replicated at many US institutions, including Stanford University, Cornell University, and the University of South Florida. And various other incarnations (and names) exist, including MIT's Research Slam, the Institute of Physics's Three Minute Wonder, and the pitch competitions at the annual Falling Walls Science Summit.

The competitions are usually face-to-face events, meaning that presenters are live on a stage, but alternatives include online and prerecorded contests. In the California State University (CSU) system, where the 3MT competition is

called the Grad Slam, the 23 CSU campuses hold local competitions either live, online, or prerecorded. The top two finalists from each campus then advance to a CSU-wide competition, which is hosted online by one campus. Marc d'Alarcao and Cheryl Cowan at San José State University (SJSU) began the CSU Grad Slam competition there in 2021. D'Alarcao says the primary motivation was professional development for the students: "Students believe that this is an incredibly transformative experience for them, and as educators, we owe

Alexi Musick, a master's student in physics at the time, presents at the 2024 San José State University Grad Slam. (Photo by Robert C. Bain, © 2024 SJSU.)

our students the opportunity to provide it."

Competitions in the 3MT style are not only wonderful opportunities for the students but also incredibly valuable for the universities involved. They generate buzz on campus, and they allow other students, faculty, and audience members to quickly learn about various topics. In d'Alarcao's experience, attendees almost invariably leave a 3MT competition raving about how articulate and impressive the students were.

Pitches in the classroom

It can be hard to find funding and institutional support for a campus-wide competition. One possible stepping stone toward that goal is to add an elevator-pitch-style exercise into an existing course so that students gain a taste for that style of presentation. Importantly, the exercise should be ungraded so that students can focus on speaking colloquially and are unmoored from the burden of trying to get everything perfect. We both employ this technique in our classroom instruction and have found it to be a fun and entertaining way to break students out of their routine and gain a deeper level of conceptual understanding.

In one of our (Anderson's) advanced physics laboratory courses, for example, students rotate through approximately eight stations over the course of the semester. At each one, they are tasked

Marc d'Alarcao, one of the organizers of the San José State University Grad Slam, delivers opening remarks at the 2024 event. (Photo by Robert C. Bain, © 2024 SJSU.)

with completing a classic experiment in physics, such as the single-photon double-slit experiment to demonstrate wave–particle duality or the Cavendish experiment to measure the gravitational constant. At the end of each experiment, they are asked to stand in front of their classmates and deliver a three-minute speech that describes what the experiment is about.

The professor gives them guiding questions on how to approach their talk: What is the name of the experiment? What are you trying to measure? Why is it important? What are the experimental procedures? Each group is given about 10 minutes to prepare for their first three-minute speech. They are generally quite nervous about the task—several students said they felt nauseous—but they muddle through. After the talk, there is a short question and answer session, with the group that presented previously asking the first question.

The exercise is repeated after each experiment. After three or four speeches, the students start becoming more comfortable speaking in front of their peers. They realize that they are simply talking to their friends and classmates, many of whom have the same questions they have. They also realize that they are conveying something useful to the other groups: Because their peers will also be carrying out the same experiment, they are providing them with a mental framework for future assignments.

One interesting aspect of the exercise is how students begin to develop a scientific language. Students have a particular way of speaking to each other, which, of course, does not always resemble the way seasoned scientists speak to one another. It is fascinating to watch students learn how to use the rigorous descriptive language of a professional scientist without alienating their classmates.

Once the students become more comfortable with the three-minute speech, the professor can throw a wrench into the machinery by asking the students to give another speech to a different target audience: perhaps an eighth grader, or an aunt who never went to college, or an uncle who believes that Earth is flat. That added wrinkle forces students to think about their audience and the message they are trying to get across. As one might expect, students initially grumble about having to give another speech. But in our experience, those feelings quickly give way to excitement and a marked increase in energy level. We generally see applause after every speech, great questions, and raucous laughter—which is practically unheard-of in a lab course!

In class surveys, students were extremely positive about the elevator-pitch exercise, with 90% agreeing that it would improve their public-speaking skills. When asked to rate the value of the exercise on a scale from 1 to 5, students gave it an average score of 4.7. Implementing the elevator-pitch exercise isn't difficult. It's a low-stakes, ungraded task that does not require an inordinate amount of class time. Moreover, it's well worth the effort: It leads to a marked improvement in students' engagement with the course and their public-speaking skills.

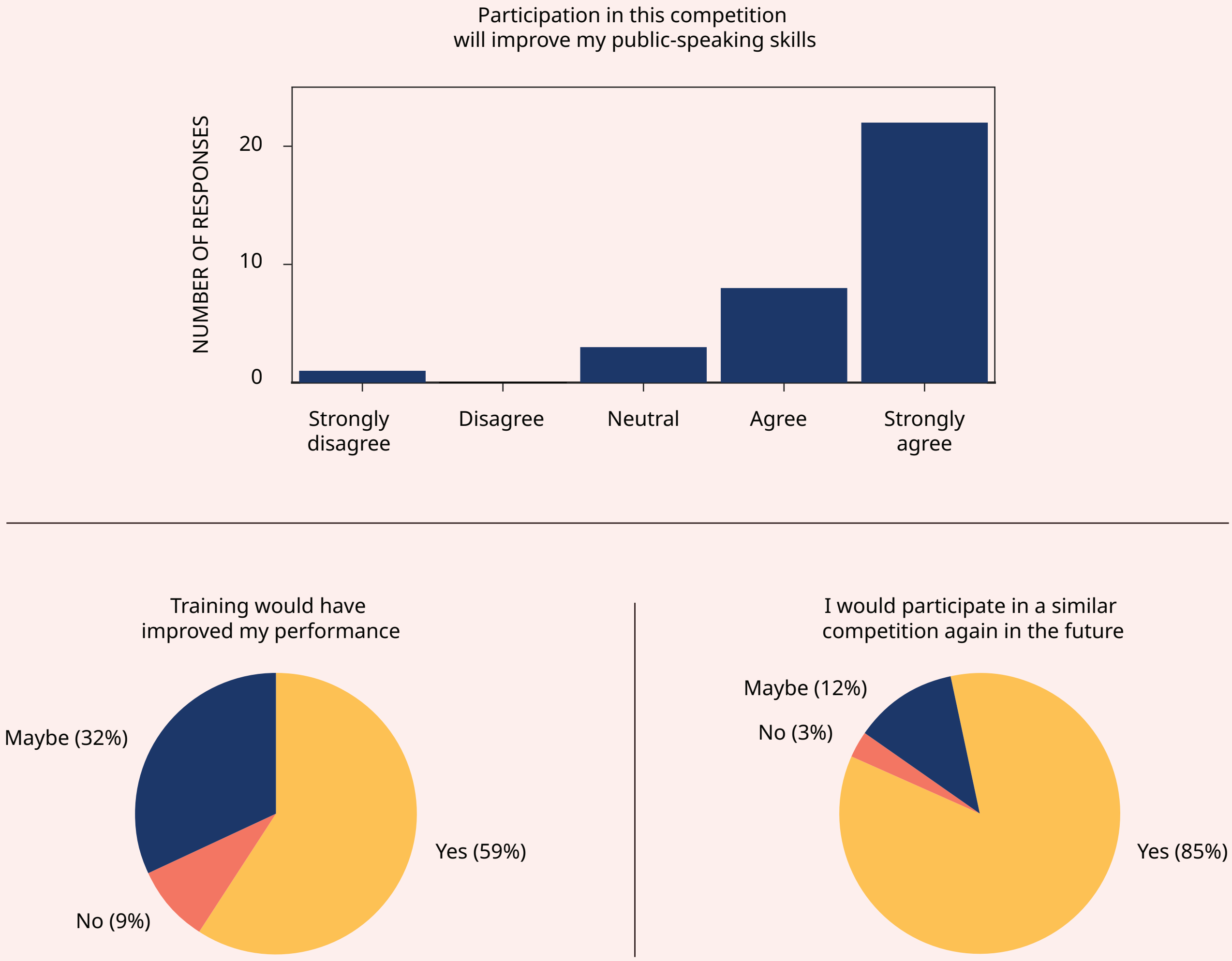
Building educational impact

We conducted surveys in 2025 at the San Diego State University (SDSU) Grad Slam and the CSU-wide finals to attempt to quantify the impact of participation in the event. Between the local competition at SDSU and the CSU-wide competition, we received 34 responses from participants and 38 responses from audience members. One takeaway was that students were extremely happy to have taken part in the competition. Of the responders, 88% said they agreed or strongly agreed with the statement, "I feel that participating in this competition will improve my public speaking/presentation skills." And 85% said they would participate again if given the opportunity.

Many students reported that participating in the competition helped with managing the nervousness associated with public speaking. Participants were significantly more nervous just before their talk than they were during it. That experience—a decrease in anxiety over the course of a stimulus—is called habituation and is a central tenet to treating social anxieties.[1] Repeated exposure to public speaking has been shown to greatly improve confidence and reduce the anxiety associated with it.

But one of the challenges that many students face is the lack of resources to help them prepare to compete. Nearly two-thirds of our survey responders said they felt training would have improved their performance and they would have been interested in training if it were available to them. While an increasing number of universities are offering 3MT-style competitions, only a few have structured training programs in scientific communication. That is a missed opportunity because training programs could provide an invaluable way to have a lasting impact on professional development.

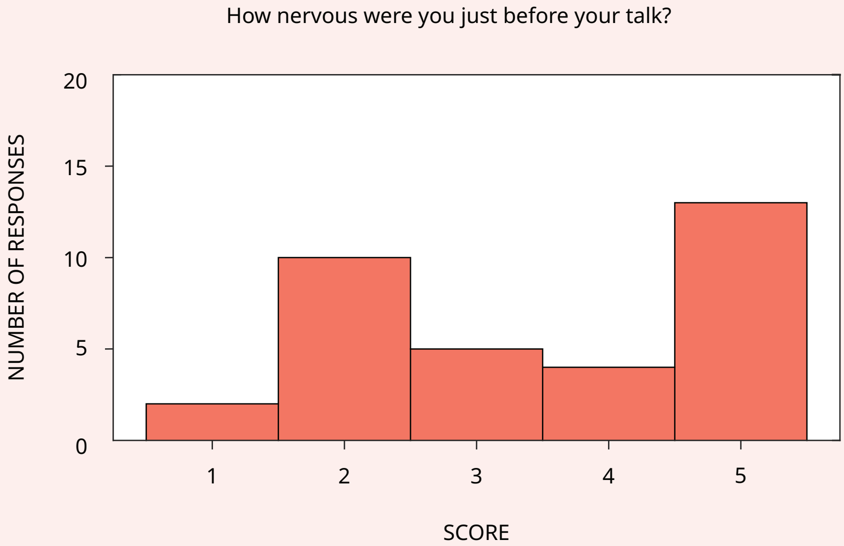
Of the universities that participate in the CSU Grad Slam, SJSU stands out because of its highly developed and competitive training program:

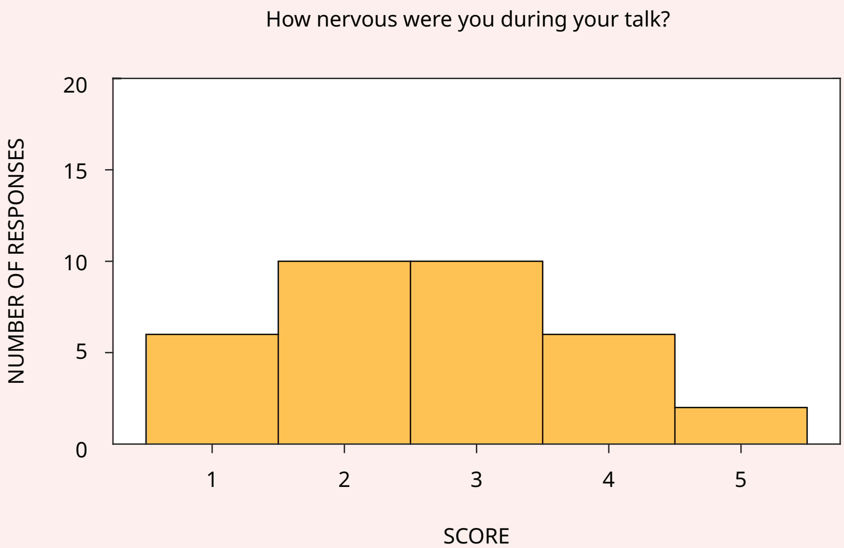


Results from participant surveys taken in 2025 at San Diego State University's Grad Slam event and California State University's system-wide Grad Slam finals. Respondents overwhelmingly agreed that participation in the three-minute thesis competition improved their public-speaking skills and that they would eagerly do it again. Most, however, felt that they would have benefited if they had received more training in public speaking.

So many students apply that they cannot all be accommodated. SJSU organizers require that the students who are accepted take it seriously. For three months, they meet weekly with an accomplished speaker from campus who serves as their coach and helps them conceptualize their topic, organize their thoughts, and distill everything down to three minutes. "It's the preparation for that event that really provides the benefit for the student," says d'Alarcao. "At least five people … have gone through our program and later told me that this was the single best thing that happened to them at San José State University."

Several studies have been conducted about how to craft a winning 3MT pitch.[2–4] They note that winning talks often follow nearly identical structures and contain similar rhetorical elements. There needs to be a hook that grabs the audience's attention, a problem statement, an explanation of the solution, a statement about the implications of the work, and a closing statement that connects back to the hook to complete the story. Another important aspect to consider is performance skills. Including some coaching in acting and in how body language relates to pub-





More results from the surveys taken in 2025 at the SDSU and CSU Grad Slam events. Participants were significantly more nervous before their talk than during it, which illustrates how habituation to presenting in public helps improve public-speaking anxiety.

lic speaking can instill valuable skills that students may not otherwise develop as part of a physics education.

It's important to note that the 3MT competition is not just for doctoral students: Anyone working in science can benefit from signing up. At Cal State Long Beach, the participants are nearly entirely master's students. The Grad Slam is critical for students to develop the skills to "effectively communicate, effectively engage, and particularly engage those outside of their discipline," according to Dina Perrone, the school's interim dean of graduate studies and organizer of the campus's competition. Participating in the contests can have a broad and lasting impact on students' careers, whether they pursue opportunities in academia or industry.

In the academic world, the ability to present your work clearly at conferences and to the broader public has a tangible benefit. But being a good communicator can open additional career opportunities. Perrone notes that attention spans are shorter today. "The elevator pitch is becoming more important and critical in determining a variety of opportunities," she says. "That three-minute spiel has a greater impact and opens up more doors to you than it probably did in the past."

Setting up an elevator-pitch competition

Although it's incredibly rewarding to establish a 3MT-style contest at your university, it can be quite daunting. Here we present some of the key steps to doing so. Interested readers should also consult the extensive resources available on the University of Queensland's official 3MT webpage that are designed to help individuals start a similar competition at their institution. (If you want to use the 3MT name, you will also need to receive permission from the University of Queensland, which has trademarked the logo and brand.)

The first step is to recognize that one individual usually needs to spearhead the push to start an elevator-pitch competition on campus.

That person needs to not only get the administration excited about hosting a competition but, more importantly, secure financial backing. Costs for a pitch contest vary depending on scale, but there are typically five main expenditures to consider: room rentals, catering, prizes for winners, promotional materials and badges, and, if you want to incorporate a training program into the competition, the cost of a speaking coach. That usually runs to around $20 000 in total, according to d'Alarcao. Administrators may be swayed by the argument that a competition is beneficial to students, but they are often more easily persuaded when informed about how its public-facing nature provides the university with exposure to the local community and the alumni base.

The second step is more complicated: working out the logistics of the competition. When and where will it be held? Who will be the judges and moderators? What training, if any, will be provided? How will students sign up? How many students is there space for? Those issues and many others need to be worked out at least six months in advance. Organizing an online competition presents its own challenges. Although they are generally more accessible and allow family and friends to easily watch loved ones present, online events are a "huge lift" on the back end, says Perrone.

Recruiting students is the next step. That can be accomplished by emailing the graduate student body and securing small cash prizes to use as an incentive. Sharing footage from similar competitions can assist in recruiting participants. Another helpful tip is to mention the competition to faculty members, who are usually eager to have their group's work publicized and can nudge their students to enter. The application process should require students to state how far along they are in their project, and that information can be used to filter out applicants if too many individuals enroll. We suggest that after students sign up, organizers reach out to each one's adviser to make sure that they are on board with their student com-

A personal experience

I first discovered the Three Minute Thesis competition in 2017 during the first year of my PhD program at the University of Western Australia (UWA) in Crawley. I've always had a lot of anxiety about public speaking, so my initial reaction was that the competition was definitely not for me. Fortunately, I had met a few other PhD students who had entered the competition before. They convinced me that it was fun and that I should give it a try. So I pushed my nerves aside and signed up.

At the time, UWA offered a few modest training programs to help students prepare for the competition. I attended a workshop on how to write my talk, and another one, led by someone from the theater department, about how to deliver it. That second workshop was particularly memorable because I had never considered the performative aspect of giving a talk. I spent hours writing my talk and practiced delivering it every chance I could get. I remember reciting it aloud in the shower, while walking around campus, and in the lab when I needed a break from other work.

Finally, the day of the competition came, and I was so nervous. With sweaty palms and shaky knees, I got up and delivered my talk, "No hard feelings: Using tissue stiffness for non-invasive cancer detection." I was so consumed by nerves that I don't think I paid much attention to the other talks. At the end of the day, tension was high as they prepared to announce the winner. To my surprise, it was me! I was awarded an oversized check and a trip to Brisbane to represent UWA in the regional Asia–Pacific Three Minute Thesis competition. Because the competition was filmed, I also ended up with a nice video to show my family and explain what I was doing with my PhD.

Even though I was less successful at the regional competition, the experience was transformative. I received a huge confidence boost in public speaking, and I still use the skills that I learned in the workshops in my conference presentations today. Although I still get nervous every time I give a talk, I now know that it's something I can handle.

Gavrielle R. Untracht

peting and that there are no intellectual property issues with the project topic. Once students are registered, training can begin.

The competition itself typically involves preliminary and final rounds, which each have three judges and a moderator. At SDSU, for example, 24 students are accepted into the competition. In the preliminary round, they are split into four groups of six students. The top two students in each group advance to the finals. Each speaker has three minutes to give their presentation; their background slide is preloaded onto a computer. Remaining time is indicated on a large countdown clock. After each talk, the judges tally the scores while the moderator briefly interviews the speaker about their future research plans and what they hope to do after graduating. Judging takes about two minutes to complete, so each participant should be allotted about five minutes. With a bit of extra time for introductions and conclusions, the preliminary rounds usually take about 45 minutes, and the final typically lasts about an hour.

Marie Haverfield, one of the judges at the 2025 San José State University Grad Slam, watches attentively during a presentation. (Photo by Robert C. Bain, © 2025 SJSU.)

A critical need

Science communication is fundamental to bridging the gap between researchers and the public, for fostering public trust, and for ensuring that scientific knowledge informs public policy. Especially in the current political climate, which is rife with misinformation and distrust, scientists have a responsibility to ensure that our research can be communicated in a way that the public understands. So much depends on that communication, including convincing legislators to allocate funding to scientific research, ensuring access to the most up-to-date public-health policies, and fighting climate change. Participating in competitions like the 3MT can provide emerging research leaders with the skills that they need to become scientific ambassadors to the public.

In the words of Mark Telling, the director of the Institute of Physics's UK- and Ireland-wide Three Minute Wonder competition, "At a time when a growing number of platforms demand succinct sound bites, the ability to communicate STEM ideas to lay audiences across different sectors using inventive yet clear and credible ideas has never been so important." PT

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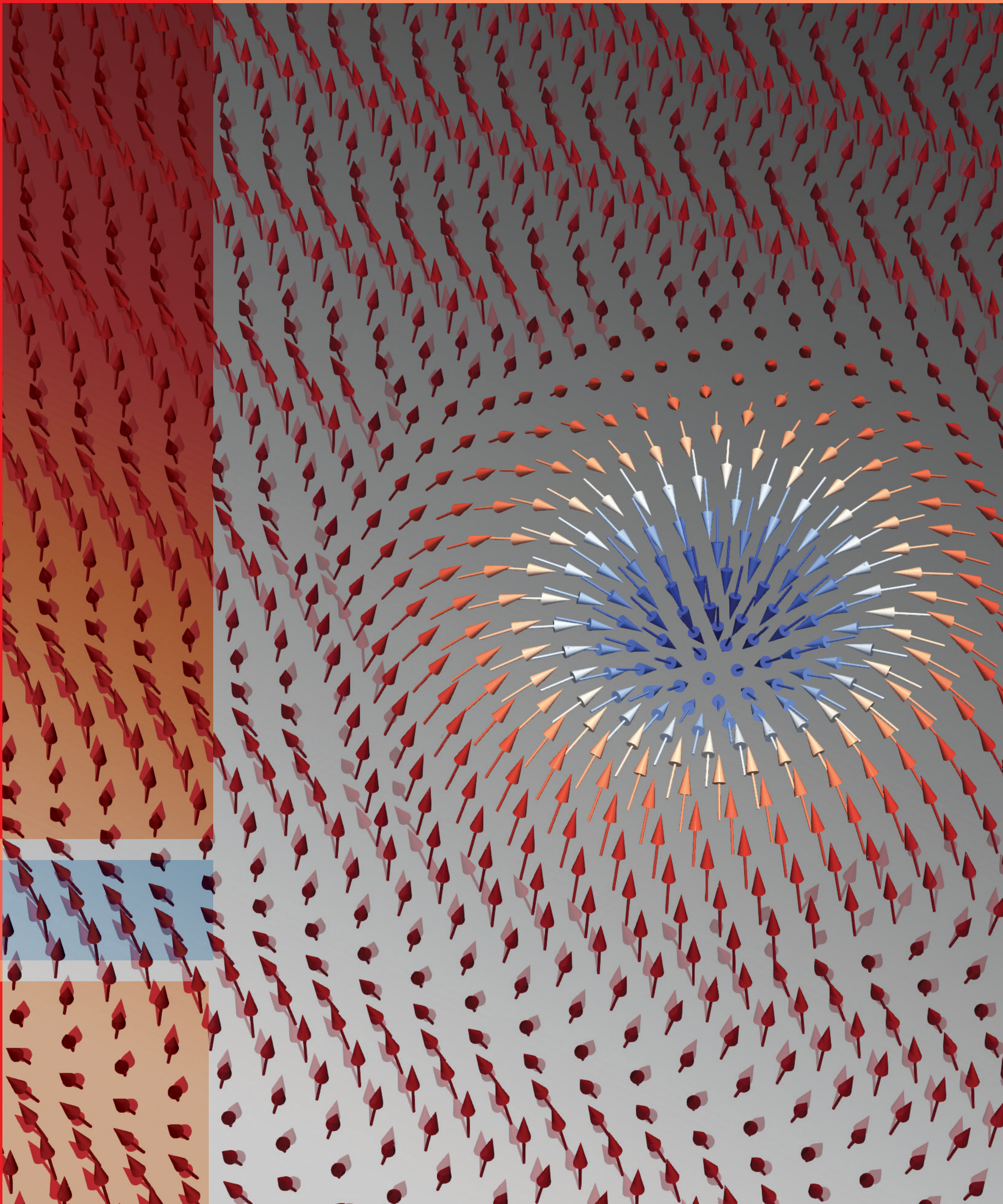
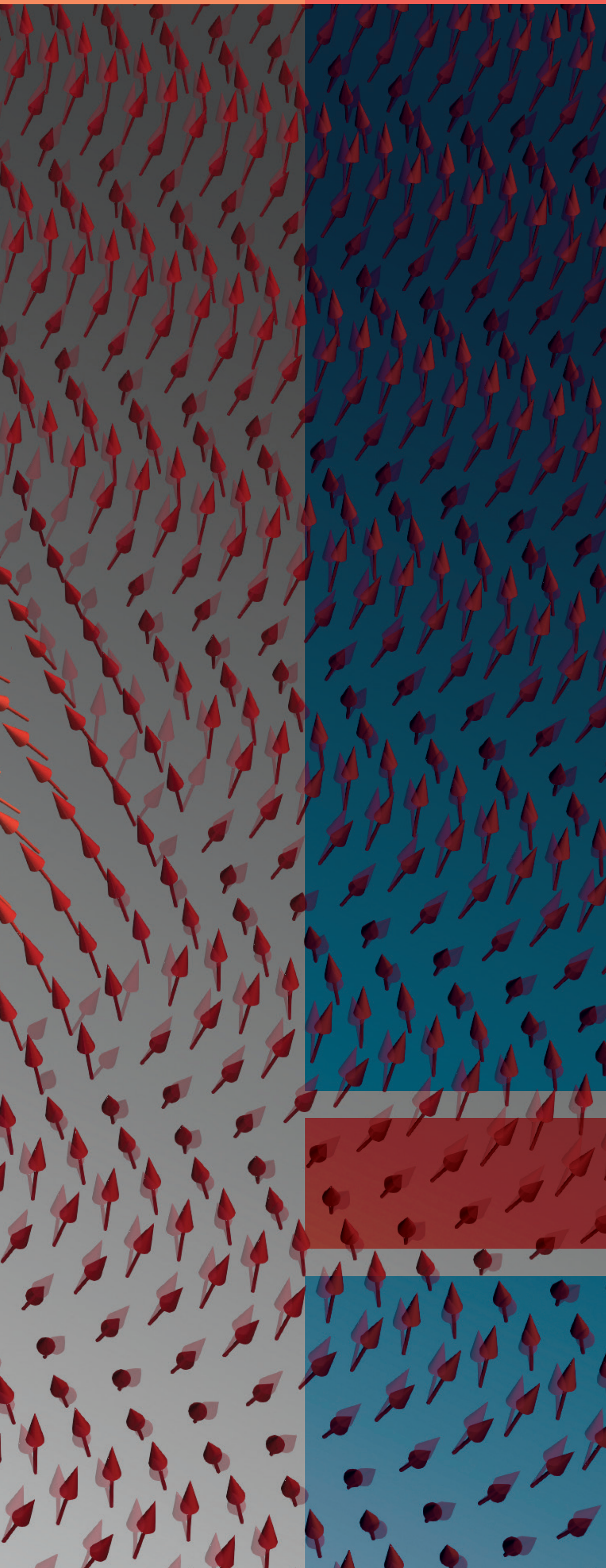
Gavrielle Untracht, who won the 2017 3MT competition at the University of Western Australia, is an assistant professor in the department of health technology at the Technical University of Denmark in Kongens Lyngby. Her research focuses on biophotonics. After being selected as an Optica ambassador in 2024, she developed a training workshop to help students prepare for three-minute pitch competitions. **Matt Anderson** is a Senate Distinguished Professor in the physics department at California's San Diego State University, where he is the director of the Grad Slam competition. His research focuses on ultrafast optics and physics education. He also promotes physics on his popular YouTube channel, Physics with Professor Matt Anderson.





Magnetic skyrmions: A new frontier for quantum computing

Christina Psaroudaki and
Christos Panagopoulos

Nanoscale, topologically protected whirlpools of spins have the potential to move from applications in spintronics into quantum science.

Chirality, a geometric property that distinguishes an object from its mirror image, is a foundational concept in physics. It appears in the asymmetry of a hand, in the spiral of DNA, in the helicity of neutrinos in the standard model of particle physics, and even in the structure of galaxies. Chirality also organizes fields, such as circularly polarized light, and excitations in matter, such as graphene's low-energy electronic quasiparticles, effectively massless fermions whose handedness is tied to the direction of motion. In each case, chirality is more than just a visual feature; it affects how particles interact, limits their behavior, and produces measurable effects.

In condensed-matter physics, chirality is also manifested in magnetic skyrmions, illustrated in figure 1, which are nanoscale spin textures characterized by smooth spatial winding and topology that protects them against small perturbations. (See the 2020 *PT* article "The emergence of magnetic skyrmions," by Alexei Bogdanov and Christos Panagopoulos.) First proposed in particle physics and later identified in magnetic systems, skyrmions bridge abstract mathematics and real materials. Recognized for their robustness, small size, and efficient response to tiny currents, magnetic skyrmions have been explored in the past decade for ultradense memory, reconfigurable logic, and neuromorphic devices in the field of spintronics.

Chirality can also act as a quantum variable. Circularly polarized photons already serve as qubits in optical platforms.[1] Nanophotonic waveguides—tiny structures that guide light on a chip—enable directional emission and spin–photon conversion. Chiral electronic channels, such as quantum Hall edge states, enable one-way signal routing and support devices like microwave circulators in superconducting circuits. Magnetic skyrmions offer a geometric path to similar functionality. Their internal twist, known as helicity, indicates the handedness of the spin rotation. In suitable materials, that degree of freedom can be promoted from a continuous angle to a quantized two-state system. Helicity itself becomes the information carrier, which opens a route toward scalable quantum architectures rooted in magnetism and topology.

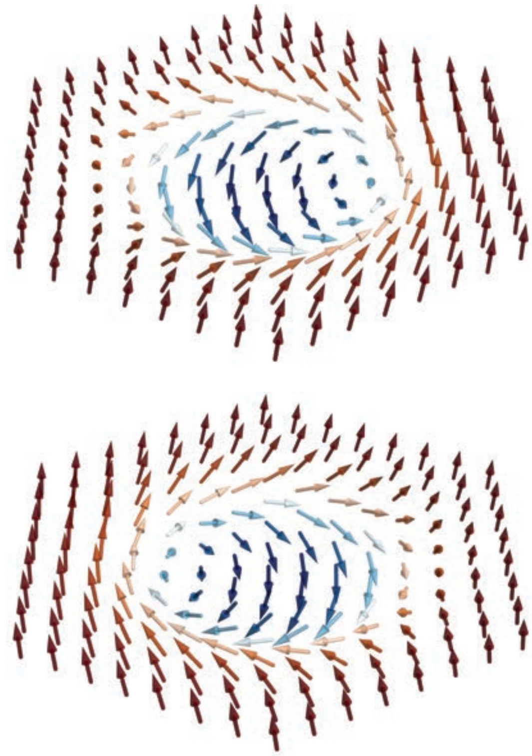


Figure 1. Magnetic skyrmions. These nanoscale whirls of spins are characterized by central spins that point opposite the surrounding magnetization. Colors indicate the local spin direction, which rotates within the plane as an observer moves outward from the center. The skyrmions shown have a skyrmion number of 1, corresponding to a single robust topological twist. Skyrmions are chiral, meaning that they are not identical to their mirror images.

Topological textures in magnetism

Magnetic skyrmions are nanoscale whirlpools of spins whose orientation winds smoothly from core to edge. At the core, the spins point opposite the ambient magnetization. As you move outward from the center, the magnetization rotates within the 2D plane of the skyrmion until it aligns with the ambient magnetization at the perimeter, as shown in figure 1.

That winding is captured quantitatively by the skyrmion number, a topologically invariant integer that counts how the spin directions evolve across the texture. In a skyrmion, the spins point in all possible directions as an observer moves from the center to the edge; the full range of orientations is covered once. That topological characteristic endows skyrmions with an unusual kind of robustness against defects and disturbances: A skyrmion texture may be perturbed, stretched, or translated, but it cannot be unwound without introducing a discontinuity, and that makes skyrmions exceptionally stable.

The stabilization of skyrmions in materials depends on competing magnetic interactions and material symmetry.[2] In systems that lack inversion symmetry, such as certain chiral magnets, spin–orbit coupling gives rise to the interactions that favor chiral spin arrangements and can stabilize skyrmions that have a fixed helicity. Skyrmions were first observed in those systems, in materials such as MnSi and FeGe. They appear in a narrow temperature and magnetic field range near the magnetic-ordering transition—the point at which a material's spins collectively settle into an ordered state.

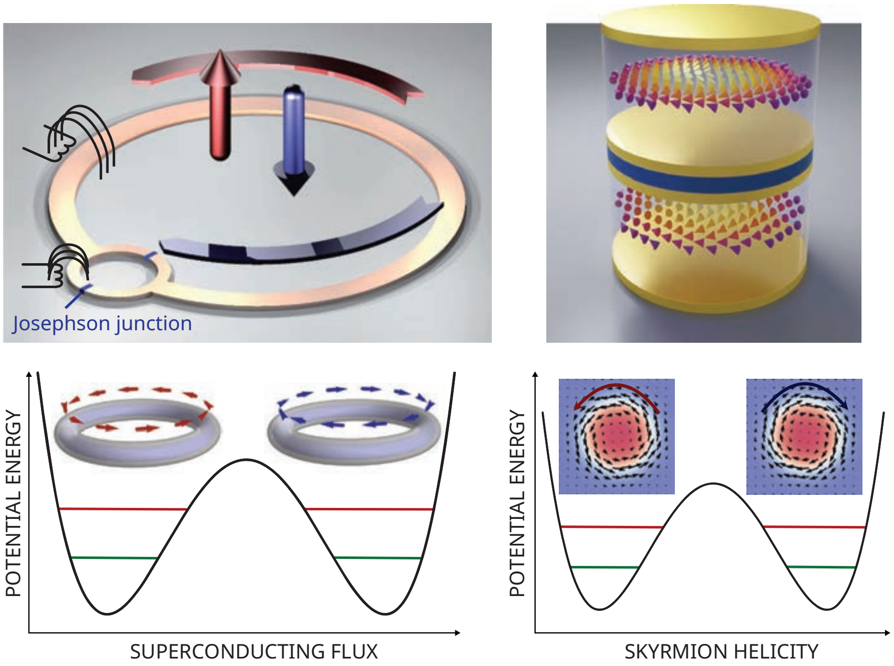


Figure 2. Chiral qubits. In a superconducting loop **(top left)** interrupted by Josephson junctions, clockwise and counterclockwise circulating currents form the two states of a flux qubit. In magnetic skyrmions **(top right)**, helicity can be promoted from a continuous variable to a quantized two-state system that can be used as a qubit. In both cases, the double-well potential illustrates how chirality provides a natural two-level structure for quantum information. Green and red lines mark the lowest and first-excited quantized energy levels, respectively, and they are split by quantum tunneling between the two wells. (Figure adapted from refs. 6 and 12.)

More recently, skyrmions have also been realized in a novel category of centrosymmetric frustrated magnets, which includes materials such as Gd_2PdSi_3 and $Gd_3Ru_4Al_{12}$. In those materials, competing quantum mechanical exchange interactions and spin–spin couplings that favor incompatible spin alignments create conditions in which skyrmion helicity is no longer fixed but instead can vary continuously at low energy. That continuous variation makes it easy to manipulate dynamically using external fields.

Some of the compelling advantages of skyrmions have been demonstrated in classical information technologies.[3,4] Their small scale, from tens of to a few hundred nanometers, suits high-density storage, and the low currents needed to move them imply energy-efficient operation. In classical spintronics, those qualities have motivated the vision of racetrack-memory devices, in which skyrmions act as mobile bits whose interactions can also implement logic operations.

A separate line of work proposes to exploit the nonlinear dynamics and multistability of skyrmions for neuromorphic (brain-inspired) and certain neural-network functionalities. Such proposals further illustrate the versatility of the textures in classical systems. This article examines a different application: skyrmions as a controllable quantum state in magnetic materials with weak energy loss, the conceptual foundation for skyrmion-based qubits.

Quantizing helicity

The discovery of stable atomic-scale skyrmions at temperatures of a few kelvin has highlighted the limits of classical micromagnetism. Quantum signatures appear in the spectra of magnons (quantized spin-wave excitations), in texture dynamics, and in phase transitions, and theory shows that even skyrmions comprising thousands of spins can display such behavior, which blurs the line between classical and quantum particles. Together with advances in quantum-sensitive magnetometry and materials with low ohmic dissipation, those developments have given rise to a research direction focused on the quantum properties of skyrmions.[5]

At the heart of that line of investigation is the realization that internal degrees of freedom in skyrmions can be quantized and used as qubits. Among them, helicity, the sense of in-plane spin rotation along a radial path from the center of the skyrmion outward, is a promising candidate because it can support coherent and controllable two-level dynamics.[6]

Unlike the skyrmion's topological charge, which is always quantized and robust, helicity can remain continuous in systems without strong spin–orbit coupling or crystalline constraints. In such environments, often realized in centrosymmetric magnets, helicity can be dynamically excited by external fields, anisotropies, or pinning potentials and, under the right conditions, quantized. By engineering the potential-energy landscape, researchers can create a bistable system in which the skyrmion occupies one of two energetically favorable states, clockwise or counterclockwise in-plane spin swirlings, as illustrated in figure 2. Classically, those states are distinct, stable configurations. But in the quantum regime, tunneling between them gives rise to superpositions and enables qubit behavior.

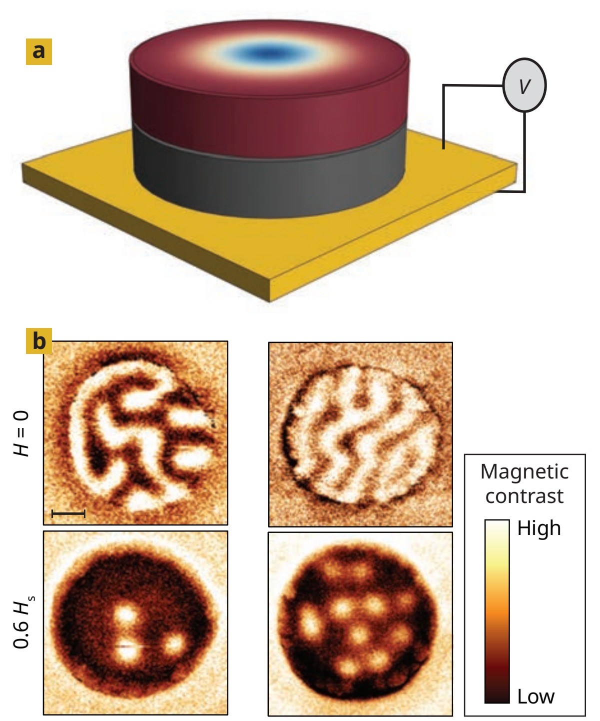


Figure 3. Skyrmion devices. **(a)** A conceptual sketch of a skyrmion-hosting nanodisk, consisting of a magnetic multilayer stack (cylinder) combined with a piezoelectric layer (gold) and a voltage electrode for local electrical control. **(b)** Experimental realization of confined magnetic textures in nanodots fabricated from multilayer stacks of iridium, iron, cobalt, and platinum, and imaged by magnetic force microscopy (scale bar is 100 nm). As the applied magnetic field *H* is increased toward the saturation field H_s, stripe domains evolve into isolated, stable skyrmions, demonstrating controlled skyrmion confinement. (Panel (b) adapted from ref. 13.)

Quantized helicity leads to discrete energy levels that naturally form a two-level system. Thus, the helicity states readily map onto the familiar language of quantum computing. Left- and right-handed helicities form the two logical states of a qubit, while their coherent superpositions mirror the quantum states used in today's qubit platforms. Like other qubits, the system can be prepared in either state or in a quantum superposition of both, and external fields can be used to drive transitions between them. (For more information about different qubit platforms, see the box on page 53.)

The parallels between superconducting flux qubits and skyrmion helicity-based qubits are depicted in figure 2. For both, chirality provides a natural double-well potential that enables two-level quantum dynamics. For helicity-based skyrmion qubits, the energy splitting is typically in the gigahertz range and is directly compatible with standard microwave technologies already employed in superconducting and spin-based qubits. At cryogenic temperatures, where thermal excitations are suppressed, the coherent dynamics of helicity qubits become experimentally viable.

Skyrmion qubits offer an operating regime that's complementary to but distinct from superconducting and semiconducting platforms. Their quantum states are encoded in collective spin textures rather than charge, so they are intrinsically less sensitive to electric field noise, charge fluctuations, and dielectric loss, which are dominant decoherence channels in charge-based architectures.

In magnetic insulators, the absence of conduction electrons removes ohmic dissipation. The remaining sources of dissipation are magnetic and phononic baths, which are typically weaker and more controllable. Although the helicity states themselves are not topologically protected, the underlying skyrmion texture is a robust, spatially extended object, which provides resilience to disorder and to local fluctuators that would strongly affect single-spin qubits.

Architecturally, skyrmions occupy 20–50 nm disks. Even with local control structures such as near-field microwave lines, nanoscale gates, or magnonic waveguides, the practical qubit spacing lies in the 10–100 nm range, which is three to four orders of magnitude denser than superconducting circuits. Perhaps most importantly, the same mechanisms that allow classical skyrmions to be moved, written, and erased via electric currents or magnetic fields can be employed in the quantum regime to manipulate and read out qubit states. Thus, skyrmions benefit from full compatibility with the mature spintronics ecosystem, including thin-film multilayers, nanodisk patterning, and on-chip microwave or gating architectures already established in magnetoresistive random-access memory (MRAM) and nanomagnonics.

Several recent works have outlined how skyrmion qubits could be created, manipulated, and even entangled in tailored thin-film or multilayer environments, but those concepts remain theoretical at present. Examples of experimental skyrmion confinement are shown in figure 3. But the quantization of the helicity mode, the appearance of discrete helicity levels, and the coherent manipulation and readout of that internal degree of freedom remain to be observed. Those key experimental milestones would elevate the skyrmion from a classical information carrier to a genuine solid-state qubit. The control, readout, and coupling approaches discussed below should be viewed as prospective pathways, grounded in known skyrmion dynamics, the mature spintronics-fabrication ecosystem, and quantum sensing tools. The vision is clear: qubits that combine stability, scalability, and seamless compatibility with spintronic technologies.

Control, readout, and decoherence

A robust qubit must support reliable initialization, coherent manipulation, accurate readout, and long coherence lifetimes. For helicity-based skyrmion qubits, the control of skyrmion helicity is rooted in the same physics that governs classical skyrmion manipulation.

The helicity qubit can be initialized by biasing the system into a chosen helicity state using static electric or magnetic fields, or by relying on thermal relaxation to reach the ground-state orientation. Oscillating external fields can drive transitions between helicity states and provide the basis for quantum gates. Magnetic systems also offer a diverse toolkit for fine-tuned manipulation: Electric fields can modify anisotropies through magnetoelectric coupling, strain can alter exchange interactions, and spin-transfer torques or local gating can shape the helicity potential.[7]

A skyrmion-based qubit approach is particularly appealing for quantum information applications because the relevant excitations emerge from the collective motion of many spins. In the helicity mode, the dynamics are not confined to a single spin but instead involve the coordinated motion of many spins across the entire skyrmion texture. That delocalization provides some degree of protection against local noise sources and defects, and that protection enhances coherence. At the same time, the collective nature of helicity makes it more vulnerable to global fluctuations and dissipative processes in the host lattice, both of which can drive decoherence and the loss of quantum information.

Primary decoherence channels include thermal spin-wave excitations, lattice vibrations, and material imperfections. Achieving coherence times sufficient for quantum gate operations within the microsecond regime demands high-purity materials, low-loss dielectrics, clean interfaces, and precisely engineered heterostructures. Operating at cryogenic temperatures reduces the thermal population of magnons and phonons, which helps to maintain the delicate energy splitting that defines helicity levels.

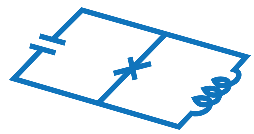
Readout at the quantum level has not been realized, but several strategies have been proposed. Magneto-optical techniques, such as Kerr or Faraday effects, may register changes in magnetization associated with distinct helicity states. Spectroscopic approaches, such as Brillouin light scattering and ferromagnetic resonance, offer the possibility of detecting transitions in the gigahertz regime. Electronic detection might exploit helicity-dependent skyrmion motion driven by spin-transfer torques or other current-induced effects. That motion could produce measurable electrical signatures, for example, through spin pumping or a helicity-dependent contribution to the Hall response. Each readout scheme requires optimization for quantum sensitivity and minimal disturbance.

Coupling and scaling up

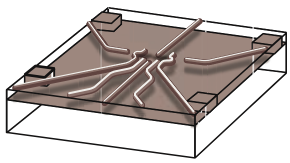
Quantum computation depends on entangling qubits, which in turn relies on coherent coupling mechanisms.

Diverse qubits serve diverse purposes

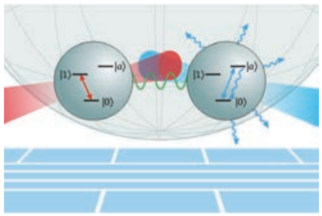
Superconducting circuits



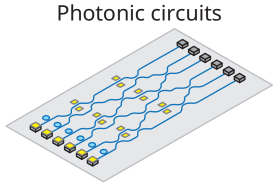
Solid-state spins



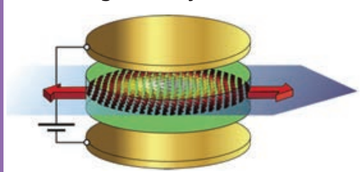
Trapped ions



Photonic circuits



Magnetic skyrmions



Researchers developing various quantum computing platforms, such as superconducting circuits and trapped ions, have made remarkable progress in recent decades. Yet each platform faces unavoidable trade-offs in performance and design flexibility. A diversity of approaches is key to overcoming trade-offs in coherence, scalability, and control. That has motivated the search for alternative realizations that can introduce new physical advantages.

Different architectures bring complementary strengths: Superconducting circuits enable fast gate operations and scalable chip integration, solid-state spins promise dense integration, trapped ions offer exceptional coherence and high-fidelity control, and photonic circuits excel at long-distance communication. In that landscape, skyrmion-based qubits stand out as candidates that could unify several transformative features such as nanoscale dimensions, compatibility with thin-film technologies, and the exceptional robustness of topologically protected spin textures. Advancing the skyrmion platform not only diversifies the quantum hardware toolkit but also opens pathways that may complement the capabilities of today's leading approaches.

(From the top down, figures are adapted from ref. 14; adapted from ref. 15; adapted from ref. 16; courtesy of Galan Moody; and adapted from ref. 17.)

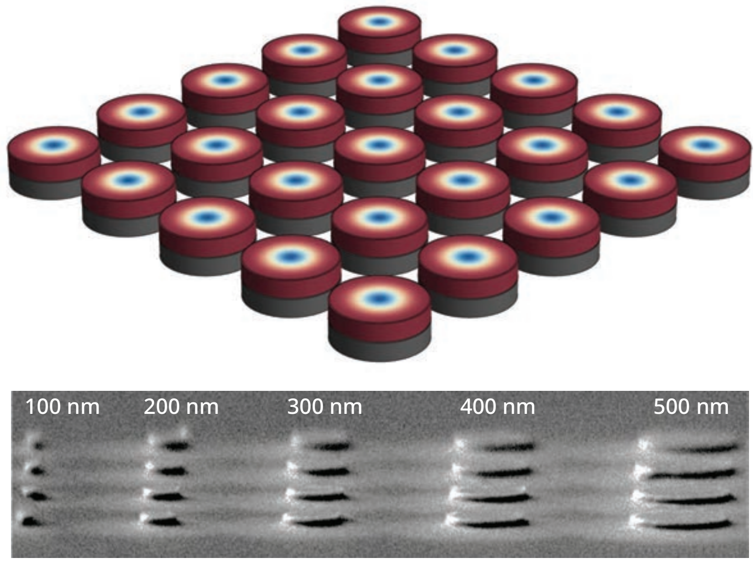


Figure 4. Scalability of skyrmion qubits. Skyrmions can be confined in lithographically defined nanodisk arrays, as shown schematically in the top panel. The nanodisk diameters are on the order of 20–50 nm. Skyrmions have been generated in arrays of layered nanodots of different sizes. One such array is shown in the lower panel. Optimized fabrication processes continue to improve the scalability of such materials. (Lower panel adapted from ref. 13.)

In multilayer magnetic films, skyrmions can couple via exchange interactions if the textures are aligned closely or via dipolar magnetic interactions when the distances are slightly larger.[6] Inter-skyrmion coupling can be engineered to depend on helicity, because the relative position of two skyrmions sets their interaction energy. That helicity–helicity interaction can be harnessed to implement two-qubit gates, fundamental building blocks for universal quantum computation.

Engineers can tune coupling strengths through materials engineering, such as the use of magnetic multilayers with spacer layers that control direct skyrmion–skyrmion interactions. Another strategy is hybrid coupling via microwave cavities. If skyrmion-hosting films were embedded in electromagnetic resonators, qubits could interact through virtual photons, and that would enable long-range entanglement and integration into larger quantum networks. Growing research interest in cavity optomagnonics and quantum magnonics is reflected in work that couples spin excitations to cavity photons.[8]

From a fabrication standpoint, skyrmion qubits would benefit from compatibility with planar nanofabrication and could be used with techniques already common in the magnetic memory and spintronics industries. Figure 4 highlights the scalability of lithographically defined skyrmion arrays. Skyrmion-based devices inherit the same degree of CMOS compatibility as established spintronic platforms such as spin–orbit torque MRAM, where thin-film magnetic stacks and on-chip microwave structures are routinely integrated with silicon.[9] Lithographically defined patterns in thin films can guide skyrmion positioning, while local gates or current lines enable individual addressability, allowing for the fabrication of 2D skyrmion-qubit arrays.

Although large-scale skyrmion-based processors remain a long-term objective, researchers have already stabilized, transported, and controlled multi-skyrmion arrays in nanotracks and sub-100-nm dots using established fabrication techniques. Scalability in quantum devices is not just about fitting many qubits together. It also requires that each qubit can be operated and read out reliably, without interference from its neighbors, and that the system can be kept cold enough to preserve quantum coherence. Achieving that across a large array of skyrmions is challenging, since it demands uniform materials and precise control of their spacing and interactions. Encouragingly, research in skyrmionics has already made progress in patterning, controlling pinning sites, and tuning interactions, and that work has provided a strong foundation for future quantum designs.

The road ahead

Despite an elegant theoretical framework, skyrmion-based quantum computing is still in its infancy. The first decisive milestones will be the experimental demonstration of helicity quantization in a solid-state system and the detection of coherent superpositions of helicity states. Showing that a collective spin texture can host a quantized internal degree of freedom would not just validate the idea of a helicity qubit—it would represent a breakthrough for condensed-matter physics by revealing new ways in which geometry and quantum mechanics intertwine.

Reaching that point will require advances on several fronts. Materials optimization is critical to hosting stable, long-lived skyrmions that remain coherent at cryogenic temperatures. The helicity degree of freedom must be tunable yet robust, and maintaining that balance demands precise control over interfaces, defects, and anisotropies. At the same time, researchers need tools capable of detecting and manipulating helicity with high fidelity. Hybrid approaches that link skyrmions to superconducting circuits, optomechanical resonators, or spin defects may provide the sensitivity and control needed to take those first steps.

That road map echoes the early days of other qubit platforms. Superconducting qubits, now a leading platform, began with crude Josephson junctions and evolved over two decades into mature systems with coherence times exceeding 100 μs.[10] Similarly, nitrogen–vacancy centers in diamond grew from spectroscopic curiosities to precision quantum sensors.[11] Progress in all cases has been driven by a nonlinear feedback loop between theory, materials development, and advances in experimental design. Skyrmion-based quantum systems may follow a similar trajectory.

Beyond their technological promise, skyrmion qubits raise deeper scientific questions. They challenge us to see topological spin textures not as static curiosities but as dynamic, quantum-coherent objects. If realized, skyrmion qubits could both expand the practical toolkit of quantum information science and reshape how we think about the quantum potential hidden within condensed-matter textures.

A twist in quantum technology

Spin patterns remind us that some of the most notable advances in quantum science arise directly from the geometry of matter itself. Magnetic skyrmions mark a striking new frontier in the search for robust and scalable quantum platforms. Their properties make them particularly suited for both conceptual insight and practical innovation. Although challenges remain in materials, control, and coherence, the combination of robustness and quantum behavior suggests a path to devices that go beyond incremental advances. It points to new ways of processing information rooted in the geometry of condensed matter.

Chirality links phenomena as diverse as the double helix of biology and the handedness of particle physics. Skyrmion-based qubits would use that geometric property to encode and manipulate quantum states in collective spin textures and represent an intersection of topology and quantum information science. Should we succeed in guiding these textures into coherent superpositions, the future of quantum computing may rest on the graceful twist of a spin vortex. **PT**

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

Steluta Dinca puts solar shingles to the test

By Toni Feder

Photovoltaic reliability engineer, GAF Energy

BS, physics, University of Bucharest, 1997
PhD, physics, Syracuse University, 2010

What was your research focus?

Charge transport and modeling in solar cells. While at Syracuse University as a postdoc and other research positions for more than a decade, I developed an *in situ* solid-state polymerization method that creates ordered, extended polyacetylene chains with unique electrical properties.

(Photo by Thierry Nguyen.)

What were you looking for in a job?

I wanted to explore a topic related to solar cells and renewable energy. When, as a postdoc, I got an NSF grant, I was very happy. But I asked myself, Do I want to do this all my life? I decided I would try industry.

How did you make the transition into industry?

I looked at companies that seemed in line with my interests and reached out via LinkedIn to people to learn about their career paths and why they left academia. I asked a few to mentor me. I applied to 15 jobs that matched 80% to 90% of my skills, got 4 interviews, and joined GAF Energy in 2024.

How do you spend your time?

GAF Energy makes solar energy shingles that combine solar cells with traditional asphalt shingles. I conduct reliability and stress testing to assess product performance.

What new skills did you need?

I have learned new characterization techniques and gained experience in programming. I am also learning about being a part of a team, not only as a leader but also as a collaborator.

What do you like about your job?

I am working on many projects and learning about every aspect of the business. I like the team I work with and the fact that we are working toward the same goal. My job allows me to stay true to my values while helping make clean energy more accessible.

Is there anything you'd like to add?

My advice is to become a well-rounded scientist: Specialize, but also keep the broader picture in mind and consider how your skills can be transferred. Step out of your adviser's shadow. And don't underestimate the value of networking for your future. PT

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

FROM THE ARCHIVES
June 2006

What makes for smooth, creamy chocolate?

Chocolatiers adjust properties of chocolate's ingredients to confect a treat that feels as good as it tastes.

By Erich J. Windhab

Editor's note: The Quick Study department debuted 20 years ago with this piece on the rheology of chocolate.

Many people, when describing what happens after they bite off a piece of chocolate, would say that the chocolate melts in their mouth, then they swirl it around with their tongue to best enjoy the sweet, creamy sensation. Food scientists might describe the process differently. They'd observe that the tongue induces a shear flow within the melted chocolate layer between tongue and palate. According to Newton's law, the shear stress τ applied by tongue is the product of chocolate's bulk shear viscosity η and the shear rate, which itself is approximately the ratio of the tongue's velocity to the thickness of the melted chocolate layer. Chocolate rheology, however, is non-Newtonian; the viscosity depends on shear rate, time, and temperature. What typical consumers consider "smooth and creamy" corresponds to a viscosity of 1.5–3.5 Pa·s (pascal-seconds), at a representative shear rate of 20/s and body temperature 37 °C.

The challenge to the chocolatier and food scientist is to understand how the microstructure of melted chocolate mirrors chocolate rheology. Melted chocolate contains sugar, cocoa, and milk powder particles dispersed within a Newtonian fat melt, typically cocoa butter. Those dispersed particles assume a number of forms: They might look like cubes, platelets, fibers, or coils. Added surfactants cover the interfaces between the suspended particles and the continuous fluid phase. When the melted chocolate is sheared, a number of mechanisms all operating at the same time can induce structure in the suspension. The figure illustrates those mechanisms: deformation, orientation, deagglomeration, and agglomeration. The first three mechanisms, loosely speaking, lead to a more uniformly structured suspension and so are called structuring effects.

The structuring effects are triggered when the shear stress exceeds a characteristic value τ_0, called the yield value. Typically, τ_0 is in the range of 5–12 Pa. Once the yield value is surpassed, melted chocolate ceases to behave like a solid. With increasing shear stress, the structuring effects get further developed, and as a consequence, the viscosity decreases. At fixed shear stress, developing structure would also lead to a decrease in viscosity with time, until a shear-stress-specific equilibrium structure is reached. At a second characteristic shear stress τ_1, the viscosity reaches its minimum value η_{min}, which is typically about 0.5–2.0 Pa·s; the structuring is said to be "completed." As the shear stress increases beyond τ_1, the viscosity remains constant until a new characteristic stress τ_2 is reached. Once τ_2 is exceeded, shear-induced structure collapse or "superstructuring" may occur; one type of superstructure consists of agglomerated flocculated particles. As a consequence of those structural changes, the viscosity increases with shear stress or shear rate and with time. As yet another stress τ_3 is surpassed, any superstructure degrades, and viscosity once again falls with increased stress, shear rate, and time. If structure collapse or superstructuring doesn't occur, the high-shear viscosity keeps the value η_{min}.

Surfactants such as lecithin affect interparticle interactions. Thus they help determine the characteristic stresses τ_0 and τ_1.

The fluid substrate

The structure of the particles suspended in chocolate, considered in and of itself, affects the rheology of chocolate. But those particles are suspended in a fluid with which they interact. The idea of fluid immobilization (FIM) allows one to describe the complex relationship between rheology and microstructure in chocolate. Specifically, FIM quantitatively describes how the suspended solids' concentration, size, and shape affect the shear viscosity of chocolate. In essence, FIM postulates that changes in the solids' properties lead to concomitant changes both in the quantity of fluid immobilized and in how the fluid phase is bound to or otherwise immobilized by the suspended particles.

Fluid immobilization occurs via three main mechanisms. In volume FIM (V-FIM), fluid is trapped in the pores and voids of the suspended particles or particle agglomerates. Surface FIM (S-FIM) arises when fluid is bound to particle or agglomerate surfaces. The third mechanism, hydrodynamic FIM (H-FIM), is associated with fluid binding that arises from the position and motion of the particles in the chocolate flow. H-FIM is less important for concentrated suspensions like chocolate than for dilute suspensions.

A large fraction of the solid particles in chocolate—sugar, cocoa, and milk solids—form agglomerates during the manufacturing process, in particular during the refining and mixing operations. During conching, which is a mechanical deagglomeration treatment, and other flow processes that occur after refining, those agglomerates usually become somewhat deagglomerated. As a result, the immobilized fluid fraction changes. How much it changes is a function of mechanical stress and time.

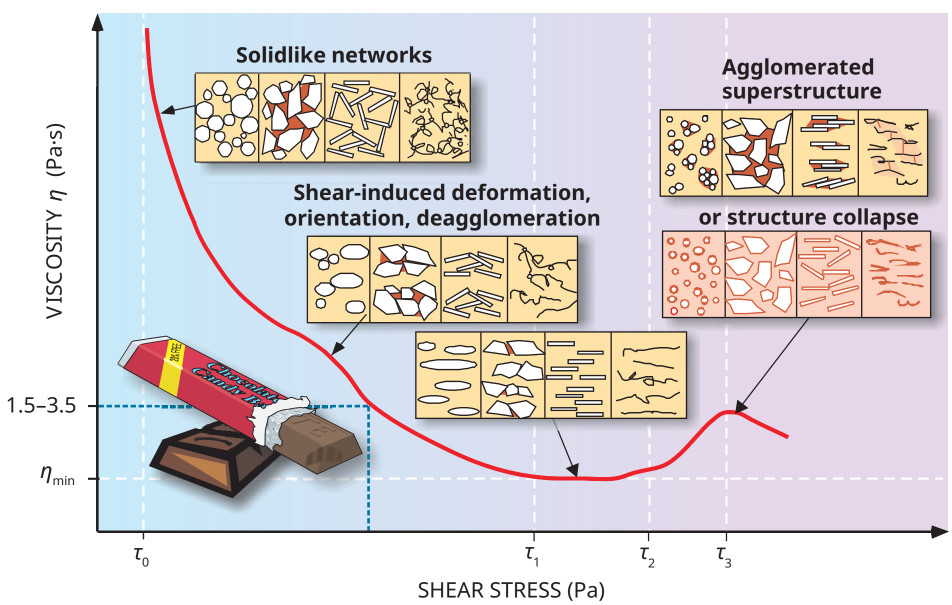
When a particle agglomerate breaks down, the fluid that had been immobilized in the agglomerate's pores or voids is released, which leads to a lower viscosity. Such deagglomeration, however, also generates new interfaces at which fluid can be immobilized, which contributes to higher viscosity. If the agglomerates have a large inner-pore or void volume, V-FIM will dominate and deagglomeration will make the viscosity decrease. Conversely, when dense agglomerates or unagglomerated primary particles are refined, S-FIM at the newly generated particle interfaces dominates and viscosity increases. Which effect will be most important in practice depends on the details of the manufacturing process.

The shapes of individual particles and the morphology of particle agglomerates also play a role in fluid immobilization and so affect viscosity. Particles can have a number of shapes, ranging from spherical to fiberlike. Because particles in dilute suspensions can move more freely, orientation and rotation effects allow the H-FIM mechanism to be more strongly developed. In concentrated chocolate suspensions, shear flow can lead to an orientation of non-spherical particles parallel to the shear direction. In the oriented suspension, a particle's rotation is hindered by its neighbors. As a consequence, H-FIM is minimized and, thus, so is viscosity. Systematic investigations with spin milk powder (fiberlike milk-powder particles) confirmed the reduction of viscosity with concentration and observed a viscosity minimum when the fiberlike particles were 10–15% of the total solid content by volume.

The most important particle morphology parameters are porosity and the distribution of inner-pore sizes. Consider different kinds of milk powders. Those with fully incorporated milk fat and high inner porosity would be expected to show the greatest V-FIM effects. And studies have indeed shown that those samples had the highest milk-chocolate viscosities. Other samples with the same milk-fat content were formed by a process in which the fat was sprayed on top of the milk-powder particles. In that case, the viscosity was reduced by more than a factor of five when compared with the maximum-viscosity systems. Moreover, the greater the fraction of particles covered with fat, the greater the reduction.

Happy customers

With the fluid immobilization concept, one can derive general rules that relate particle size, shape, and agglomerate morphology to viscosity. To obtain chocolate with low shear viscosity, one should have large particles, a high solid packing density, a low tendency



Particle microstructure has a significant impact on the rheology of chocolate. Increasing the order among the particles suspended in chocolate leads to decreased viscosity; details of how viscosity varies with shear stress (red curve) and definitions of the characteristic stresses are given in the text. The dashed blue lines correspond to a representative shear rate in the mouth of 20/s. Particle–fluid interactions also affect the rheology of chocolate. For the particle structures with yellow backgrounds, fluid is immobilized principally by being trapped in pores or voids; for the other structures, surface binding is the main cause of fluid immobilization.

to agglomerate, and a low continuous fluid phase affinity to the solid-particle surfaces so that S-FIM is minimized.

Suspensions with many different particle sizes generally form agglomerates with a high packing density. However, the small particles may also form their own agglomerates, which are not necessarily very densely packed; those tend to increase viscosity due to V-FIM. Large particles or agglomerates may also be associated with an undesirable rough texture in the chocolate. Indeed, the finest chocolate manufacturers use intensive refining techniques, including conching, to ensure that particle structures are no more than about 25 microns in diameter.

The formation of agglomerates and their packing density strongly depend on the intensity of attractive particle interactions. The particles' own properties are important, of course, but surfactants in the continuous fluid phase also have an important influence. Long-chain surfactants can strongly inhibit agglomeration. If, nonetheless, agglomeration still takes place, the surfactants' chains may encourage the formation of looser agglomerates with an increased volume-immobilized fluid fraction. That effect would lead to increased viscosity.

Consumers like smooth, fast-melting, low-viscosity chocolate. To keep them happy, chocolate makers must take into account not only a complex array of particle properties but also how particles interact, both with like entities and with specific other materials—including, of course, the palate and tongue. **PT**

Further reading

- E. J. Windhab, in *Proc. Third International Symposium on Food Rheology and Structure*, I. Marti, P. Fischer, E. J. Windhab, eds., Kerschensteiner Verlag (2003), p. 489.
- H. Attaie, B. Breitschuh, P. Braun, E. J. Windhab, "The functionality of milk powder and its relationship to chocolate mass processing [...]," *Int. J. Food Sci. Technol.* **38**, 325 (2003).
- E. J. Windhab, "Fluid immobilization—a structure-related key mechanism for the viscous flow behavior of concentrated suspension systems," *Appl. Rheol.* **10**, 134 (2000).
- E. J. Windhab, D. Hugelshofer, P. Braun, in *Proc. Thirteenth International Congress on Rheology*, D. M. Binding et al. eds., British Society of Rheology (2000), p. 416.

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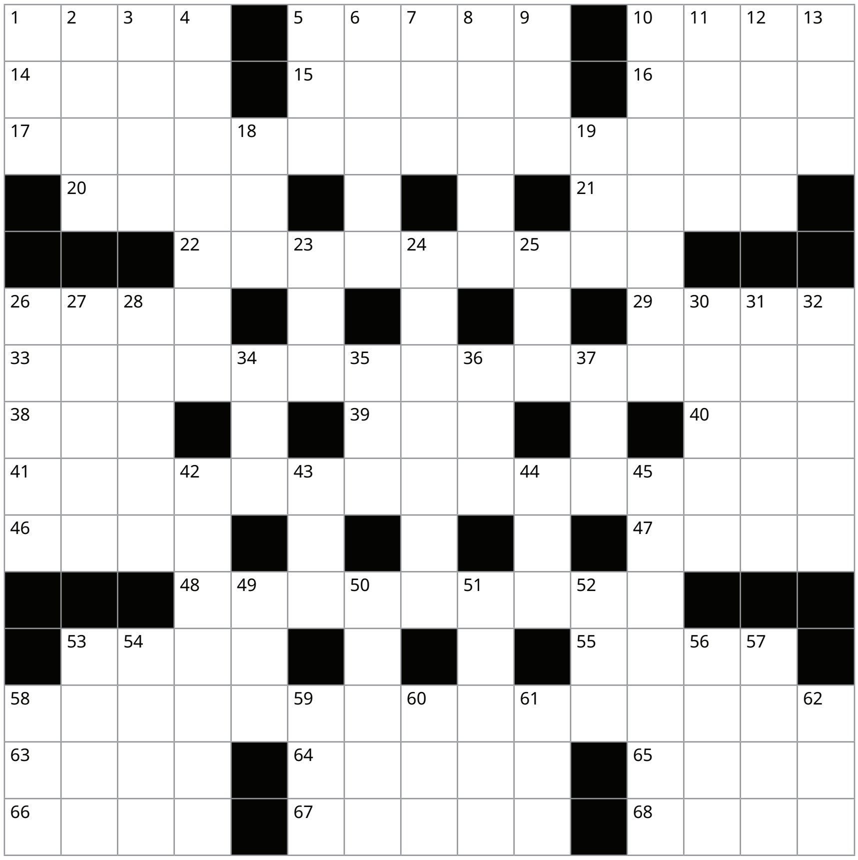
CROSSWORD



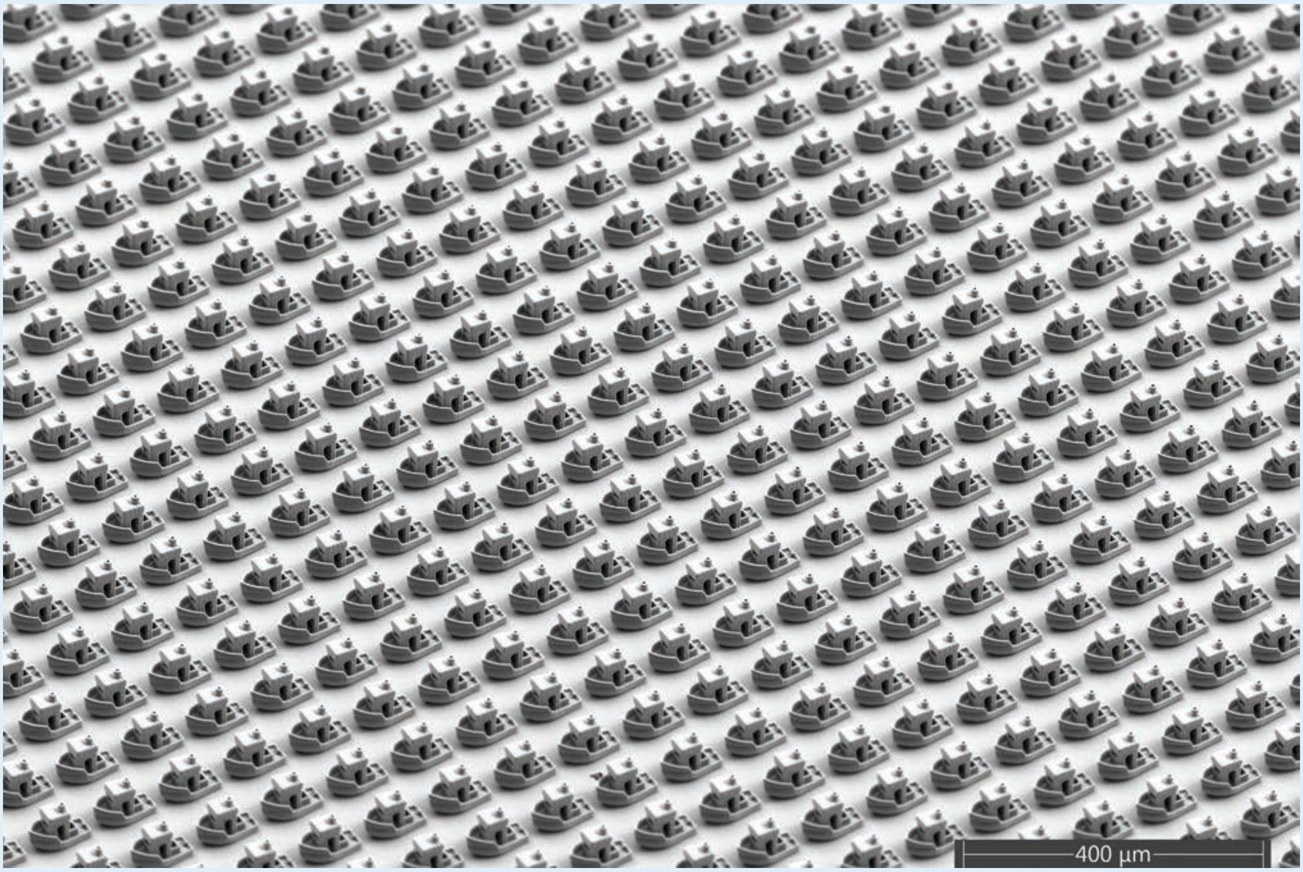
By Doug Mar

ACROSS

1 Electronic component in a credit card
5 It may be hazardous
10 Ceremonial splendor
14 Sharpen, as skills
15 Love, in French
16 Spirited horse breed
17 Too many of these might lead to sunburn
20 Quantum ____ (artificial atoms)
21 Number for one?
22 Fully informed
26 Ski lift, or the symbol for the top antiquark
29 Metal that you can pump?
33 Predecessor mission to the spacecraft alluded to by the hexagonal pattern of the inner dark squares in this puzzle's grid
38 Greek letter used to designate dynamic viscosity
39 Numerical rating system used in chess (named after its physicist inventor)
40 Unit of energy a bit greater than the proton rest energy (abbr.)
41 Output of a thermal imaging camera
46 Repetitive learning method
47 Perceive acoustic waves
48 Physics phenomenon that can break a wine glass
53 Famous supernova remnant, or a unit of x-ray intensity
55 Android with a positronic brain and a pet cat named Spot
58 What the human eye can see
63 Off-rd. transporters
64 Animal that appears on the flags of Kazakhstan and Egypt
65 Coin whose back side has 12 stars
66 Category
67 Company that manufactures microprocessors
68 Harvest, as crops or benefits

DOWN

1 Steven ___, former energy secretary with a Nobel Prize in Physics
2 Grasp
3 Fascinated by
4 Apply a force to influence a trajectory
5 Sound-file extension
6 ___ acid (protein component)
7 Singer Phillipa of *Hamilton*
8 Iconic flower of Turkey
9 Before, in poetry
10 Lampoonish
11 Thesis defense, often
12 Healthcare clinic with its main office in Minnesota
13 Nonprofit network with shows like *Nova*
18 Venomous snake
19 Lao-___
23 Make a knot in
24 Fictional physicist Cooper from *The Big Bang Theory*
25 Part of a cyclone with the lowest barometric pressure
26 *A League of ___ Own*
27 Words that precede "cigar"
28 Toward the stern
30 Extreme storm wave
31 Musical drama in which a Valkyrie might appear
32 Under no circumstances
34 Meadow
35 Three-way joint named for its shape
36 Chop off
37 SI base unit defined by a specific property of cesium, for short
42 Escalation action in a poker game
43 Blog feed format (abbr.)
44 Ammonium or fluoride
45 Performance venue
49 Flow back, as the tide
50 Neptune's domain
51 Object that had an impact on Isaac Newton?
52 Public health org. based in Atlanta
53 Population center
54 Answer an invitation
56 T, on a test
57 Surrounding glow
58 Large container for liquids
59 Hawaiian garland
60 The Beatles' ___ Pepper
61 Unagi, at a sushi bar
62 Floor cleaner



Tiny boats demonstrate a new nanolithography technique

By Sarah Wells

Each of these tugboats is 85 μm long, roughly twice the size of a human skin cell. Made from an acrylic polymer, the boats are a demonstration of a new lithography technique for 3D-printing applications. The technique was introduced by Xiaoxing Xia of Lawrence Livermore National Laboratory, Jonathan Fan of Stanford University, and their colleagues.

The new approach is an iteration of two-photon lithography (TPL), which uses a femtosecond laser to polymerize nanoscale features, such as the hull of one of the boats pictured, in a photoresin. Unlike standard photolithography, TPL does not require a photomask as a stencil. TPL has been used to demonstrate proof-of-concept applications in the lab for areas like microelectronics and biomedicine, but it can be slow and is difficult to scale. Instead of employing the standard TPL approach, which involves a laser with a single focal spot, Xia, Fan, and colleagues used ultrathin optical elements called metalenses to split the laser into up to 120 000 coordinated focal spots that can print simultaneously across an inch-scale area at about 1000 times the rate of a standard TPL technique. As part of a demonstration, the researchers used a smaller metalens array of a similar design to print this fleet of 10 000 boats in 30 minutes.

Xia says that the new technique may enable TPL to transition from a tool for labs to one useful for high-precision manufacturing. Beyond printing tiny boats, metalens TPL eventually could be used to, for example, produce fuel capsules for nuclear fusion experiments. (S. Gu et al., "3D nanolithography with metalens arrays and spatially adaptive illumination," *Nature* **648**, 591, 2025; image courtesy of Songyun Gu.) **PT**

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