PHYSICS TODAY

August 2025 • volume 78, number 8

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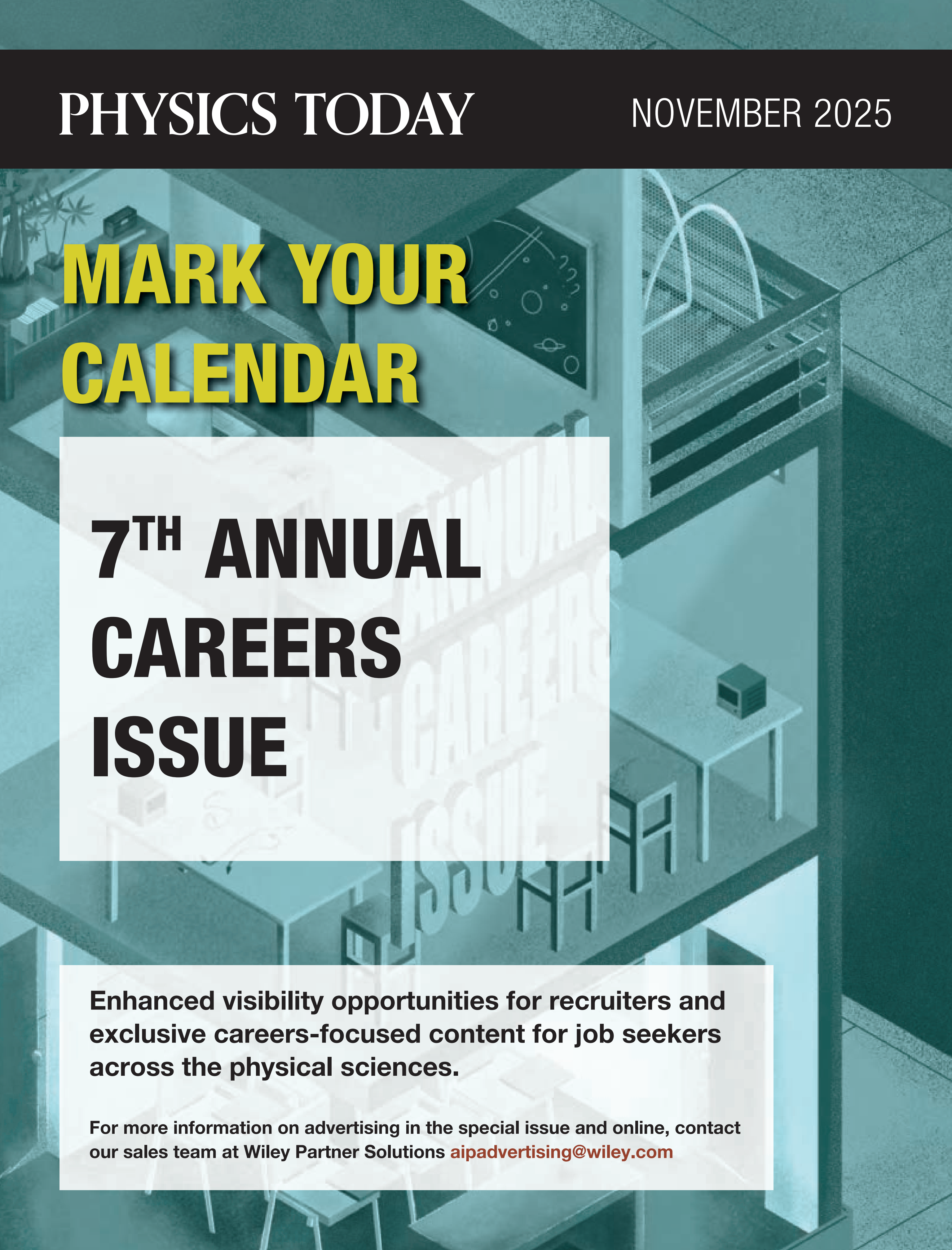
DESIGNING WITH STATIC ELECTRICITY

Machine learning for earthquake forecasting

Conference attendance faces challenges

A quick, easy probe of biomolecular structure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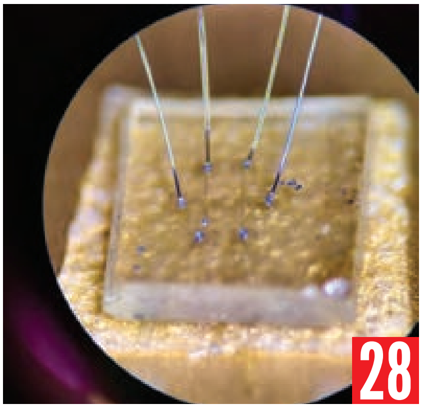

FEATURES

ON THE COVER: The everyday phenomenon of static electricity can be exploited to arrange microparticles into virtually any pattern, such as this horse. After being rubbed across the surface of a silicon dioxide wafer, micron-sized acrylic particles acquired positive charges and adhered to a horse-shaped fluorocarbon-coated region that had become negatively charged. To learn more about using electrostatic forces to design granular materials, turn to the Quick Study by Ignaas Jimidar and Joshua Méndez Harper on **page 54**. (Image courtesy of Ignaas Jimidar.)

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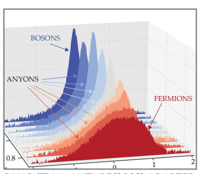

DHAR ET AL., *NATURE* (2025), ADAPTED

Anyons in 1D

Particles in three spatial dimensions must be either fermions or bosons. But in reduced-dimensional spaces, theory allows for a continuum of other possibilities—called anyons—with distinct quantum statistics. Two groups have now experimentally shown how to coax atoms in 1D quantum gases into behaving like anyons.
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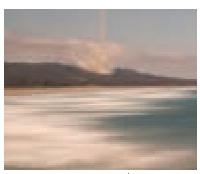

NASA/BILL INGALLS

Sea-level change

A new analysis of legacy gravity data from satellites extends the record of sea-level rise caused by melting ice back to 1993. By putting their data into a model that corrects for uncertainty at land–ocean boundaries, the researchers obtained a more reliable estimate of sea-level rise.
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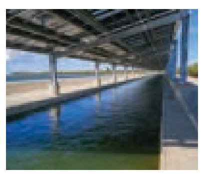

TURLOCK IRRIGATION DISTRICT

Solar panels over canals

Large-scale generation of solar power requires a lot of space. One candidate is the area above irrigation canals. Projects in California and Arizona are exploring whether reduced water evaporation, increased photovoltaic efficiency, and other benefits would justify the high costs of installing solar panels over canals.
physicstoday.org/Aug2025c

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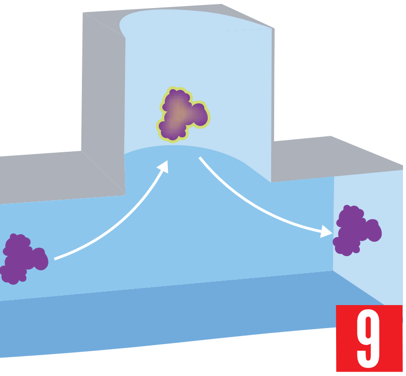

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Commentary

A defense of science communication

It's easy to believe that the US scientific community is in crisis. The daily news is full of stories about cuts in funding and oppressive visa restrictions. Organizations that champion scientific communities are marshaling their resources, attempting to counteract a barrage of destructive new policies from Washington. We as physicists must speak up, by either contributing to organizations that lobby for science or speaking directly to government representatives. However, we can expect public support only if people understand what we have to say. And that means we must end the physics community's lackadaisical view of science outreach. It is this belief that has motivated me to speak up for science, through efforts that include hosting a successful YouTube channel and writing articles and opinion pieces for national news outlets—work that was recently recognized when the American Physical Society (APS) awarded me the Dwight Nicholson Medal for Outreach.

We can expect public support only if people understand what we have to say. And that means we must end the physics community's lackadaisical view of science outreach.

The disconnect between researchers and the public is not a new problem. In the physics community, outreach has often been viewed neutrally at best. Careers are advanced by writing papers and getting grants, not by communicating to the public via books and videos and talks. Over the past few decades, when I've told my colleagues that it is important to talk to the public about science, their responses have been often incredulous and sometimes even hostile. Science, they believe, is supposed to speak for itself. The data and the process should be persuasive and need no further support. I would like to see this mindset change. Scientists' current simplified view of how scientific knowledge should be disseminated and adopted doesn't even work among their colleagues, let alone among the general public.

If the public had a better sense of how physics research has improved their lives, perhaps we would not be in our current situation. The science that the public encounters has only a hazy resemblance to the results published in the literature. The public consumes science information that has often passed through the filter of traditional and social media, where even good-faith reports include watered-down or misunderstood material and preliminary reports are presented as established fact and without the cautionary nuance that is the hallmark of frontier research. Even worse, that good-faith research news is competing with misinformation and even disinformation.

Certain bad actors have economic incentives to muddy the waters with untrue claims that sound persuasive to nonexperts. For that reason and others, we find ourselves in a cacophonous hubbub in which many citizens believe that there is controversy surrounding topics that the scientific community has already settled. In reality, it is well established that anthropogenic climate change is real, vaccines are both highly effective and do not cause autism, and Earth is not flat.

In November 2024, APS released a policy statement on the value of physics-related public outreach. In it, APS "urges educational institutions, national laboratories, and companies that employ physicists to recognize the high value of public engagement when making hiring, assessment, promotion, and investment decisions." I believe that this statement was overdue. (Full disclosure: I was a member of the group that proposed this policy statement to APS.) It is important for physicists—indeed, all scientists—to embrace the value of public outreach.

There are very real dangers in not having conversations in the public sphere. One example is the universal hazard that faces all citizens: the possibility that policymakers will make bad decisions because they are ignorant or because they have heard and believed bad information. (And, of course, some have used bad information despite knowing it's wrong, but that is its own separate issue.) Policymakers cannot be expected to have expertise in all matters, and science is a broad and challenging field. For governmental and industry leaders to make the best choices on matters of social policy, they need to have an adequate understanding of the science relevant for those decisions. And, when it comes to science, there is no better source of information than the consensus of the scientific community. If the case for science is not effectively presented, our leaders could well make flawed decisions.

There are lots of reasons to join those of us who have long participated in physics outreach, but it may be that you yourself are not inclined to take part in the conversations that ripple through society. For some, it's just not that appealing. The good thing is that not all scientists need to be visible to the public. In fact, it's better if the task of public communication is handled by scientists who enjoy the experience of talking with nonexperts. But people responsible for hiring and promoting scientists need to recognize public communication as a valuable skill worthy of recognition on par with other service work.

DON LINCOLN GIVING A TALK titled "The Birth of the Universe, Recreated" in 2012. The talk was given at TED@NewYork, an event that was part of a worldwide TED talent search. (Photo by Ryan Lash/TED.)

Not all scientists need to become science communication experts—certainly not in the modern world, which values specialization. In physics, people become theorists or experimentalists, but they are rarely both. In my own field, experimental particle physics, the specialization is even more specific: Some people design accelerators, while others design detectors. Some specialize in the flow of data around the world and others in statistics or machine learning. But it is essentially unheard of for any individual to master all of those skills. So I am certainly not proposing that all scientists master the art of communication.

Large physics departments should include a member or two who spend some fraction of their time engaging with the public and helping the community advertise the value of physics research. Importantly, I am suggesting that this be done not by communications professionals (although they are also important) but by practicing physicists. By virtue of their scientific expertise and skills at science communication, these communication-minded physicists are best suited to share the excitement of scientific research with the public in a way that is accurate. If excellent science communication skills were recognized in the hiring and tenure processes for scientists, it would make all of our lives easier.

In a world of social media, where many voices can be heard, it is important that the voice of science be strongly represented. Who can do that better than a scientist? And if it's not something you want to do, consider supporting and rewarding those who do it well.

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Fermilab
Batavia, Illinois

Editor's note: If you are inspired to speak up for science, a forthcoming article will tell you how to get started.

LETTERS

A complementary perspective on quantum history

Complementarity applies not only to quantum physics but to its history. Ryan Dahn's article "Demythologizing quantum history" (Physics Today, April 2025, page 38) provides the side of the story that comes naturally to historians, who weave webs of interconnections among all participants, figuring out who contributed what and who influenced whom. With that perspective, it is hard to give too much credit to a singular act of discovery, because the "aha" moment has been preceded not only by the preparatory work of the individual but by the work of many others as well.

The complementary perspective is that of the research physicist. Research can be frustrating. One can spend large amounts of time getting precisely nowhere. Then, suddenly, there might be a moment of clarity, a new way forward. Few have experienced a breakthrough as significant as Werner Heisenberg's in the summer of 1925, but similar, if usually lesser, rewards are what researchers crave.

The details of an actual breakthrough may not appear very impressive. The Wright brothers' famous "first flight" in 1903 traveled only 37 meters and lasted only 12 seconds, but it opened up a whole new universe of aviation. It is likewise not surprising that Heisenberg's *Umdeutung* ("reinterpretation") paper was sketchy and hard to understand. It is also not surprising that he was uncertain (no pun intended) about the worth of his achievement; new ideas often do not pan out. It is greatly to the credit of Max Born and Pascual Jordan that they were able to turn Heisenberg's insight into a cogent theory of the atomic world.

Looking back in 1963 on his trip to Helgoland, Heisenberg said he remembered feeling, "Well, now something has happened."[1] In later years, he may have been vague on the details, but the reality of the breakthrough seems to have been seared in his memory.

Reference

1. W. Heisenberg, interview by T. S. Kuhn, 22 February 1963, session VII, p. 14, Oral History Interviews, Niels Bohr Library & Archives, https://doi.org/10.1063/nbla.wbnv.eibc.

Alan Chodos
(alan.chodos@uta.edu)
University of Texas at Arlington

A quick and easy probe of biomolecular structure

By how long they take to escape an entropic trap, slender molecules can be distinguished from compact ones.

Structural biology has a fundamental disconnect. The biochemical world is inherently dynamic—the whole reason that proteins and other biomolecules are important is because of the functions they perform, in a complex liquid environment that's far from equilibrium. But the main tools used to examine their structures, x-ray crystallography and cryoelectron microscopy (cryoEM), require static samples that are either crystalline or frozen.

It's not just a conceptual separation but also a physical and logistical one. X-ray crystallography and cryoEM require different instrumentation and expertise than studies of biochemical function. Structural measurements of proteins, therefore, are performed in specialized labs by specialist researchers, often far from the chemistry and biology labs that sparked the molecules' study.

Now Madhavi Krishnan, of the

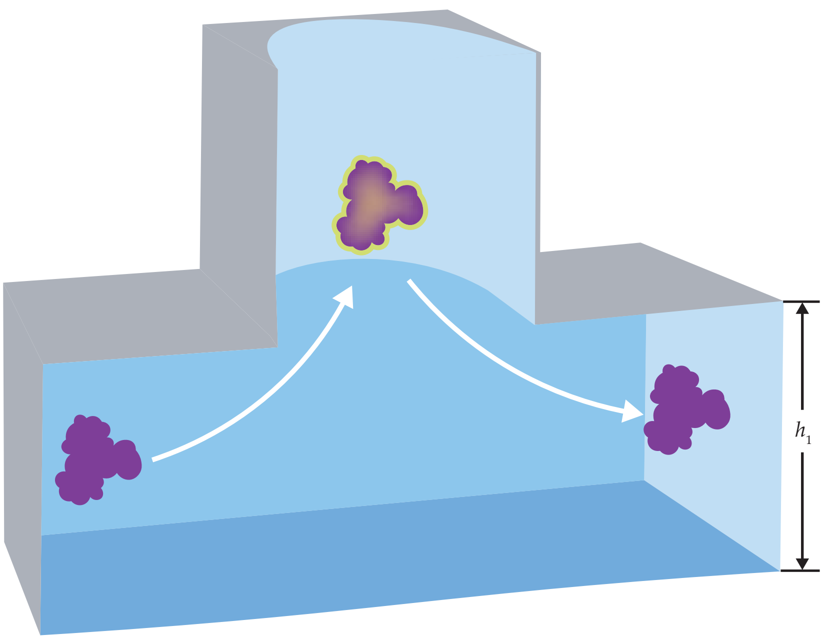

FIGURE 1. WHEN A WANDERING BIOMOLECULE (purple) diffuses into a pocket trap etched into a microfluidic channel, it gets confined for a few tens of milliseconds before it can find its way back out. The average escape time, which can be accurately measured with fluorescence microscopy, depends on the molecular size and shape and on the height h_1 of the exit channel. (Figure adapted from ref. 1.)

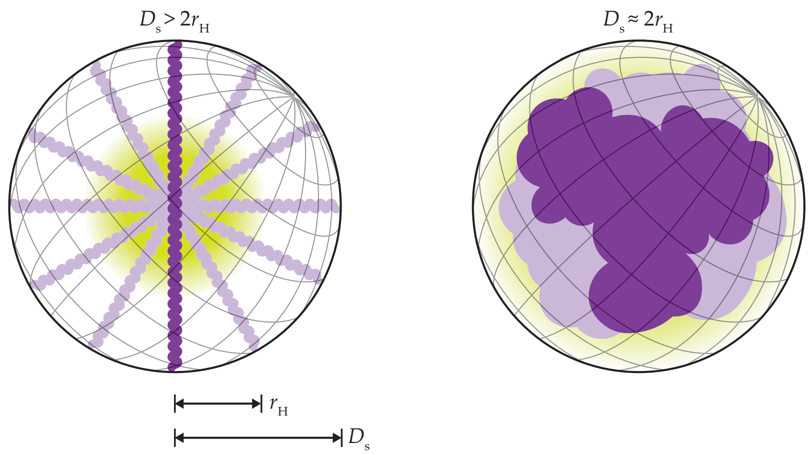

FIGURE 2. SLENDER AND CHUNKY MOLECULES have significantly different values of the two structural parameters that are probed with escape-time measurements: the hydrodynamic radius r_H and molecular-envelope diameter D_s. (Figure adapted from ref. 1.)

University of Oxford in the UK, and her colleagues have taken a step toward bridging those gaps.[1] They've developed a method for gleaning some structural information about a biomolecule from the answer to a simple physical question: When a molecule diffuses into an open cylindrical pocket, like the one shown in figure 1, how long does it take to diffuse back out?

The method is by no means a replacement for x-ray crystallography or cryoEM. Measuring only a single quantity at a time yields nowhere near enough information to reconstruct a whole molecular structure. But the information it does provide is often enough to distinguish similar molecules or different conformational or chemical states of the same molecule, in some cases even if the molecular state is constantly changing.

And the technique has the considerable advantage of being able to meet biomolecules where they are: in the solution phase and in biology and chemistry labs. It requires no highly specialized equipment, and a typical measurement can be completed in one minute.

Full charge

The origin of the technique dates back to 2010, when Krishnan was a postdoc in the group of Vahid Sandoghdar, who was then at ETH Zürich in Switzerland. She and her colleagues showed that they could use cylindrical pockets for trapping nanoparticles by means of their electrical charge.[2]

A technique already existed for trapping nanoparticles in solution—namely, optical tweezers (see PHYSICS TODAY, December 2018, page 14). Tweezers, however, rely on particles' optical polarizability to create the trapping force, so the technique is limited in the sizes, shapes, and materials of the particles it can trap. Pocket electrostatic traps, in contrast, can capture any particle, as long as it carries a net negative charge, which most of them do.

The principle is almost deceptively simple. The pockets are fabricated in a nanofluidic channel made of silica and glass. Those surfaces also pick up negative charge in solution, so there's a repul-

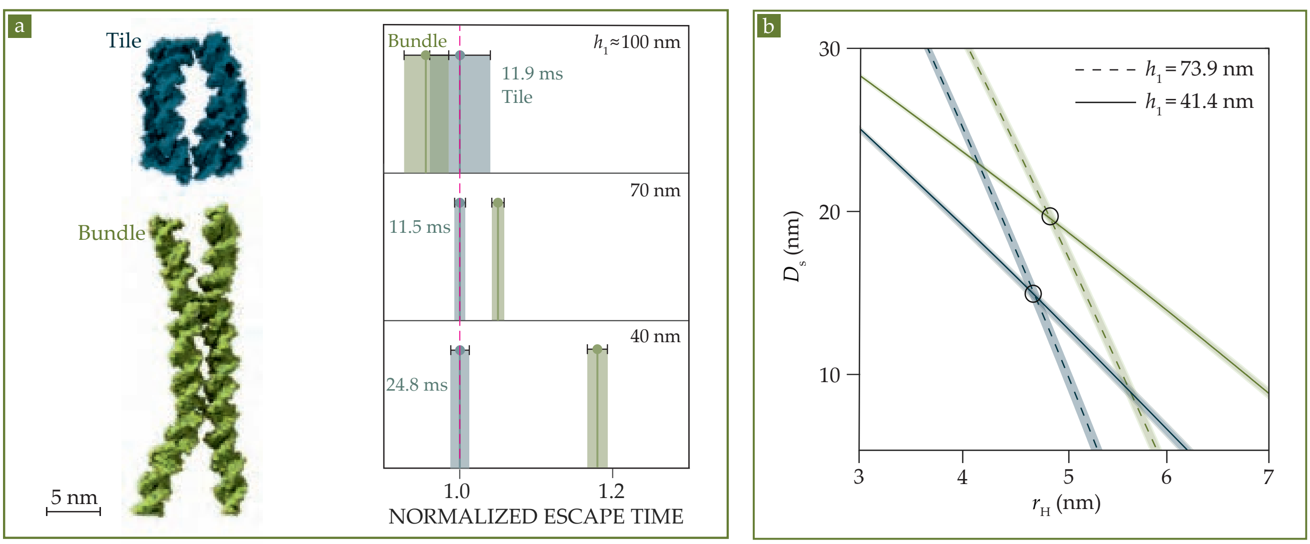

FIGURE 3. DNA NANOSTRUCTURES of similar size but different shape can be distinguished through their escape times. **(a)** The tile and bundle structures each consist of 240 nucleotides. But as the height h_1 of the exit is decreased, the bundle's escape time shoots up. **(b)** From escape-time measurements on two chips with different h_1 values, researchers can solve for the hydrodynamic radius r_H and molecular-envelope diameter D_s of both molecules. (Figure adapted from ref. 1.)

sive electrostatic force between the particles and the channel walls. The repulsion creates a deep potential-energy well in the center of each pocket. Particles meander into the wells under ordinary diffusion, but once in, they're prevented from escaping, and they can remain trapped for hours.

Although the researchers' initial focus was on nanoparticles, they argued that the same principle could be used to trap single proteins and other biomolecules. "But I don't know if anyone really believed us at the time," says Krishnan. The application of the technique to molecules, however, ended up going in a different direction. Krishnan realized that if she could design the traps not to be so deep that they're inescapable, she could learn useful information from how long it took the molecules to escape.[3]

Escape probability per unit time is exponentially related to the energetic depth of the trap, which in turn is proportional to the effective amount of charge on the molecule. By measuring average escape times, the researchers could get a sensitive look at how much charge molecules carry.

One can measure escape times easily and accurately by fluorescently labeling the molecules and watching them under a fluorescence microscope. Pockets light up when they have molecules in them, and they go dark when empty. Meanwhile, molecules that are in transit between pockets don't show up on the microscope image because they're moving too fast. Escape is a stochastic process, so the researchers need to observe many events to calculate the average escape time—which is typically in the tens of milliseconds—but they can do that with a minute's worth of data.

Because molecules don't carry charge randomly, escape-time electrometry, as Krishnan and colleagues called it, gave some useful information about structure. DNA, for example, carries a fixed amount of charge per base pair, so DNA segments of different lengths can be distinguished by their escape times.[4] "We spent about a decade on this obsession with charge," says Krishnan. But the technique could do much more: It could access structural information directly.

Two measures of size

The time it takes a molecule to escape from a pocket depends not just on its charge but on its size: All else being equal, bulkier molecules take longer to escape than compact ones do. But unlike the exponential dependence on charge, the size dependence sits in the prefactor. "We thought that the size measurements would be less sensitive," says Krishnan, "so at first, they seemed less exciting."

Moreover, to access size information at all, the researchers would need to eliminate the influence of charge, which would otherwise be overwhelming. They could do that by adding salt: Flooding the solution with ions blunts the repulsive force between the charged molecule and the charged walls. But it seemed like that would be sacrificing the technique's greatest advantage, so for a long time, they never tried.

Krishnan credits her postdoc Xin Zhu with taking the eventual leap. "He's an excellent experimentalist, and one day he said, 'I'm just going to try it,'" she says. "And it worked—once, twice, and then there was no looking back." It was only once they had the experimental data in hand that the researchers realized the real power of the size measurements: Bigger molecules are slower to escape for two distinct reasons, so the escape time probes two properties of molecular structure.

With the electrostatic repulsion having been screened out, it's primarily entropy that keeps the molecules in the traps. Only a few of the many possible random trajectories lead toward the exit. So the first way that size affects escape time is through diffusion speed: Bigger molecules move more sluggishly, and they can make fewer attempts to escape per unit time. Escape time is therefore directly proportional to the hydrodynamic radius r_H—also called the Stokes radius—which is defined as the radius of the sphere that diffuses at the same speed as the molecule does.

If that were all there is to it, it wouldn't be very exciting. "There are lots of ways to measure the hydrodynamic radius," says Krishnan. But it's not enough for a molecule to diffuse to the edge of the trap; it must also fit through the exit. Specifically, the number of trajectories the molecule could take through the exit depends on the total clearance it has on either side. That clearance can be written as $h_1 - D_s$, where h_1 is the height of the exit, as shown in figure 1, and D_s is the diameter of the smallest sphere that contains the molecule.

The relationship between r_H and D_s is shown in figure 2. For long, slender molecules, D_s is large and r_H is small. But for rounder molecules, the hydrodynamic sphere and the smallest sphere that contains the molecule are nearly the same, and $D_s \approx 2r_H$.

The average escape time is just one quantity, so a single measurement isn't enough to determine both r_H and D_s. But by repeating the measurement on two or more chips with different h_1 values, the researchers can solve for both structural parameters, and they can distinguish similar molecules. Figure 3 shows an example of how it can work. The researchers made two DNA nanostructures folded into different shapes: a compact tile and a slender bundle. The molecules have the same number of nucleotides, with the same total mass and charge, so they should have similar r_H values. But the bundle has a much larger D_s.

The difference becomes apparent as h_1 is decreased, as shown in figure 3a: When $h_1 \approx 40$ nm, the bundle takes much longer to escape than the tile does. Figure 3b shows how, with two measurements on chips with different h_1 values, the researchers can distinguish the molecules.

The tile and bundle are known structures that were deliberately synthesized, and they don't interconvert. But the same measurements could be used to characterize molecules that switch between different shapes and sizes in unknown ways: proteins toggling between two different structures, for example, or enzymes binding and unbinding from a molecular substrate. "With a mix of two different escape times, we'd have a biexponential distribution," says Krishnan, "but as long as the interconversion time is long compared to the escape time, we can distinguish a molecule flip-flopping between two states by following it in time through the landscape of traps."

Shining brightly

The technique is intended for proteins and other biomolecules, but it also works on organic molecules with as few as a couple of dozen carbon atoms. In that regime of relatively small molecules, the escape-time measurements have sufficient resolution to distinguish molecules that differ by one or two atoms.

A limitation of the measurements—especially significant for smaller molecules—is that the molecules of interest need to be fluorescently labeled, because that's how the researchers detect whether a molecule is in a pocket or not. For the proof-of-concept experiments on smaller molecules, the bulk of the molecule was the fluorescent dye itself, so it's not yet possible to apply the technique to arbitrary organic molecules.

"But that's not a theoretical limitation," says Krishnan. "Broadly, there are two ways to optically detect a molecule in solution: either through fluorescence or because the molecule itself scatters light. We can't do these experiments with scattered light yet, but maybe in the future, the technology will have advanced enough to enable label-free operation. All the physics of the measurement remains the same in either case."

The ability to measure D_s was a surprise, and the researchers look forward to more surprises in store. "The moment you have a new technique, I like to think you have very little predictive power in where it's going to go," says Krishnan. "We know that molecular conformation is very important, and that it's tied to interactions, chemical affinities, and reactions. But the hope is that something completely unexpected comes out of this."

Johanna Miller

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UPDATES

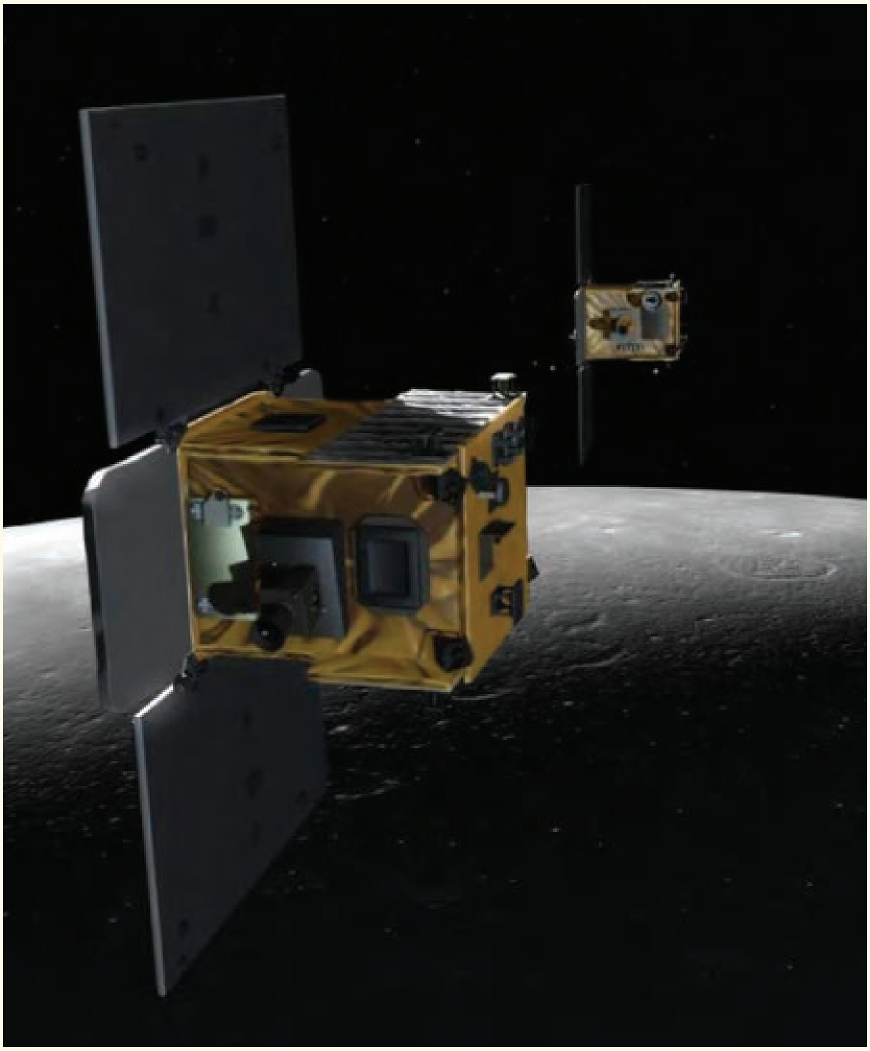
The Moon's interior is surprisingly irregular

Even though NASA's gravity-mapping GRAIL mission ended 13 years ago, the data are still yielding new insights.

Although the Moon is Earth's closest neighbor, some of its fundamental properties are not well understood. A better grasp of the composition and thermal structure of the lunar interior, for example, would help researchers trace the evolution of the Moon and the origins of its volcanic deposits and other surface features seen today. To help probe the Moon's interior, two spacecraft with NASA's GRAIL mission, *Ebb* and *Flow*, collected observations in lunar orbit in 2012. Small displacements in the orbits of the instruments were used to generate a map of the lunar gravitational field.

From early analyses, it appeared that the Moon's deep interior was roughly spherically symmetric. Many researchers, therefore, assumed that the observed compositional and temperature asymmetries were too small to help explain how the Moon formed and evolved. That assumption, however, now seems to be overturned. Using GRAIL data, Ryan Park of the NASA Jet Propulsion Laboratory and colleagues found an unexpectedly large time-varying gravity signature that they report is consistent with uneven temperatures in the Moon's deep interior.

The Moon's gravitational field is typically estimated using the mathematics of spherical harmonics. In the equations, the dimensionless Love number k characterizes a body's response to tidal forces—in this case, from Earth—over time. The GRAIL results published a



THE TWIN SPACECRAFT *EBB* AND *FLOW*, which orbited the Moon for roughly a year in 2012 as part of NASA's GRAIL mission, carefully monitored each other's distance from one another to collect lunar gravity data. (Artist's depiction courtesy of NASA/JPL-Caltech/MIT.)

decade ago found a value of k consistent with a spherically symmetric Moon. They were based on data from the primary mission, which ran from March through May 2012. Park and colleagues developed their gravity map using the primary data plus measurements acquired during the extended mission, from August through December 2012.

In using the entire suite of GRAIL data, the researchers found a puzzling, physically unrealistic k value: It was 72% higher than what was expected for a spherically symmetric Moon. The team spent years painstakingly testing its high-resolution gravity map against alternative possibilities and have concluded that the Moon's interior must be asymmetric.

The asymmetry can't be explained by variations in mantle composition. If it were, the Moon's center of mass would be offset from its geometric center by much more than what's observed. The more likely explanation is that the Moon's nearside interior is 100–200 K warmer than the farside. Lunar models show that compared with the Moon's farside, its nearside has more radiogenic elements, including thorium and titanium. They could have supplied differing quantities of heat to the interiors. Over billions of years, the uneven heating could have led to the hemispheric differences in basalt that are observed on the Moon's surface today. (R. S. Park et al., *Nature* **641**, 1188, 2025.)

Alex Lopatka

In the Great Lakes, heat waves and cold spells are on the rise

Modeling of climate data reveals an ongoing phase of longer, more frequent, and more intense lake temperature extremes that began with a record-breaking El Niño event in 1997–98.

A record-setting cold snap hit portions of North America in the first few months of 2014 when a disruption of typical atmospheric circulation patterns extended the range of the polar vortex southward. The prolonged cold spell lowered the surface temperatures of the Great Lakes (shown in figure 1). Evaporation from the lakes slowed for several years, which contributed to a rise in the lake surface level from 2015 to 2020 that produced widespread flooding in the region. With a span of hundreds of kilometers and coastlines that border Indigenous communities and major cities in the US and Canada, the Great Lakes have a widespread impact on humans and ecosystems.

Extreme temperature events leave less time for adaptation than do incremental changes, and they can have radiating effects on water levels, regional climate, and fishery and ecosystem health. Those widely felt impacts motivated Hazem Abdelhady, of the Cooperative Institute for Great Lakes Research at the University of Michigan, and colleagues to take a deeper look at how climate change has affected the frequency and intensity of extreme events.

Comprehensive lake surface temperature data collected by satellites go back only to 1995, so Abdelhady and colleagues turned to another dataset that goes back to 1940. Produced by the European Centre for Medium-Range Weather Forecasts, the ERA5 dataset assimilates historical weather and climate data into physics-based models to estimate historical weather conditions and fill in gaps in global coverage. The dataset was the input to a 3D model of the Great Lakes that accounts for hydrodynamics of the lakes and atmosphere, heat fluxes, ice formation, and albedo changes.

With their model, Abdelhady and colleagues compiled a detailed estimate of lake surface temperatures going back eight decades, as shown in figure 2. To focus their statistical analysis on the extremes, they removed long-term trends, including a gradual temperature increase caused by global warming. They found that both heat waves and cold spells have become more frequent, longer, and stronger. Lake Superior, the deepest and coldest of the lakes, saw the most dramatic jump in heat waves, with a 258% increase in the average of the summed intensity and duration of such events between 1996 and 2022 compared with 1941–96. Lake Erie, the shallowest and warmest of the lakes, showed the greatest increase in cold spells.

The researchers' analysis revealed connections to distant, larger-scale cli-

FIGURE 1. THE FIVE GREAT LAKES, captured in this satellite image from 15 March 2020, form the largest lake system in the world, and they exert considerable influence over the regional climate. Analysis of long-term climate data reveals that large-scale ocean circulation patterns, including El Niños, have driven changes in the temperatures of the inland lake system. (Image created from modified Copernicus Sentinel data and processed by the European Space Agency/CC BY-SA 3.0 IGO.)

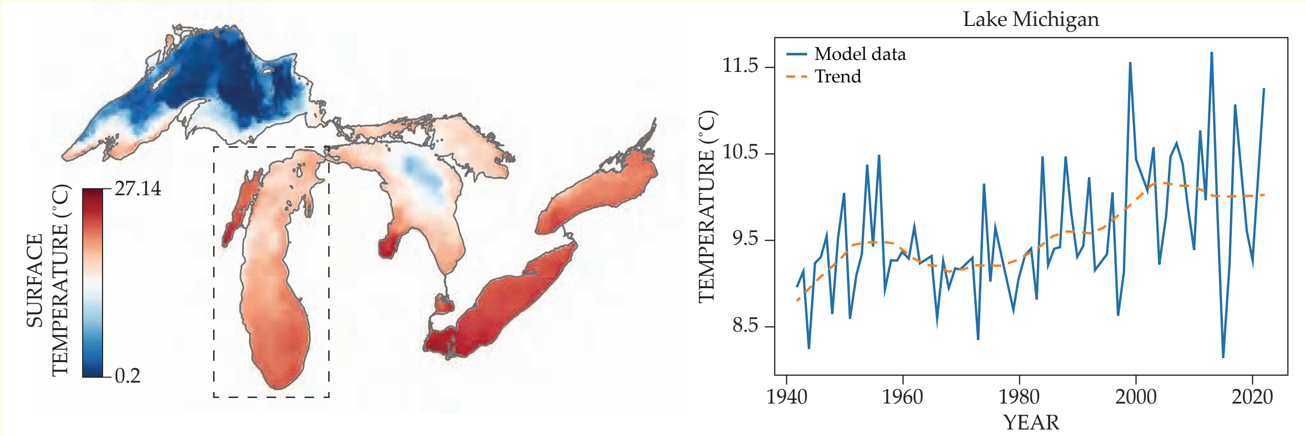


FIGURE 2. A SNAPSHOT OF LAKE SURFACE TEMPERATURES from 18 July 2018 **(left)** from the hydrodynamic–ice model used by researchers to reconstruct the past eight decades of Great Lakes water temperatures. A graph of the average lake surface temperatures for Lake Michigan over the past 80 years **(right)** shows both extreme events and a longer-period trend. (Figure adapted from H. U. Abdelhady et al., *Commun. Earth Environ.* **6**, 375, 2025.)

mate systems. Lake Erie and Lake Ontario both shifted to a phase of greater cold extremes in the mid 1970s, corresponding to a major shift in Pacific Ocean temperature patterns in 1976 that yielded two decades of warmer water off the northwest coast of North America. And all the lakes moved into a phase of more intense heat waves starting in the 1990s. The researchers attribute that phase shift to a record-setting El Niño event in 1997–98.

"The Great Lakes got very, very warm, and they stayed warm all the way until that Arctic polar vortex in 2014," says Andrew Gronewold, who leads the Global Center for Climate Change and Transboundary Waters and was part of the research team.

"It gets at this idea that some of the changes we experience in the Great Lakes as a consequence of global warming are happening in abrupt shifts rather than as a long-term trend," says Gronewold. "From a management and adaptation perspective, that makes a huge difference for our lives, for our safety, and for ecological health." Funding and using forecasts of such shifts could provide guidance for policymakers to inform adaptation strategies for future changes. (H. U. Abdelhady et al., *Commun. Earth Environ.* **6**, 375, 2025.)

Laura Fattaruso PT

Conference organizers, potential participants fault US policies for falling attendance

Uncertainty about funding and visas takes a toll on networking.

An early-career researcher at a major US university was thrilled to be invited to speak at the International Liquid Crystal Elastomer Conference this August. Presenting would be a feather in their cap and an opportunity to network and learn about state-of-the-art developments in their field.

But in May, the researcher contacted the conference organizers to cancel: The event takes place in Finland, and with heightened scrutiny of travelers under the Trump administration, the researcher, an assistant professor who is from China, decided not to risk being denied reentry into the US. (This researcher and a handful of others, including US citizens, who spoke with Physics Today requested anonymity so as not to draw attention to themselves or their institutions.)

Visa woes and worries about being hassled, detained, or denied entry at the US border are contributing to falling attendance at many scientific conferences. So are cuts and threats to funding, rules that hamper travel for scientists employed by the US government, and protests against new US policies by potential participants. Statistics are not yet available—and many professional societies keep details close to the vest. Even before this year, conference attendance had taken hits from COVID-19 and concerns about the impact of travel on climate change (see Physics Today, May 2023, page 23). Some meetings, to be sure, have had robust attendance, including the American Physical Society's (APS's) Global Physics Summit in Anaheim, California, this past March. But others report drops in turnout of roughly 20–30%.

Some organizers are canceling conferences or moving them online or out of the US. And many scientists are adjusting their conference-attending strategies, with US-based researchers looking more locally and non-US based ones focusing outside the US.

Reconsidering conference travel

This year's International Conference on Supersymmetry and Unification of Fundamental Interactions is planned for mid-August at the University of California, Santa Cruz. Conference cochair Howard Haber expects about 150 participants, down from around 200 in recent years. He says that some international scientists have canceled their participation because they are "spooked by stories in the news of scientists and tourists who have been detained" by US border security.

Warwick Bowen, a quantum physicist at the University of Queensland in Australia, organized Gordon Research Conferences in the US and in Switzerland this summer. Through the US National Institutes of Health, the conferences provided travel money to participants, but the money was delayed, says Bowen, which meant that "we were unable to support people who depended on the assistance." And, he adds, the showing of US-based scientists at the July meeting in Switzerland would likely have been larger "if not for the visa issues."

The Canadian Association of University Teachers has advised academic staff that they should travel to the US only if essential, "given the rapidly evolving political landscape in the United States and reports of individuals encountering difficulties crossing the border." The advisory recommends that academics exercise particular caution if, for example, they "have expressed negative opinions about the current U.S. administration or its policies," their passports bear stamps showing recent travel to countries that have diplomatic tensions with the US, or they are transgender. Some countries have issued similar advisories.

With colleagues who are members of groups that are "being overly scrutinized and challenged at the border, I feel like, in solidarity, I should not enter the US right now," says Nancy Forde, a physicist at Simon Fraser University in Burnaby, British Columbia. Moreover, she says, she doesn't want to support the US economy when President Trump is threatening her country's sovereignty. But she does want to "en-

THE GLOBAL PHYSICS SUMMIT, the American Physical Society's meeting in March, drew more than 15 000 attendees. But many conferences are seeing drops in participation and cancellations among speakers. (Photo courtesy of APS.)

gage in great scientific discussions with colleagues in the US and from around the world. It's tricky."

Forde attended the APS Global Physics Summit. It was the first time she found it stressful being in the US: "I wondered, if I jaywalked, could I be deported?" She is weighing whether to honor her commitments to present at other upcoming conferences in the US. "I now make sure my flights are fully refundable," she says.

Barry Sanders of the University of Calgary in Alberta says that a small conference on quantum information that he had planned to attend in early May at the University of California, Berkeley, was canceled. Between objections from Canadian participants about going to the US and worries by some US-based researchers about reentering the US if a meeting is moved outside the country, he says, "we are still discussing how we will handle our next meeting." He adds that his students are increasingly choosing to attend conferences in Europe.

A researcher at a top US institution who requested anonymity says that they pulled a student from participating in a meeting in Europe because of funding concerns. That student will instead attend a local conference. "We have a lot of free or low-cost, one-day conferences close by," says the researcher. "I think we will go to more of those and fewer of the big national and international meetings."

Hoops and symptoms

Scientists who work for the US government are having to forgo conferences or jump through more hoops to attend them. Last February, when the Biophysical Society held its annual meeting, NIH scientists' travel was restricted. Some 29 speakers canceled, says Lynmarie Thompson, the society's president and a professor at the University of

THE BIOPHYSICAL SOCIETY MEETING in Los Angeles last February saw attendance within its usual range of 4000–5000. But the society refunded about $20 000 total to scientists, including more than two dozen speakers, who canceled because of travel restrictions for US government employees. (Photo by Brandon Ogden, courtesy of the Biophysical Society.)

Massachusetts Amherst. Sessions to help researchers navigate applying for grants from NSF and NIH had to be canceled.

Peter Littlewood, a physicist at the University of Chicago, is running a conference on AI and energy in London this September. It is jointly sponsored by NSF and the Royal Society, but, he notes, US participation is limited by US government employees' "current inability to use federal funds for travel."

Many conference goers and organizers mentioned similar scenarios: A NIST scientist withdrew from a conference because it wasn't "mission critical"; an NIH physicist was unsure they could attend a conference until they received approval at the last minute; government scientists seek nongovernment money—or pay out of pocket—to attend conferences. Some government employees have second affiliations that they can travel under. Several government scientists and agency spokespeople declined requests to speak with Physics Today or did not respond.

Visa hurdles are not limited to the US. Chinese visitors face problems entering India, too, and for people of some nationalities, getting a timely visa to enter Europe can be a challenge. Some conferences alternate their locations to distribute the burdens of travel, cost, and visas.

Conference venues are often booked years in advance. Beth Cunningham, the CEO of the American Association of Physics Teachers, says that the association faces a penalty if fewer than 80% of rooms are booked at a conference center. "We have hotel contracts through 2027," she says, "but we are holding off on future contracts until we have a better understanding of what we need." She attributes the drop in attendance to the rising costs of registration and hotels, restricted budgets because of threatened and cut grants, and increasing consciousness about carbon footprints.

An officer from another professional society who requested anonymity notes that sinking conference attendance has broad implications for all professional societies: "reduced revenue, increased instability, declining participation and engagement, and heightened uncertainty regarding the future of conferences, all society products, and the future of scientific associations overall."

Conferences are critical for training new generations of scientists, says the Biophysical Society's Thompson. "They get exposure to other fields and approaches, receive feedback on their work, and form collaborations."

Thompson and others stress that falling conference attendance is symptomatic of larger issues. The threatened funding cuts will significantly reduce the number of research projects and the number of students and early-career researchers who can enter STEM fields, notes Santa Cruz's Haber. If they materialize, he says, "it will decimate science research and innovation in the US. It will take a generation to repair."

Toni Feder

Europe's particle-physics community weighs its next collider

Looking to solidify their post-LHC plans, CERN and its partners are considering an ambitious project that would stretch to the end of the century.

After the Large Hadron Collider (LHC) shuts down, probably in the early 2040s, what comes next?

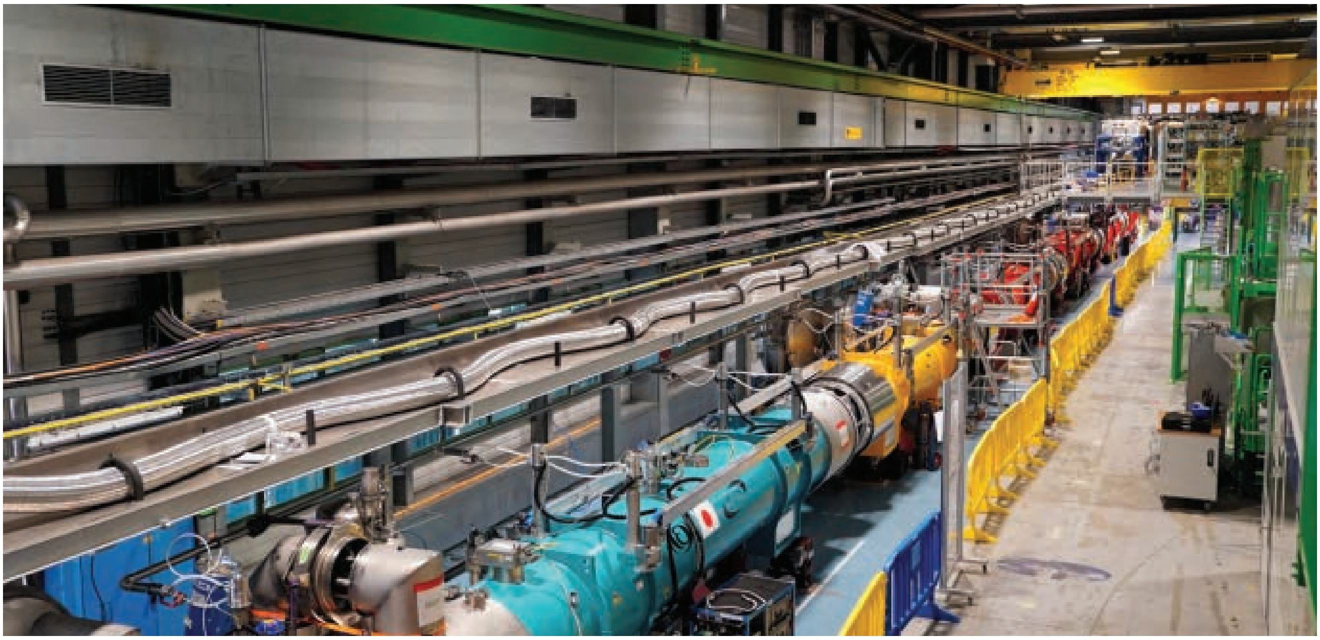
That question is the focus of Europe's particle-physics community as it discusses the latest update to the European Strategy for Particle Physics (ESPP). The updates, organized by CERN every five to seven years, set a shared agenda for Europe's particle physicists. Community input collected throughout the year will be compiled in December by a group of stakeholders into a strategy, which will then go before the CERN Council for a vote in June 2026.

This particular update has high stakes: It could lead to CERN pursuing a new world-leading particle collider with a $10 billion–plus price tag.

Meet the Future Circular Collider

As part of the strategy process, CERN solicited proposals from the community. It received 263 submissions from researchers in more than 40 countries, including CERN's 25 member states. The submissions range from the considered thoughts of individual scientists to feasibility studies from collaborations. There are also national submissions, the shared opinions of a given country's physicists.

WITH A CIRCUMFERENCE OF NEARLY 91 KILOMETERS, the tunnel for the proposed Future Circular Collider (FCC) would be more than three times as long as the current tunnel for the Large Hadron Collider (LHC). (Image from CERN.)



USING THE HIGH-LUMINOSITY LHC TEST STAND, CERN researchers will experiment with magnets and other components that should enable a substantial increase in the LHC's particle collision rate. The High-Luminosity LHC program is scheduled to run from 2030 to 2041. (Photo by Florence Thompson/CERN.)

Two of the submissions detail the leading contender for Europe's next collider. First suggested in 2011, the Future Circular Collider (FCC) would occupy a 91-kilometer loop under France and Switzerland and would run in two stages.

The first stage, the FCC-ee, would serve as a Higgs factory. The machine would produce many Higgs bosons by smashing electrons and positrons, which are elementary particles and thus would produce a clearer signal than do the proton collisions of the LHC. A Higgs factory has been a goal of the community since the previous strategy update in 2020 (see Physics Today, September 2020, page 26). "The consensus that the previous strategy came to is, We've found the Higgs boson, now we need to study it," says Patrick Koppenburg, chair of the Advisory Committee of CERN Users and a researcher at Nikhef, the Dutch National Institute for Subatomic Physics.

The FCC-ee submission to the ESPP includes a detailed feasibility study, which proposes that the machine begin construction in the 2030s, start operation in the 2040s, and run for 15 years. It would run at four energies for the detailed study of various particles, with the Higgs-focused phase colliding particles at 240 gigaelectron volts and producing around 3 million Higgs bosons. Researchers would be able to measure properties of the Higgs boson that have been predicted but are difficult or impossible to observe with the LHC, such as its decay into charm quarks, to check whether they match the predictions of the standard model of particle physics.

The next step, the FCC-hh, would collide protons (a type of hadron, hence the double h). Although a proton's makeup in terms of quarks and gluons makes its collisions less predictable, its greater mass would allow the machine to achieve energies of 85–100 teraelectron volts, about six or seven times that of the LHC. Such a machine could follow up on any hints of new physics from the FCC-ee and try to directly produce particles inferred from indirect effects. Using the same FCC-ee tunnel, the FCC-hh would begin construction in the 2060s, start running in the 2070s, and operate until roughly 2100.

Both stages are expected to be expensive. The FCC-ee is projected to cost 15 billion Swiss francs (about $18 billion), of which 6 billion francs covers civil engineering, including the tunnel. That would require funding beyond CERN's operating budget of around 1.4 billion Swiss francs per year; CERN would have to request funds from member countries. Even with the tunnel already dug, the FCC-hh would cost another 19 billion Swiss francs, mostly for the powerful 14 tesla magnets required to control its proton beams. Magnets that strong have yet to be built, but the report discusses several promising pathways where, in many cases, the necessary material properties have already been demonstrated.

Growing convergence

The FCC-ee isn't the only Higgs factory that CERN could build. A linear collider would require less space than the FCC-ee and reach higher energies, but it would collide fewer particles and thus gather less data. One plan builds on older proposals; another, called CLIC, would use technology in development to reach high energies in a relatively small machine. Advocates for a linear collider point to greater flexibility, with opportunities to upgrade with emerging technologies.

Although a linear collider could be cheaper (with estimates around 8 billion Swiss francs), both plans have a later upgrade that brings the total cost to the same ballpark as the FCC-ee. With the cost savings not obvious and the disadvantage in data volume, physicists are turning away from linear options and toward the FCC. "My feeling is that for once, there is convergence," says Troels Petersen, a member of the LHC's ATLAS collaboration based at the University of Copenhagen.

That convergence is clearest in the national inputs. Most countries state that the FCC is their preferred option, with the Swiss particularly insistent that no other proposal is comparable. The Dutch and Austrians strike a more neutral tone, supporting a Higgs factory more broadly and emphasizing the importance of going ahead with plans to upgrade the LHC to collide particles at a higher rate.

A pivotal moment

What nearly everyone agrees on: The decision cannot be postponed. If CERN does not budget for the project, a new machine would not start until long after the LHC shuts down.

"If there's a big gap, we run the risk of losing valuable expertise and top talent to industry," says Thea Aarrestad, a researcher at ETH Zürich and a member of the Physics Preparatory Group's detector instrumentation working group, which reviews proposals for particle detector technology for the ESPP.

The urgency doesn't make the decision easier. At stake is a commitment not only to a Higgs factory but potentially to the FCC-hh as well: The FCC-hh may no longer be necessary if the FCC-ee shows no signs of new physics or if riskier technologies with higher potential, like a muon collider, prove feasible (see PHYSICS TODAY, October 2022, page 22). A muon collider would combine the advantages of the FCC stages with signals as clear as electrons' at energies more comparable to protons, but the muon's short lifetime presents a major challenge for building and running such a machine. Meanwhile, a competing Chinese Higgs factory could be ready a decade before the FCC-ee, potentially making both stages superfluous (see "China plans a Higgs factory," PHYSICS TODAY online, 17 December 2018). "If you go for the FCC program, you're betting on what kind of physics you want to do in 2070," Nikhef's Koppenburg says.

If funding doesn't materialize, CERN has backup proposals that involve reusing the 27-kilometer LHC tunnel for less ambitious projects than the FCC or a linear collider. But in a way, ambition is the point. While trying to understand the universe, CERN pushes the limits of technologies like magnets and high-speed data processing. "In a technologically competitive environment, which other research field would you say that Europeans dominate alone?" says ATLAS's Petersen. "Are we going to give that up so easily?"

Matt von Hippel

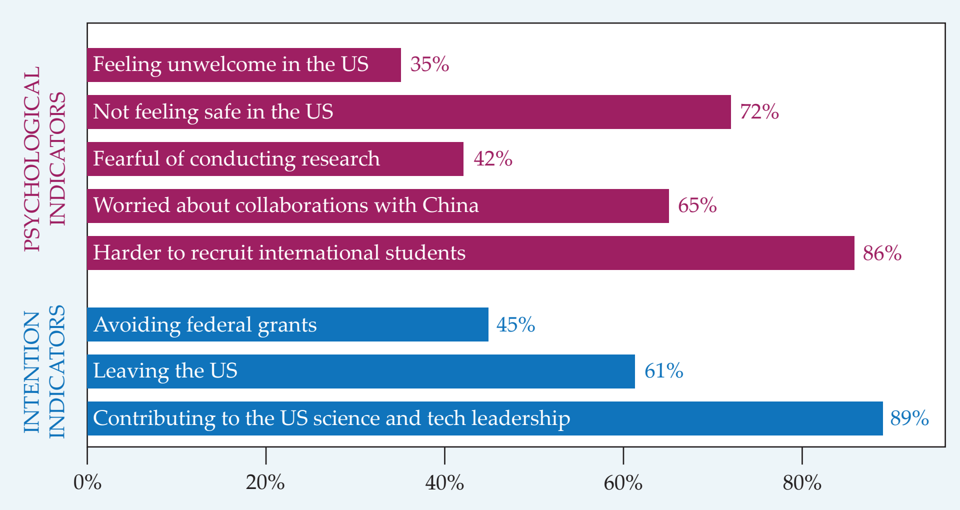
Q&A: Xiaoxing Xi on the wrongful arrest that upended his research and his life

The physicist now advocates for other Chinese-born scientists in the US suspected of spying for China.

XIAOXING XI (Photo by Joyce Xi.)

Xiaoxing Xi and his wife, Qi Li, were part of a growing wave in the 1980s and 1990s of scientists moving from China to the US at a time when US funding, facilities, and research were considered the best in the world. They had earned their PhDs in experimental condensed-matter physics at Peking University. From there, they went to Karlsruhe, Germany, for a couple of years before moving to the US in 1989.

Xi and Li eventually became professors at the Pennsylvania State University and naturalized US citizens. In 2009, Xi joined the physics faculty at Temple University, where he still is. His research was thriving until the early hours of 21 May 2015, when he was wakened by pounding on his front door. Agents from the Federal Bureau



MANY CHINESE AMERICAN TENURE-LINE RESEARCHERS at US universities feel unsafe, are worried about collaborations with China, are thinking of leaving the US, and are avoiding applying for grants from federal agencies, according to a survey conducted in late 2021 and early 2022 for the Asian American Scholar Forum. (Figure adapted with permission from Y. Xie et al., *Proc. Natl. Acad. Sci. USA* **120**, e2216248120, 2023/CC BY-NC-ND 4.0.)

of Investigation arrested him at gunpoint for what he later learned were charges of economic espionage, the sharing of trade secrets with a foreign state actor. The charges were dropped four months later.

In the decade since his arrest, Xi has helped other Chinese-born university professors in the US who have been caught up in the campaign against economic espionage. Many of them were among the hundreds of Chinese American academics and scientists targeted under the China Initiative. The US Department of Justice launched the initiative in 2018 as part of a trend to tighten research security (see PHYSICS TODAY, June 2025, page 16). It was discontinued in 2022.

Xi is suing the US government. But his case is progressing slowly, he says. "They violated my constitutional rights. They did something wrong and should be held responsible." And, he adds, he'd like to learn more about why the government was after him.

PT: Why did you go into physics?

XI: I grew up in Beijing during the Cultural Revolution. When I graduated from high school in 1976, there were no college opportunities for most people. I was sent to the countryside to be reeducated. That meant working in the fields, tilling the land, and harvesting. And digging pigsties.

I thought I would be there for my entire life. When the Cultural Revolution ended, Deng Xiaoping [then vice chair of the Chinese Communist Party's Central Committee and vice premier] restarted the university entrance exams.

It was a big shock. Before this, you tried to learn something so that you could have a better chance in your life to do something more than just simple labor. Now, you studied for the college entrance exam. I was studying in the countryside during my spare time.

In late 1977, I took the entrance exam for college. There was a general idea that if you are smart, you go into physics. You go to the physics department at Peking University, which is the best university in China. That's how I got into physics.

PT: And you got into Peking University's physics department?

XI: Yes. I started in January 1978, as part of the first class after the Cultural Revolution. I was 20 years old. I had classmates who were 16, 17—some hadn't finished high school—and others who were over 30 years old. After 10 years of no opportunity, everybody worked extremely hard.

PT: In the 1980s, many US graduate physics programs started to see an influx of students from China. Did you consider continuing your studies in the US?

XI: A lot of my classmates went to the US after they graduated. But I was thinking, "I'm not the smartest, and I'd like to be an academic in China, so probably I should establish myself more in China before I go abroad." I found the best opportunity in China: I did my PhD at Peking University. My adviser, Weiyan Guan, was the director of the Institute of Physics of the Chinese Academy of Sciences.

Of course, the conditions for doing research were poor compared to the US and Europe. But I think it taught me to be resourceful—to accomplish things under less-than-optimal conditions.

PT: What was your research area?

XI: My PhD was on superconductivity. My adviser got his degree in the Soviet Union with [Pyotr] Kapitsa. I made multilayers of aluminum and silicon. I was able to see the critical temperature of aluminum increase when I mixed it with silicon by bombarding the multilayer with an ion beam.

PT: Where did you go from there?

XI: I went to Karlsruhe, Germany. There, I became the first person to make high-quality epitaxial yttrium barium copper oxide thin films.

Venky Venkatesan, a prominent physicist at Bellcore working in the same area, visited. He learned that my wife and I were interested in coming to the US. He made offers to us, and we came in 1989.

First, we were at Rutgers University. When Venky moved to the University of Maryland, we went with him. We were there for five years as research scientists, on soft money. Among other things, I worked on high-temperature superconductor field-effect transistors. Then my wife got an offer from Penn State. I was the add-on hire.

After we moved to Penn State, my wife and I decided to work on things that do not overlap. I focused on ferroelectrics, and my wife worked more on magnetism. My group at Penn State successfully applied UV Raman scattering to ultrathin ferroelectric films. We also developed a highly effective technique to produce superconducting magnesium diboride films.

PT: Did you want to stay in the US?

XI: At the time, the US was the best place to do science. In China, it was more difficult. And they were behind in terms of the quality of the research and the quality of facilities.

After we had children and were relatively established, it was clear that our home would be in the US.

PT: Tell me about your arrest.

XI: It came out of nowhere. One morning, someone pummeled my door, and when I opened the door, I saw all these armed agents. They had a battering ram. They announced that I was arrested, but they wouldn't tell me why.

These guys with bulletproof vests and guns came running into my house yelling, "FBI! FBI!"

My wife opened the bedroom door to see what was going on. The men had a gun pointing at her and ordered her to raise her hands and walk out. At the time, both of my daughters were home. They were treated the same way when they were ordered to walk out of their bedrooms.

They put handcuffs on me. I had been asleep when they arrived and had put on only shorts and slippers when I went to the door, as the pounding was so urgent. I opened it barechested. They let me put on a shirt and a pair of pants. They took me away in front of my family. It was very scary.

My wife and I had lived through the Cultural Revolution, so we had heard of people being taken away, and you never knew how long they wouldn't see their family. My wife was very concerned about our younger daughter, who was 13 at the time.

PT: What were you charged with?

XI: They took me to their field office in Philadelphia. I was strip-searched by a US marshal. They asked me to bend over against the wall to check whether I had hidden anything in my body. You get many humiliations. I was released on bail that afternoon.

After they arrested me, they interrogated me. They read me the Miranda rights. I of course knew that I should not talk to them without a lawyer. But if I didn't know what they were charging me for, how would I prepare for my defense? I decided to talk to them.

They asked me questions about my work. Do you have students from China? Do you travel to China? When you travel to China, do you carry your computer and give a talk? Those kinds of things. But they still wouldn't tell me what they were charging me for.

Finally, I found out they were charging me for sharing information about a pocket heater, a device by a company with collaborators in China. The word "absurd" came out of my mouth. There was absolutely no possibility that was true.

PT: What was your connection to the pocket heater?

XI: The pocket heater was a widely known technology developed by a German professor. While I was on sabbatical with the company, I had made important contributions to the modification of the device to work with magnesium diboride instead of oxides. Later, I bought one from an inventor of the heater for my lab at Penn State.

PT: The charges were dropped. How did that happen?

XI: The Department of Justice charged me based on four emails I sent to my collaborators. None of the emails had anything to do with the pocket heater. It's not surprising that they didn't understand the emails, but they should have consulted experts.

My lawyers contacted the most authoritative experts in my field and also one of the inventors of the modified pocket heater. We gave them all my email communications with my Chinese collaborators. They wrote affidavits saying that my emails had nothing to do with the pocket heater. The emails were all about my own published research.

The Department of Justice dropped the case at the last minute before we had to file our motion to dismiss the charges.

PT: How did being falsely charged affect your personal and professional life?

XI: During that time, I was put on administrative leave. I was removed from chairing the department. I had the chance of being convicted and going to jail for 80 years. It was a real possibility. It was a very difficult time for myself and my family. Everyone in my family has continued trauma from the experience.

Nowadays, a lot of Chinese scientists in the US talk about a "fear factor." I know exactly what they mean. Whenever members of my family communicate, we are afraid that the FBI could twist anything we have said in our emails or phone calls.

Nearly half of Chinese professors who responded to a survey said they would not apply for federal funding anymore [see the figure]. For a lot of professors charged under the China Initiative, it was because of the so-called nondisclosures in their grant proposals and in their conflict-of-interest disclosures with their university. If you don't take federal money, then your risk of getting in trouble is smaller.

PT: Do you still apply for federal funding?

XI: Yes. I still have federal funding. If I don't have funding, I have to teach three classes. If I do, I teach one class. I have two grants; one is on my own and one is a team proposal. I had nine grants when I was arrested. And I had 10 students. Now I just have two senior people working with me, no students.

I used to have two major research areas: magnesium diboride and oxides. My group had developed a powerful and versatile technique that can build oxide films one atomic layer at a time. That research has stopped.

The experience of being falsely charged took a huge chunk out of my desire to apply for federal funding. Now I work under a combination of fear and still wanting to do something.

PT: How is your experience relevant in today's climate of heightened tensions between the US and China?

XI: My experience 10 years ago taught me that Chinese scientists are being unfairly treated. That has not changed. Former FBI director Christopher Wray said there were a slew of nontraditional collectors for China: Professors, scientists, and students are suspected of spying for China. And recently, Senator Jim Risch said that each and every Chinese student in the US is an agent for the Chinese government. [Risch (R-ID) was speaking at a Senate Foreign Relations Committee hearing, "The Malign Influence of the People's Republic of China at Home and Abroad: Recommendations for Policy Makers," on 30 January 2025.]

With the new administration, it's not just Chinese scientists. It's all international students, professors, and scientists. They could be deported for no real reason.

PT: Tell me about your advocacy work.

XI: I have been taking every opportunity to tell my story and talk to various audiences about the racial profiling against Chinese scientists. I have been following all the cases and government pronouncements closely, so I have become quite knowledgeable in the legal and science policy areas.

My lawyer often asks me to be a reference for Chinese scientists who are charged. I see that some of them cannot eat. They cannot think. They cannot sleep.

As a scientist, I had absolutely no idea how the legal process worked. I think everybody should have some knowledge so they know what to expect if they are arrested and charged with espionage. And I think educating the public about the issues is something I can and should do given my unique experience.

PT: Is there anything you would like to add?

XI: I will be very pleased if people remember me for my research in addition to the advocacy work I have been doing in the last 10 years.

Toni Feder

Scientist-ambassadors promote science in Europe

Through lectures, lobbying, and more, ERC ambassadors convey the importance of fundamental research.

A bevy of researchers is setting out to raise the profile of science among purse-string holders and the public across Europe. Former or current recipients of prestigious European Research Council awards, they serve in the Ambassadors for the ERC program launched in April jointly by the council and the Association of ERC Grantees.

The volunteer positions were competitive: The first cohort of 32 was chosen from more than 200 applicants. Samantha Christey, who heads the global outreach and stakeholder relations unit of the ERC communications department, says that the aim is to have one or two ambassadors in each of the 46 countries—the 27 European Union members and 19 associated countries—that are eligible for ERC grants.

Ideally, Christey says, ambassadors will also represent the fields the ERC funds and the different awards it offers. Known for their generous size and for their support of topics driven by scientists, the grants span the physical and life sciences, engineering, social sciences, and humanities.

The individual ambassadors are, together with the Association of ERC Grantees, "co-inventing the program as we go," says association president Axel Cleeremans. Activities will take place at the local and national levels; ideas floated so far include holding events along the lines of TED Talks, meeting with policymakers, collaborating with national funding bodies, and publishing open letters. The ERC is offering the ambassadors training in science communication, with a focus on social media.

SCIENTISTS MEET WITH GOVERNMENT LEADERS in Poland in February 2025. The political leaders are (starting second from left of front-facing people): Marcin Kulasek, minister of science and higher education; Małgorzata Kidawa-Błońska, marshal of the senate; Donald Tusk, prime minister; and Andrzej Domański, minister of finance. Michał Tomza (lower right corner), now an ERC ambassador, was one of the half dozen scientists in the room. (Photo from the Chancellery of the Prime Minister of Poland.)

For Michał Tomza, who heads the quantum molecular systems group at the University of Warsaw's Institute of Theoretical Physics, becoming an ERC ambassador was a natural extension of his ongoing activities. This past February, for example, he met with Poland's prime minister to promote science. "We are trying to make society more aware of how important science is, and what the public gets from it."

"If you want a revolution, you need long-term investment," says Jan Lagerwall, a physicist who focuses on liquid crystals at the University of Luxembourg. He became an ERC ambassador because of his love of outreach and his concern "that science is under threat in a crazy way."

The ERC ambassador program also aims to foster networking among grantees and to gather information about how the awards are encouraged in different countries. "In some cases, institutions don't offer support to scientists who want to apply," says Cleeremans. "The association could help. The goal is to collectively think about how to improve the experience of competing for and having ERC grants."

Toni Feder

EUROPEAN RESEARCH COUNCIL AMBASSADORS at a launch event in Brussels on 28 April. (Photo © ERC.)

FYI SCIENCE POLICY BRIEFS

Spectrum auctions raise concerns for scientists

The reconciliation spending bill signed by President Trump in July directs the Federal Communications Commission to auction 800 megahertz of radio spectrum to commercial users through fiscal year 2034. The new law, however, does not specify protections for scientific research, despite worries from scientists who say access to certain bands is essential for observations in astronomy and atmospheric science. A summary from the Senate states that the auction revenue would reduce the deficit by $85 billion.

In May, American Astronomical Society (AAS) president Dara Norman sent a letter to the Senate Committee on Commerce, Science, and Transportation requesting that bands allocated to the radio astronomy service be "excluded from consideration for repurposing and auction." Those allocations are made "based on the frequencies at which we can observe specific physical phenomena in the universe," Norman wrote, meaning radio astronomers cannot use other bands to make the same observations. Some bands are similarly important for atmospheric observations. For example, the Next Generation Weather Radar system relies on bands from 2.7 to 2.9 gigahertz to map precipitation patterns and movements. (AAS is a member society of the American Institute of Physics, which publishes Physics Today.)

The few carveouts included by lawmakers relate to bands that are heavily used by the military, Roohi Dalal, deputy director of public policy at AAS, told FYI before the final bill's passage. Auctioning any of the bands protected for radio astronomy, Dalal said, "would just be another, almost, nail in the coffin for US leadership in radio astronomy." —CZ

National Academies committee seeks ways to cut red tape in research

In response to the Trump administration's interest in deregulation, a National Academies of Sciences, Engineering, and Medicine committee formed this year is working on a report that will suggest ways to reduce the administrative burden placed on researchers. "We cannot resign our research community and the laboratory and university staff who support them to die the death of a thousand ten-minute tasks," said Michael Kratsios, director of the White House Office of Science and Technology Policy (OSTP), in a speech in May at the National Academy of Sciences.

OSTP is looking at current requirements and wants to receive actionable and detailed recommendations from the committee to reduce administrative burden, said Lynne Parker, the office's principal deputy director. The committee is seeking to complete its report quickly; it requested outside input through a survey that closed in June.

Suggestions from attendees of the committee's kickoff meeting in May included developing solutions to minimize the amount of time that principal investigators have to spend on paperwork, standardizing grant application and review procedures across federal agencies, and creating a central mechanism within the White House Office of Management and Budget (OMB) to streamline and harmonize research regulations. The COGR, an association that represents 229 academic research organizations, has submitted 16 recommendations in response to a broad request for deregulation ideas issued by OMB in April.

There has been around a 170% increase in regulations on research in the past decade, National Academy of Sciences president Marcia McNutt said at the meeting. "This could be a game changer for a time when many in the research community are feeling all sticks and no carrots," she added. "This is a chance to actually deliver a win for them." —LM

Higher-ed groups propose new indirect-cost models

The Joint Associations Group (JAG), which includes the Association of American Universities and the COGR, is floating changes to the federal government's model for reimbursing research institutions for indirect costs. The effort comes as the Trump administration is attempting to cap those rates at a fraction of their previous levels. The proposed Financial Accountability in Research (FAIR) models reframe indirect costs as "essential research support costs," which presenters at a 12 June public webinar said makes clearer their relevance to research.

Indirect costs, also known as facilities and administrative costs, are used to cover research-related expenses such as equipment and facilities maintenance, IT services, and administrative support. Under the current model, those costs are often calculated as a percentage of the direct research costs. Since February, four agencies have attempted to cap indirect cost rates at 15%, arguing that the caps will ensure that funds go toward direct scientific research costs rather than to administrative overhead. As of Physics Today's press date, court orders have largely gone in the research institutions' favor and have blocked the implementation of 15% caps at all four agencies.

One of JAG's FAIR proposals, described in the June webinar, would set rates for indirect costs using two adjustment types: the institution type and the type of research funded by the grant. The other proposal would treat indirect costs as direct ones by breaking down those costs as line items for each individual grant, with an additional fixed percentage for "general research operations" that are not easily assigned to a project. JAG plans to use community feedback to create one final model, which could be a hybrid of the two proposals, to present to Congress and the executive branch. —CZ PT

FYI (https://aip.org/fyi), the science policy news service of the American Institute of Physics, focuses on the intersection of policy and the physical sciences.

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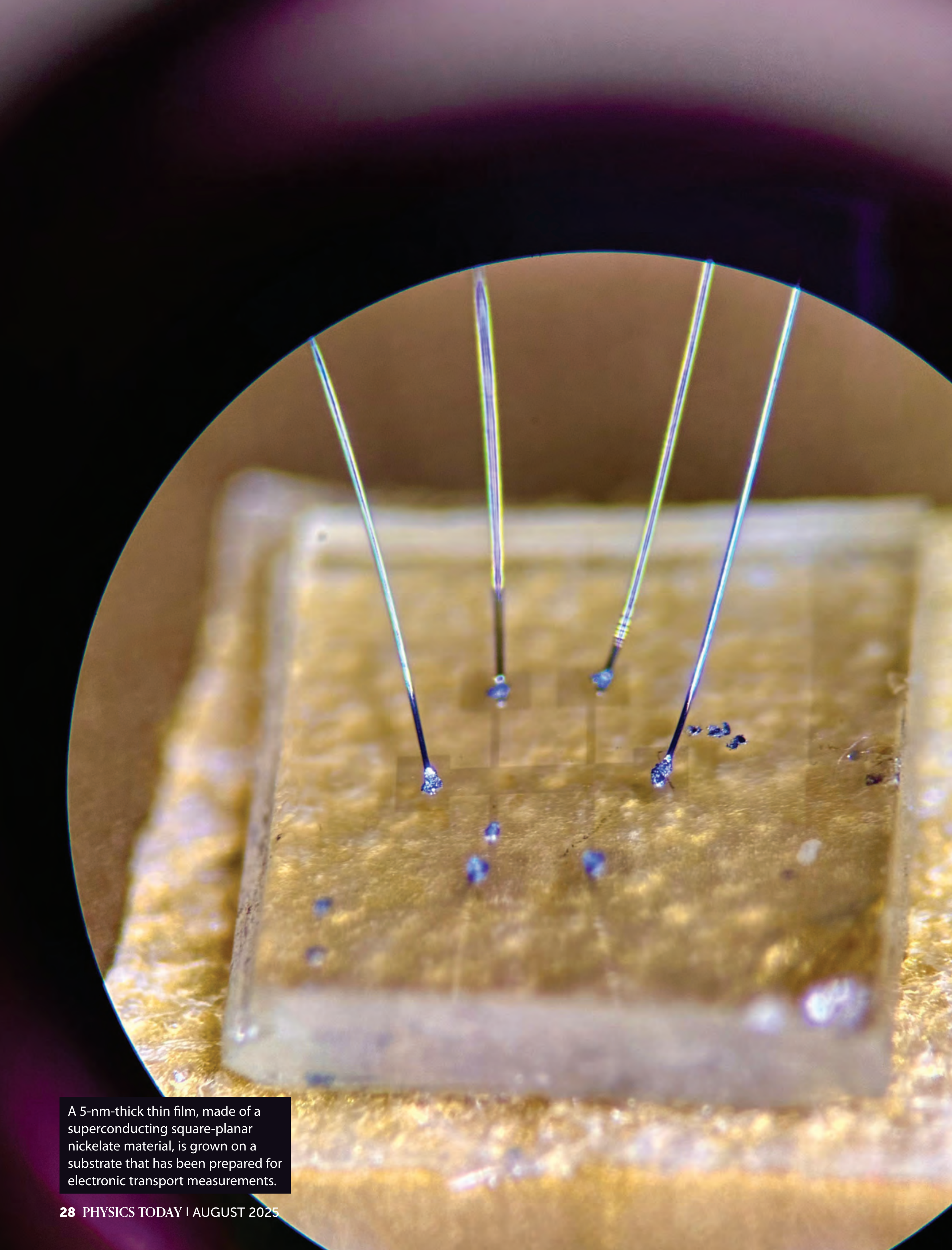

A 5-nm-thick thin film, made of a superconducting square-planar nickelate material, is grown on a substrate that has been prepared for electronic transport measurements.

Berit Goodge is a group leader at the Max Planck Institute for Chemical Physics of Solids in Dresden, Germany. **Michael Norman** directs the Argonne Quantum Institute at Argonne National Laboratory in Lemont, Illinois.

Nickelates provide answers about high-temperature superconductivity—and raise new questions

Berit H. Goodge and Michael R. Norman

Shortly after researchers synthesized a family of superconducting nickelates in 2019, surprising discoveries were found in related yet distinct nickel compounds.

The search for new superconductors—materials that expel magnetic fields and perfectly transmit electrical current below a critical temperature—has occupied countless physicists, chemists, materials scientists, and engineers for more than a century. So when a group at Stanford University discovered in 2019 that nickel oxides could superconduct,[1] a burst of research ensued to reproduce, improve, and understand their fundamental behavior and their possible technological applications.[2] (For more on the discovery, see Physics Today, November 2019, page 19.)

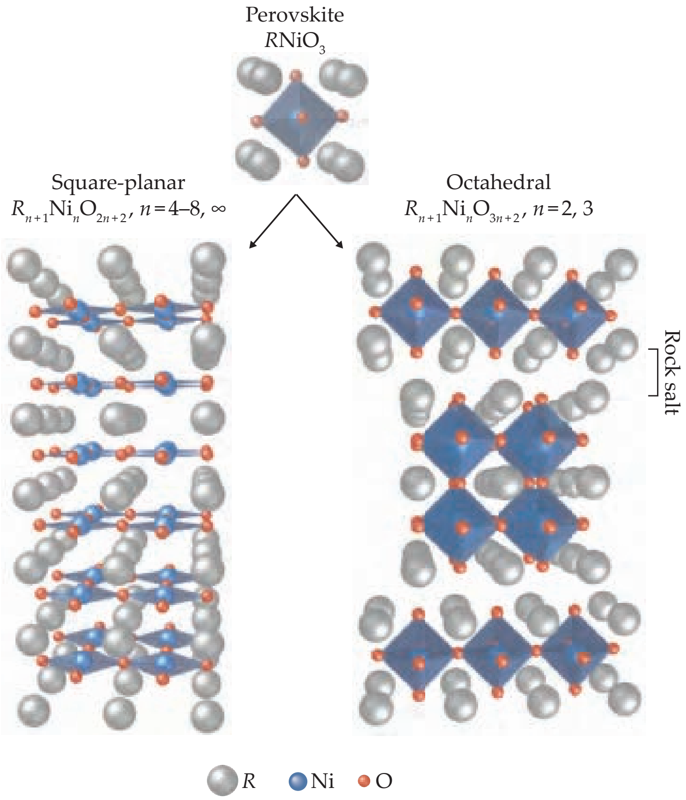

FIGURE 1. TWO NICKEL OXIDE MATERIALS with different atomic crystal structures are capable of superconductivity. The square-planar structure and the octahedral structure are both derived by modifying the cubic perovskite $RNiO_3$, where R is a rare-earth ion. When the number n of nickelate planes approaches infinity, the result is a square-planar $RNiO_2$ structure. The octahedral nickelates are formed when blocks of perovskite are stacked and offset. The listed values of n indicate the chemical formulas of both materials that have been shown to exhibit superconductivity.

Although many researchers saw the nickelate superconductivity as an unquestionable breakthrough, in some sense the finding was unsurprising. Nickelate superconductivity had been predicted as early as 1999 because the nickelates are similar to the most widely studied superconducting family in modern condensed-matter physics: the cuprates. In fact, Georg Bednorz and Alex Müller's search for a material that could superconduct at high temperature began with a nickel compound before they found success in 1986 with copper oxide, a discovery for which they received the 1987 Nobel Prize in Physics (see Physics Today, December 1987, page 17).

Cuprate superconductors hold the record for the highest critical temperature T_c—below which superconductivity occurs—under ambient pressure conditions. They are used, for example, to create sensitive magnetometers, powerful electromagnets for particle accelerators, and lossless electrical transmission cables. They are being explored to produce the strong magnetic fields that are needed to contain hot plasma in fusion reactors. From a fundamental perspective, cuprates present a tantalizing puzzle to understand how and why superconductivity emerges in, of all things, ceramics.[3]

The earliest known superconductors were metals. After decades of exploration, researchers built a well-defined theory: Under certain circumstances, electrons in a material experience attractive forces rather than repulsive ones. The attraction causes them to form coherent bound pairs, named Cooper pairs, after Leon Cooper. Cooper's original 1956 paper[4] soon led to a complete theory,[5] known as BCS, developed by John Bardeen, Cooper, and John Schrieffer, who shared the 1972 Nobel Prize for their work (see Physics Today, December 1972, page 73).

In the original BCS theory, an electron attracts positive ions because of its negative charge. But as an electron moves through a material, it takes time for the slower-moving ions to relax, which allows for a second electron to be attracted to the net positive regions left in the wake. The phonons, the collective motions of the positively charged ions in a crystal, provide the "glue" for Cooper pairing.

BCS theory, however, doesn't entirely explain cuprates and other unconventional superconductors, which are derived from magnetic insulators. In such insulators, an electron with an up spin wants to have neighbors with a down spin. The result is an induced attraction between the electrons that can be stronger than the electron–ion interactions described in BCS theory. Physicists are still building a satisfactory fundamental description of unconventional superconductors. A key part of that quest is studying new materials and, hopefully, finding common ground between them.

The family of superconducting cuprates is made up of many compounds, each with its own chemical details and crystal structure. Yet a few common traits are found across all of them. In particular, each copper ion has a $3d^9$ electron configuration: Nine of the 10 electron states of its valence $3d$ shell are occupied. The Cu^{2+} ions are coordinated in a square net of oxygen atoms that bond with the ions.

The nickelates discovered in 2019 share those traits. The nickel ions have a $3d^9$ electron configuration and are arranged in a square-planar lattice, and each NiO_2 plane is separated by rare-earth ions, as shown in figure 1. Because of their similarity to cuprates, nickelates are an enticing experimental platform to test the bounds and validity of our theoretical understanding of unconventional superconductivity.

Making nickelates into superconductors

The 20-year gap between the prediction and realization of superconducting nickelates was not because of lack of interest but because of the limits of thermodynamics. In the desired $RNiO_2$ structure—with R denoting a trivalent (3+) rare-earth ion—nickel, with its nine $3d$ electrons, is monovalent (1+) and thus unstable, so it is impossible to grow crystalline compounds directly. (The rare earths used in experiments so far include lanthanum, praseodymium, neodymium, and samarium.) Nickelates, instead, must be grown first as the cubic perovskite $RNiO_3$. The extra oxygen, which later needs

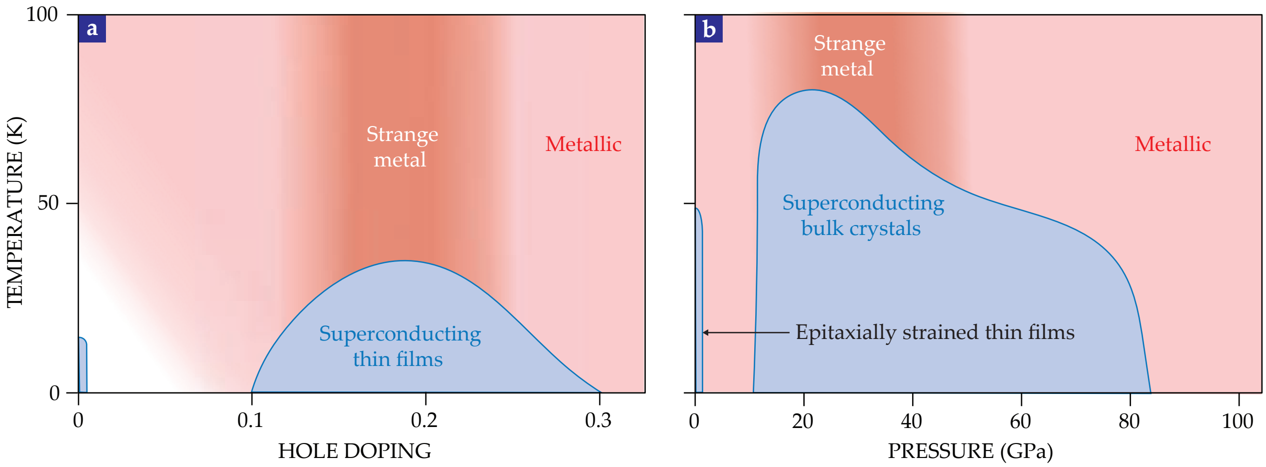

FIGURE 2. PHASE TRANSITIONS. To superconduct, **(a)** square-planar nickelates must have a certain fraction of their trivalent rare-earth ions doped by divalent ions, and **(b)** octahedral nickelates must be at high pressure. In the strange-metal region of phase space, electrical resistivity has a linear temperature dependence—a characteristic seen in cuprate superconductors and also observed in both nickelate families. In many cases, the strange-metal property precedes a superconducting transition. Some groups have reported superconductivity in undoped films (shown on the left in panel a), but the details are still under investigation.

to be chemically extracted to leave behind the desired square-planar form, enables high-quality crystals with nickel to be grown in a more stable $3d^7$ (3+) configuration.

For superconductivity to emerge in square-planar nickelates, the oxygen-reduced material needs to be doped with extra charge carriers in the nickel band structure. The most common approach is chemical substitution, in which roughly 10–30% of the rare-earth ions are replaced with similarly sized divalent (2+) ions, such as strontium, calcium, and europium, each of which can occupy the same lattice position. To maintain the global charge neutrality of the compound, the nickel-ion valence adjusts accordingly. The superconducting nickelate material with the highest T_c contains nickel with a configuration near $3d^{8.8}$ (1.2+), with about 20% doping.

A similar effect can be achieved through structural doping, in which atomically precise engineering is used to insert extra rare-earth planes ($R_{n+1}Ni_nO_{2n+2}$) into the crystal structure.[6] The process starts with the Ruddlesden–Popper crystal family ($R_{n+1}Ni_nO_{3n+1}$), with n stacked perovskite unit cells separated from the next set of layers by rock-salt blocks (R_2O_2). Then, as before, the extra oxygen atoms are chemically extracted to leave n layers of $RNiO_2$. Using highly precise synthesis methods, researchers can tune the nickel valence by controlling the density of the extra planes.

In 2023, a surprising discovery was announced: The lanthanum bilayer member ($La_3Ni_2O_7$) of the Ruddlesden–Popper series also superconducts and at a significantly higher temperature than the square-planar nickelate, although only under very high pressure.[7] Soon after, superconductivity was also found with a lower T_c in the trilayer version ($La_4Ni_3O_{10}$) under high pressure.[8] Rather than a nickel–oxygen square net, Ruddlesden–Popper nickelates are built of nickel–oxygen octahedra in a framework of rare-earth ions, as shown in figure 1.

How the new octahedral nickelate superconductors relate to their square-planar nickelate cousins remains unclear, as does how they may be related to cuprates or other high-T_c superconductors. The reduced square-planar nickelates have a $3d^9$ configuration similar to cuprates. The octahedral nickelates, however, have a different electron filling, with nickel configurations of $3d^{7.5}$ (2.5+) for the bilayer materials and $3d^{7.33}$ (2.67+) for the trilayer materials. Another distinction is that the octahedral nickelates are tuned into a superconducting state not by chemical doping but by mechanical pressure.

The distinctions between square-planar nickelates and octahedral nickelates manifest far beyond their different crystal structures and 3d electron counts. Most obvious are their critical temperatures, plotted in figure 2. Most square-planar compounds have a T_c around 15–20 K, although tuning the rare-earth chemistry appears to be a promising route to increasing T_c, with a recent report nearing 40 K.[9] The octahedral bilayer phase, on the other hand, has already reached 90 K. That temperature is an important benchmark for potential technological applications because the material can be cooled with liquid nitrogen instead of liquid helium, which is expensive and nonrenewable. (For more on helium supply issues, see PHYSICS TODAY, September 2023, page 18.)

A crucial trade-off, however, is that the octahedral nickelates must be squeezed, using diamond-anvil cells, to about 15 GPa—higher than the pressure necessary to form diamond and more than 100 times as much pressure found at the bottom of the Mariana Trench. The square-planar compounds superconduct without any applied pressure. But they must be exceptionally thin films—so far, no more than 10 nm thick—because the only way to make square-planar nickelates is with the two-step process of growth and reduction. The superconducting octahedral compounds can be formed directly as bulk crystals. Each of those requirements—thin films for square-planar nickelates and high pressure for the octahedral compounds—carries its own limitations for experimental measurements.

Another milestone was achieved in late 2024: Thin-film versions of the octahedral bilayer $La_3Ni_2O_7$ grown on a carefully chosen substrate were shown to exhibit superconductivity under ambient pressure conditions.[10] Rather than a high-pressure diamond-anvil cell, the thin film bonds to the substrate on which it forms—a concept known as epitaxial strain engineering.[11] The squeezing of the atomic lattice is sufficiently similar to putting it under high pressure. The demonstration of superconducting thin films has opened the door to various experiments that couldn't be done with high-pressure diamond-anvil cells and will hopefully lead soon to rapid advances in experimental investigations of octahedral nickelates.

Finding family ties

At a more fundamental level, the electronic, magnetic, and other characteristics of superconductors should help guide and validate theoretical models. Some parameters, such as the atomic arrangement and the average valence state of a given ion, can be probed directly through experiments. Early spectroscopic studies of square-planar nickelates, for example, showed that although the nickel ions have the same formal $3d^9$ configuration as superconducting cuprates, the relative positions of the transition metals' $3d$ energy levels differ between the two because of their different nuclear charges.

The differences lead to distinctions in the electronic structure of square-planar nickelates and cuprates, shown in figure 3. In cuprates, the Coulomb repulsion U—the energy separation between occupied and unoccupied copper $3d$ states—is larger than the charge-transfer gap Δ, which is the energy separation between the $3d$ states and the oxygen $2p$ states. Most of the doped holes, therefore, are on the oxygen sites. For the square-planar nickelates, Δ is larger because the $3d$ levels float to higher energy, and as a consequence, most of the spectral weight of the doped holes is on the nickel sites.

In both cases, the oxygen ions exchange electrons with the transition-metal ions—the latter ions thus experience a strong induced interaction between each other. The interaction is known as superexchange, which was developed from a theory by the Nobel laureate Philip Anderson.[12] Because of the large Δ in square-planar nickelates, their superexchange interaction is about half that of the cuprates.[13] Whether that difference is connected to the smaller T_c in nickelates is a matter of debate. In addition, the floating of the $3d$ levels to a higher energy pushes them closer to the nominally unoccupied rare-earth $5d$ energy levels. As a result, the $5d$ states self-dope the square-planar nickelates, which means that, unlike their cuprate counterparts, undoped square-planar nickelates are not magnetic insulators.

Identifying the pairing symmetry

Neither the nickelates' distinct electronic landscape nor the additional rare-earth $5d$ bands' contribution to superconductivity are fully understood. Oxygen-mediated superexchange in cuprates, for example, has been proposed as a fundamental origin of the cuprates' unconventional *d*-wave pairing symmetry.[3] The superconducting pairing symmetry is reflected in the energy gap that opens when the electrons condense to form Cooper pairs. In a conventional BCS superconductor, the gap is isotropic in momentum space. The pairing symmetry, therefore, is labeled as *s*-wave because it's similar to the spherical symmetry of a hydrogen atom's *s* orbital.

Unconventional superconductors, on the other hand, can have order parameters that vary strongly not only in magnitude as a function of momentum but also in sign—where the sign changes, the energy gap is zero. Pairing symmetries are again classified similarly to hydrogen-like orbitals: *p*-wave and *d*-wave, or combinations thereof, depending on the lattice symmetry.

The pairing symmetry in square-planar nickelates has not yet been definitively identified because most experimental measurements are particularly challenging to implement in thin films. But various indirect measurements can reduce the number of plausible options. To date, several groups have

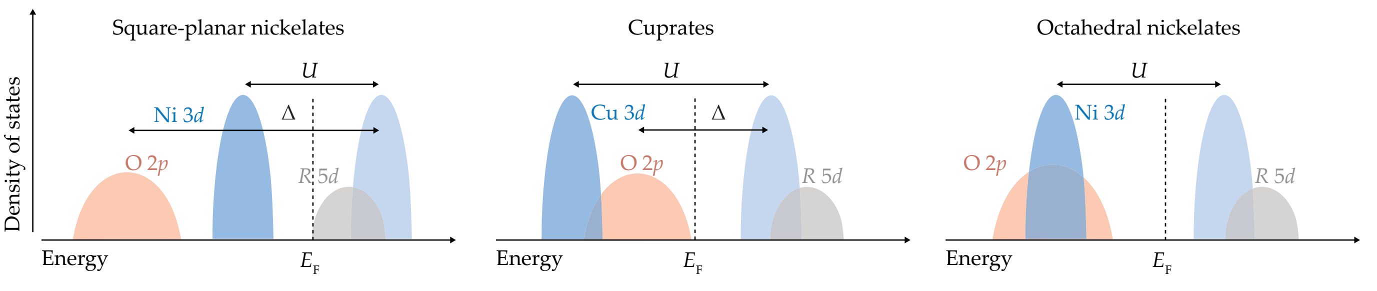

FIGURE 3. THE ELECTRONIC STRUCTURES OF VARIOUS SUPERCONDUCTING MATERIALS are apparent in Zaanen-Sawatzky-Allen diagrams.[18] Each diagram shows the number of possible electron states and their relative energy range for atomic orbitals of interest near the Fermi energy E_F. The value Δ is the charge-transfer energy gap between the oxygen $2p$ and metal $3d$ states, and U is the Coulomb repulsion between the $3d$ electrons, which results in an energy gap between the filled and unfilled *d* states below and above E_F. The actual position of E_F is sensitive to chemical doping, oxygen stoichiometry, and pressure. The significant differences in the electronic structures of the three families of materials may help explain why they each superconduct under different temperature and pressure conditions.

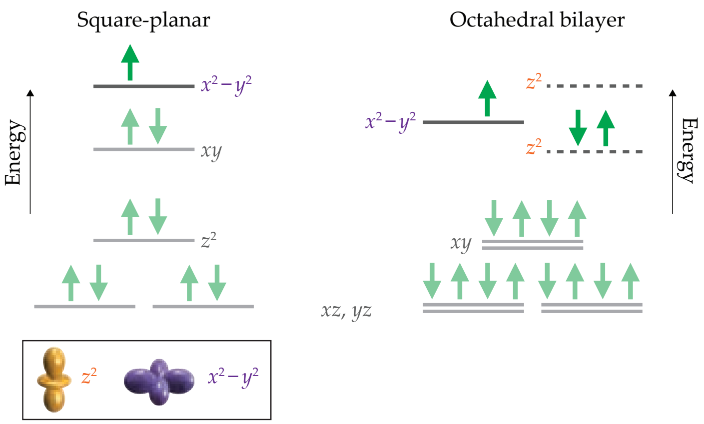

FIGURE 4. THE PARTIALLY FILLED 3D ELECTRONIC STATES contribute to the superconducting behavior in two nickelate materials. The electronic states differ because of each material's particular crystalline structure. Electrons fill the z^2 orbitals in the square-planar material, but they only partially fill the z^2 orbitals in the octahedral bilayer material. The splitting of the z^2 orbitals in the octahedral material arises from the coupling between the two nickelate layers.

reported that square-planar nickelates are, like the cuprates, consistent with d-wave pairing.[14] Other experimental and theoretical groups have put forth alternative hypotheses. Whether the pairing symmetry is similar to or distinct from cuprates—and how that emerges from key similarities or differences in superexchange or other characteristics—will help clarify the critical ingredients for high-temperature superconductivity.

The octahedral nickelates are a different beast entirely (see figure 4). Unlike cuprates, in which the active states are the $3d_{x^2-y^2}$ orbitals, octahedral nickelates have active $3d_{x^2-y^2}$ and active $3d_{z^2}$ orbitals, with the latter strongly bonded to apical oxygen atoms—those above and below the nickel ions. The strong bonds lead to paired spins, called singlets, in the $3d_{z^2}$ states between nickel layers. The $3d_{z^2}$ singlets don't occur in cuprates and square-planar nickelates because the apical oxygen atoms are missing from the square-planar structure. The first theory proposals for octahedral nickelates focused on the nickel $3d_{z^2}$ orbitals and suggested that high pressure would enhance their overlap by compressing the octahedral layers.

Early models of the octahedral bilayer material suggested an unconventional s_{+-} pairing symmetry, in which the order parameter is isotropic but with opposite signs on the two layers. More recent modeling, however, indicates that solutions of s_{+-} or d-wave pairing are extremely sensitive to a given model's parameters, which themselves depend on subtle differences in the bonding and crystalline environments.[15]

Some models have proposed that the $3d_{z^2}$ orbitals are inert, which would mean that the octahedral nickelates are more like cuprates in that only the $3d_{x^2-y^2}$ states are relevant for superconductivity.[16] Alternatively, multiple superconducting phases—or even the novel possibility of a superconductor with tunable pairing symmetry—could exist in octahedral nickelates. Some of the relevant parameters are measurable for octahedral bilayer thin films that superconduct at ambient pressure, so experiments with those materials should hopefully drive progress.

Linking the nickelates

The connection between the two nickelate families—the square-planar and octahedral materials—remains a fascinating piece of the puzzle of what makes certain materials superconduct. Despite their differences, the two families are linked by atomic structure. Removing oxygen from the trilayer octahedral nickelates that superconduct under pressure, for example, yields a trilayer version of the structurally doped square-planar nickelates, which behave similarly to the nonsuperconducting cuprates.[17] Could the reduced trilayer version also superconduct if it were doped in the other direction or if it were pressurized?

Hopefully, the rich phase space between the two families of nickelates can be studied through several intermediate nickelate compounds. Some promising possibilities include the reduced bilayer structure with a nickel configuration of $3d^{8.5}$; other naturally occurring square-planar nickelates with $3d^8$ configurations, similar to some other cuprates; and chemically doped octahedral nickelates.

Both the square-planar and octahedral nickelate families stand as triumphs of collaboration between physicists, chemists, and materials scientists. Continued advances in the materials' synthesis and engineering will improve them further. As high-quality samples become more widely available, the experimental community will hopefully continue to grow and quickly build a foundation of robust knowledge to guide the theory of superconductivity. Similarly, new theoretical insights and frameworks will elucidate key mechanisms and predict promising new routes of experimentation and exploration. Such back-and-forth will accelerate progress across the fields and advance our fundamental understanding of nickelates and, more generally, unconventional superconductivity.

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Two physics students at Wilson College use an interferometer. (Photo courtesy of the C. Elizabeth Boyd ’33 Archives, Hankey Center, Wilson College.)

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THE *Charm* SCHOOL

A summer research opportunity for women before REUs

Mathematician and physicist Dorothy Weeks brought female students into the laboratory almost two decades before NSF began funding a research program targeted at undergraduates.

Joanna Behrman

For students aspiring toward a career in science, participating in the Research Experiences for Undergraduates (REU) program has become a stepping stone from the classroom into the world of research. The opportunities are organized by many organizations, including companies, colleges and universities, and NSF and other governmental agencies. Studies show that participating in an REU helps students boost their confidence in their abilities and gain a better understanding of scientific concepts and research processes. REUs are also associated with an increased rate of degree completion and progression to graduate school, especially among underrepresented groups in science.[1]

DOROTHY WEEKS, ca. 1921, when she was working on her master's degree at MIT. (Photo courtesy of the MIT Museum.)

But decades before REUs were a common practice, there was the Charm School: a summer program exclusively for female college students that was organized for six summers between 1939 and 1948. Attended by at least 28 women, it was spearheaded by Dorothy Weeks, a professor of physics from Wilson College in Pennsylvania. She received assistance from MIT spectroscopist George Harrison, in whose lab the students worked. The history of the Charm School shows the importance of undergraduate research and illustrates how female physicists—and physicists in training—made space for themselves in a place where neither undergraduates nor women often ventured.

Finding a research niche

Weeks understood how to wedge herself into male-dominated environments. As she recalled in her memoir,[2] "I demonstrated my ability to fight very early" (page 103). Born in Pennsylvania in 1893, Weeks developed an early interest in science and mathematics, which was encouraged by her high school teachers and fueled by time spent playing with her brother's collection of electrical and mechanical equipment.[3] She attended Wellesley College in Massachusetts, where she specialized in mathematics, chemistry, and physics.

After graduating in 1916, Weeks worked as a substitute teacher and a statistical clerk before becoming the third woman to work as an examiner at the US Patent Office. But she was more interested in pursuing research and graduate work, so in 1920, she found a position in Washington, DC, at the National Bureau of Standards (now NIST), which began hiring women during World War I. There, she worked in the electrical division and took courses offered by Joseph Ames of Johns Hopkins University.[2]

In 1920, Weeks and three other women became assistant instructors in the physics department at MIT. The chair, Edwin Bidwell Wilson, found it difficult to locate qualified male instructors in the wake of World War I, so he solicited applications from women who would work as instructors while studying for master's degrees. Unfortunately, after Weeks finished her thesis, the climate on MIT's campus began to shift: Both the new department chair, Charles Norton, and the new president, Samuel Wesley Stratton, were opposed to employing women as faculty members and welcoming women graduate students.

Weeks began to wonder if science wasn't for her, and she took a job at the Jordan Marsh department store in Boston in 1924.[2] She decided to return to academia in 1928 and began her PhD studies. She was at MIT again but now

THE MIT DEPARTMENT OF PHYSICS, ca. 1920s. The four female physics instructors in the second row from the top are, from left, Evelyn Clift, Elzura Chandler, Louisa Eyre, and Dorothy Weeks. (Photo courtesy of the MIT Museum.)

in the mathematics department. Supervised by Norbert Wiener, she wrote a dissertation about the mathematics of polarized light. But she did not continue working on that topic—or in any area of theoretical physics—after her graduation in 1930.

Instead, Weeks secured a position as the professor of physics at Wilson College, which at the time was a small women's college with a primarily female faculty. Today, it is coeducational, and it still operates on the same campus in Chambersburg, Pennsylvania. As fortunate as she was to have a position, her new circumstances significantly altered her research prospects. Despite all its charms, Wilson College was no MIT. For one thing, Weeks had few people nearby with whom she could discuss theoretical physics. For another, her teaching-heavy position and lack of external research funding meant that her time and financial means were limited.[2]

Two years into her professorship at Wilson College, Weeks attended Henry Norris Russell's dedication speech for MIT's new spectroscopy laboratory. She recalled, "Before he had spoken many sentences, I was sitting on the edge of my seat and knew that this was the field I wished to study. Here was a field that was of interest to me and one which could be understood by my students. This was not true of the field for my doctorate" (page 616).[2] Moreover, she believed that the spectroscopy community was welcoming. In an interview, she said,

> In a small college, which awarded only the BA degree, one should have a research subject that could be brought down to the understanding of undergraduate students. Spectroscopy was such a subject. There were women working in the field of astronomy, and the related field of optics. It seemed therefore to me a field where less prejudice existed and was ideal for my situation.[3]

Research in spectroscopy was possible for undergraduate students to grasp and contribute to. And several prominent women were active in the field, including the stellar astronomers Cecilia Payne-Gaposchkin and Annie Jump Cannon.

Creating the Charm School

In the summer of 1935, Weeks returned to the MIT spectroscopy laboratory, where she learned how to use the equipment and began a research project on the spectrum of iron. Harrison, the head of the lab, served as Weeks's host and collaborator. At the same time, Harrison was also managing workers from the Works Progress Administration (WPA), a federal agency founded in 1935 as part of the New Deal. During the Great Depression, the WPA funded numerous projects that provided jobs for unemployed workers and produced public goods. Although the bridges, roads, and murals are probably better known today, scientific projects were also among those funded. For example, the Mathematical Tables Project, based in New York City, produced 28 volumes of exponential, logarithmic, and other functions.[4] Harrison's WPA project culminated in the publication of the first edition of the *Massachusetts Institute of Technology Wavelength Tables* in 1939, which included more than 100 000 wavelengths between 2000 and 10 000 angstroms that were used to compare various chemical elements with one another.[5]

More than 140 WPA workers contributed to the project. In the introduction to the book, Harrison credited them with "the great burden of numerical tabulation and checking."[6] Weeks, however, recalled the workers running the spectrograph as well. And she would have known, because she spent her spring, winter, and summer vacations at MIT conducting her own research as well as training some of the WPA workers. She continued to collaborate with Harrison during vacations and—as much as she could manage it—during the school year. Their work examined how the Zeeman effect influenced the spectral lines of elements such as iron, cobalt, and zirconium.[2]

Most of the WPA workers had no experience working in science beyond the training they received on the job. As the work increased in complexity from measuring wavelengths to calculating Landé *g*-factors—first-order perturbations of an atom's energy levels in a weak magnetic field—Weeks saw an opportunity for female students. Third- and fourth-year undergraduates in physics could bring increasingly valuable assistance to Harrison's project. Weeks approached Harrison and received his approval to invite female students to work in the spectroscopy laboratory for six weeks during the summer.[2,3]

As shown in the table, at least 28 students from nine institutions came to MIT during the summers of 1939–41 and 1946–48. The program paused during World War II, when Weeks went to work at the Office of Scientific Research and Development (OSRD). In the program's first few summers, the students attended Harrison's course on practical spectroscopy, but they were not paid or otherwise compensated for living expenses—in contrast to the WPA workers, who were paid employees.[6] The students paid for their own room and board, often at the MIT house or dormitory for female students. Weeks assumed that the students would feel lucky and sufficiently compensated in experience because paid summer jobs were so scarce as the US began emerging from the Great Depression.

REINA SABEL (left) **AND BARBARA WRIGHT** (right) during a radiophysics class at Mount Holyoke College. Sabel and Wright attended the Charm School in the summer of 1940. (Photo courtesy of the Mount Holyoke College Archives and Special Collections.)

Student experiences

Although it was coed, MIT had only a small percentage of undergraduate women, so the new research assistants stood out. They immediately felt the difference in being surrounded by male students after years of education at women's colleges. One student described initially feeling "stage fright at seeing so many boys around," although she eventually settled into the new environment and enjoyed the prospects for dating.[7] Harrison also noticed the contrast: Referring to the students as a "galaxy of youth and beauty," he dubbed the group the "charm school" (page 619).[2] The unofficial name stuck, even though Weeks and most of the students never used it in their correspondence. Although Harrison's chauvinistic comments are not surprising given the time period, they nevertheless underscore how the participants had

Year	College	Number of attendees	Known attendees
1939	Wilson College	2	*Betty E. Prescott*, *Frances Findley*
	Wellesley College	3	
	Bryn Mawr College	1	
	Goucher College	1	
1940	Wilson College	2	Elizabeth "Betty" Failor, Esther Johnson
	Mount Holyoke College	3	Isabel A. Barber, *Reina Sabel*, Barbara A. Wright
	Radcliffe College	1	*Katherine J. Russell*
	Vassar College	1	Molly Bigelow
1941	Wilson College	2	*Mary Schabacker*, Elizabeth Woodburn
	Connecticut College for Women	1	*Barbara D. Gray*
1946	Wilson College	2	*Marjorie Ives, Elaine Hungerman*
	Goucher College	2	Angeline "Dolly" Coultas, *June Rita Herbert*
1947	Goucher College	1	Mary Ann Lamb
	Wilson College	2	*Nancy Curtis*
1948	Wilson College	1	Nancy Connell
	?	2	Jean [last name unknown], Beverly [last name unknown]
	Hunter College	1	*Marian Boykan*

A SUMMARY OF KNOWN DATA about Charm School attendees, including the colleges attendees came from, the number of attendees per institution, and—where known—the names of attendees. The italicized names are of women who are known to have continued in physics or its allied fields through graduate study or employment after college. Other attendees may have done so as well, but records were not available. Additional women may have attended beyond the 28 there are records for.

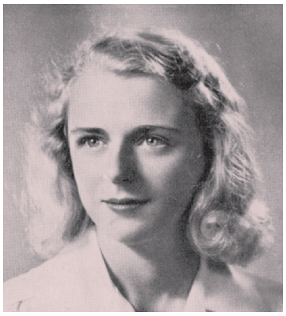
moved from women's colleges, where their academic achievements were valued over their looks, to an environment of altogether opposite values.

In the summer of 1946, two attendees from Goucher College and two from Wilson College came to MIT. The two from Wilson, Elaine Hungerman and Marjorie Ives, already knew Weeks: She had been their physics professor there. Because she was still finishing up her war work at the OSRD, Weeks could not join them that year, but Hungerman and Ives wrote frequently to her about their time at MIT.

The summer started on a high note. Harrison introduced the students to colleagues and friends at a dinner hosted at his house. The following day, he gave them a tour of the facilities and made more introductions. Hungerman felt a thrill at being treated, at least in part, like a colleague as well as a student. She wrote to Weeks, "Oh yes, we have an office complete with telephone and burglar alarm, all of which makes us feel quite important."[8]

At first, Hungerman and Ives worked directly on the equipment. Hungerman wrote, "We spent our time profitably in making comparator readings of Fabry–Pérot fringes and computing ε."[8] She was likely using a Fabry–Pérot interferometer, which uses two partially silvered surfaces and large, offset beams of light to make extremely high-resolution measurements, including ε, the fractional order of interference at the center of the circular patterns generated by the interferometer. But at times, aspects of the project were duller. In late July, Hungerman wrote, "At present Dolly [Coultas] and June [Herbert] are working on the machine while Marjorie and I are typing lists of the secondary standards. It proves to be somewhat boring but that is all right if someone can make use of them."[7]

Even though the work could occasionally be dull, the students found the surrounding environment stimulating. Ives greatly enjoyed the weekly spectroscopy seminars. That summer, the first talk was given by Harrison, and Hungerman wrote that she was excited about an upcoming visit from Walther Meissner, who remains well known today for the discovery of the Meissner (or Meissner–Ochsenfeld) effect, the expulsion of a magnetic field from a superconductor.

ELAINE HUNGERMAN, pictured in the 1946 Wilson College yearbook. She worked on infrared spectroscopy at MIT following graduation. (Photo courtesy of the C. Elizabeth Boyd '33 Archives, Hankey Center, Wilson College.) **MARJORIE IVES**, pictured in the 1947 Wilson College yearbook. She continued working in the MIT spectroscopy laboratory following graduation, and she helped run the 1947 and 1948 Charm Schools. (Photo courtesy of the C. Elizabeth Boyd '33 Archives, Hankey Center, Wilson College.) **BETTY PRESCOTT**, pictured in the 1940 Wilson College yearbook. After graduation, she went to work at Bell Labs. (Photo courtesy of the C. Elizabeth Boyd '33 Archives, Hankey Center, Wilson College.) **MARIAN BOYKAN**, pictured in the 1949 Hunter College yearbook. Boykan attended the 1948 Charm School and later became a mathematician. (Photo courtesy of the Hunter College Archives & Special Collections, Leon & Toby Cooperman Library.)

Ives graduated from Wilson College in 1947, and that summer she returned to MIT, where she helped run the 1947 and 1948 summer schools. Her letters reflect her growth in confidence as a scientific researcher and supervisor. For instance, in 1946, she described her work in general terms:

> [We] have been measuring and calculating the dispersion of some plates containing cerium. We also analyzed the plates to see what else they contained. As you can well imagine this work has been something quite new for me, but I am enjoying it immensely.[9]

But in a 1948 letter, Ives was able to go much further in detail and describe active problem-solving:

> The girls are now working on identification of the Vanadium and will finish the patterns on the plate this week. It is not going to be possible to run the film with the density traces and wavelengths marked simultaneously on the automatic comparator. As a result, they have been doing all the identification on the Hilger comparator. It is possible to run the film on paper and get density traces only—that I am going to see about this week.[10]

What her letter doesn't mention is that along with her duties at the Charm School, she was simultaneously preparing data for Weeks's research and writing a paper for Harrison. She had, in short, become a scientist.

Of course, Ives also had the increased responsibility and confidence of a person who had transformed from student to professional. She was supervising students whose shoes she used to be in. Comparing herself with Harrison, who was the dean of the MIT School of Science, she referred to herself as the "dean of the Charm School." The moniker diminished her role as a supervisor of researchers, much as it diminished the role of the student researchers themselves, but Ives wore it with pride. She had become established in the spectroscopy laboratory and had worked there as a college graduate and full-time researcher for approximately a year. She wrote to Weeks, "You know the accomplishment in winning a little seniority, especially in a lab where the women are so outnumbered."[11]

Charm School alumnae

Ives was not the only alumna of the Charm School to continue in science in some capacity. Hungerman, for example, also stayed at MIT as a paid employee. After graduating from Wilson College in 1946, she worked for a few years in the infrared group at MIT under Richard Lord.[12] And Betty Prescott, a member of the Charm School's first cohort, went on to work on spectroscopy at Bell Labs for many decades. Prescott never forgot Weeks or her undergraduate experience. She arranged for Bell Labs to donate its old spectrophotometer to Wilson College when it purchased a new one.[2]

Other graduates continued in related fields. Katherine Russell, an attendee from Radcliffe College, is better known to historians under her married name, Katherine Sopka. She became a historian of modern physics, and she conducted many oral history interviews that are available at the Niels Bohr Library &

Archives of the American Institute of Physics (which also publishes Physics Today). One of her interviews was with Weeks. In the interview, Sopka noted that the Charm School was "certainly a memorable experience for the one from Radcliffe—who is talking to you now" (page 21).[3]

Another alumna to attain some prominence in her field was Marian Boykan, who attended in 1948 after being recommended to Weeks and the program by Helen Messenger, her physics professor at Hunter College. As Messenger wrote in her recommendation to Weeks, "Temperamentally she is sudden and unexpected due to the speed at which her mind works. She has to be slowed up at intervals and calmed."[13] Unfortunately, there are no records to show if the Charm School was up to her mental speed, but Boykan certainly exercised her mind over the coming decades. She became a mathematical logician who specialized in several topics, including recursion theory, analog computing, and computability in analysis and physics.[14]

The school's legacy

Weeks was the driving force behind the Charm School, so it stopped when she did not continue it after the 1948 summer program, for several reasons. First, paid summertime employment was becoming more available, and the appeal of an unpaid research internship had lessened. Second, Weeks was awarded a Guggenheim Fellowship in 1949, which allowed her to devote more time—and funding—to her own research. She spent much of the 1949–50 academic year at MIT, where she was finally able to hire a research assistant to help with her spectroscopy work.[3]

Although the Charm School had ended, similar programs sprung up soon afterward as the US pushed to improve its science education during the Cold War.[15] Organized, paid research internships for undergraduates emerged on the national level in 1958, when NSF founded the Undergraduate Research Participation (URP) Program. Despite considerable outcry, the URP Program was eliminated in 1982 because of budget cuts under President Ronald Reagan.[16] In 1987, NSF resurrected a national program along similar lines as the URP Program under a new name, Research Experiences for Undergraduates. Both the URP and REU programs were directed at male and female students, although in the earlier decades, it was assumed that most attendees would be male. But in the early 2000s, studies emerged showing that REUs were especially effective at helping female students and students of color continue in scientific fields beyond college. Since then, new undergraduate research programs have emerged that specifically target underrepresented groups.[17]

But more than 60 years earlier, a small program had affected the lives of at least 28 female students in physics. It is hard to claim definitively that the Charm School was a turning point for any individual attendee or was merely a stepping stone on a path that they would have taken anyway.

It is unlikely that many Charm School attendees would otherwise have had a chance to carry out original research during college—those opportunities were rare in the 1930s and 1940s for undergraduates, and doubly rare for female undergraduates. And for at least four of the attendees (Ives, Hungerman, Curtis, and Prescott), attending the Charm School led them to continue research work at MIT or in spectroscopy. Finally, the fact that in a time of obvious resistance to women's presence in science, at least 11 out of 28 participants continued in science past college is a feat worthy of celebration in itself.

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Damage in Turkey from the 2023 earthquake that struck Turkey and Syria. (Photo by Doruk Aksel Anıl/Pexels.)

THE PURSUIT OF RELIABLE EARTHQUAKE FORECASTING

The elusive nature of earthquakes makes forecasting notoriously difficult. Researchers are increasingly turning to AI to tackle the challenge.

S. MOSTAFA MOUSAVI / CAMILLA CATTANIA / GREGORY C. BEROZA

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Earthquakes—a subject of fear and fascination—are among nature's most destructive phenomena, capable of causing widespread devastation and loss of life. They occur through the sudden release of gradually accumulated tectonic stress in Earth's crust. The faults that host earthquakes are part of a complex system with many unknown or unknowable parameters. Small changes in the subsurface can lead to large changes in seismic activity. Faults behave unpredictably, even in laboratory settings. Indicators of forthcoming earthquakes, such as foreshocks, occur inconsistently.

Despite advances in seismology, accurately predicting the time, location, and magnitude of an earthquake remains difficult to achieve. The slow buildup of stress along faults is challenging to model and to measure. The influence of background conditions, static and dynamic stress transfer, and past earthquake history are also hard to quantify. That unpredictability, combined with the infrequent occurrence and rapid onset of earthquakes, makes taking action to prepare for them uniquely difficult.

The advent of big data and AI has created exciting possibilities for identifying new features in vast amounts of seismic data that might portend forthcoming earthquakes. The use of such technological advances in earthquake forecasting and prediction, however, is in its early stages. Integrating AI and big data into seismology will, at a minimum, provide a more complete view of seismic activity. But it also has the potential to lead to breakthroughs that could help manage or mitigate earthquake risk.

Although the terms "prediction" and "forecasting" may seem interchangeable, seismologists make an important distinction between them. Earthquake prediction aims to identify the time, location, and magnitude of a future earthquake with enough determinism to inform targeted actions. For example, an earthquake prediction might state that a magnitude 7.0 earthquake will occur in San Francisco on 15 July 2050 at 3:00pm. That level of specificity would enable city officials to order evacuations and take other steps to protect residents.

Earthquake early warning (EEW) systems are sometimes conflated with earthquake prediction, but they are not a prediction tool. EEW systems detect the first energy released by an earthquake—after fault rupture is already underway—and then issue alerts that can provide seconds to minutes of warning before strong ground shaking arrives. Though EEW systems cannot predict earthquakes before they start, they can provide valuable time for people to take protective actions, such as seeking cover or stopping hazardous activities.

Earthquake forecasting, in contrast, offers a probabilistic description of earthquakes within a specified region and time frame. For example, a forecast might report a 20% probability of a magnitude 6.0 or greater earthquake occurring in Southern California in the next 30 years. Though such information is valuable for long-term planning and risk assessment, it doesn't enable the same level of targeted action as a prediction. Official forecasts are currently issued by many governmental agencies. Long-term forecasts inform building codes and insurance rates. Aftershock forecasts, which can include regional warnings of a short-term increase in the probability of damaging earthquakes, inform the public and first responders. Many efforts are underway to improve probabilistic forecasting, and AI is beginning to be included in them.

Traditional forecasting approaches

Currently, most of the aftershock forecasts issued by governmental bodies worldwide rely on statistical models that analyze earthquake clustering patterns. Statistical approaches use mathematical analysis of past seismicity—the frequency and intensity of earthquake activity in a given region over a period of time—to forecast earthquakes. One statistical approach, known as point-process modeling, considers earthquakes as points in time and space and uses a conditional intensity function to characterize the probability of an event occurring at a specific time and location given the history of past events.

The epidemic-type aftershock sequence (ETAS) approach is a widely used point-process model that captures complex patterns of earthquake occurrence by quantifying the stochastic nature of earthquake triggering.[1] ETAS models treat earthquakes as a self-exciting process, in which one event can trigger others. They combine random background seismicity with triggered events and assume that the rate of triggering declines over time. Figure 1 shows an ETAS model's predictions for aftershocks following a hypothetical magnitude 6.1 event on the San Andreas Fault. Although ETAS models serve as a standard for short-term forecasting and hypothesis testing, they have limitations. They struggle to predict large, infrequent earthquakes and can be sensitive to data quality and completeness (which is the inclusion in a catalog of virtually all earthquakes in a given region and time period).

Physics-based approaches use knowledge from continuum mechanics and friction theory to forecast earthquakes. Such models consider elastic deformation, imparted by previous earthquakes and other physical processes, that modifies the stresses on nearby faults and can trigger subsequent events. They combine estimates of elastic stresses with laws describing how the rate of seismicity varies in response to stress changes, and they assume that experimentally constrained friction laws are applicable.

Because earthquake processes are incompletely understood and difficult to observe, models that accurately describe all aspects of earthquake behavior are elusive. Point-process models emphasize direct triggering between earthquakes, and as such, they are particularly suitable for aftershock forecasting. (See figure 2 for how aftershock forecasting fits into the spectrum of seismic hazard characterization.) In contrast, physics-based models can be more easily generalized to explicitly account for other sources of stress, including long-term tectonic deformation, slow fault slip, dynamic stress changes carried by seismic waves, and pressure changes resulting from natural and anthropogenic fluid injection. Researchers continue to try to determine the relative importance of different driving forces and to construct forecasting models that capture them while keeping computational costs reasonable.

The fact that purely statistical models often outperform physics-based models indicates that there is unrealized progress to be made in earthquake forecasting. Physics-based models require reliable estimates of stress changes, material properties of the crust, and fault friction and a detailed knowledge of the fault system's geometry. When such information is available, physics-based models can compete with ETAS models, particularly for estimating seismicity rates far from the mainshock in space and time.[2] That has motivated the development of hybrid models that leverage the strengths of each type of approach. Hybrid models address limitations such as the lack of underlying physics in statistical models and uncertainties in parameter estimations in physics-based models and can yield better forecasting performance.[3]

Both physics-based and ETAS models can be computationally expensive. Hybrid models, like physics-based models, require high-resolution observations, which are often not available. And both statistical and physical approaches use multiple parameters that can be challenging to estimate, especially in real-time settings.

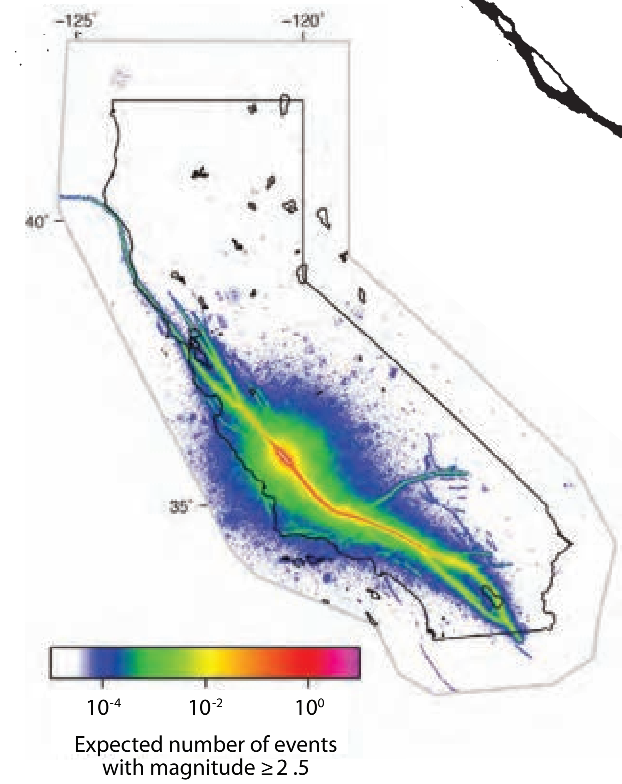


Figure 1. An aftershock forecast for a 7-day period following a hypothetical magnitude 6.1 earthquake (shown as a white line surrounded by red) on the San Andreas Fault in California. The forecast reflects the probability of aftershock events triggered by the initial event. It was made with a statistical model known as an epidemic-type aftershock sequence (ETAS), which treats earthquakes as a self-exciting process. ETAS modeling is a traditional approach to earthquake forecasting. This ETAS model also incorporates known fault geometry, which makes it more robust than a purely statistical forecast. It was generated as part of the Uniform California Earthquake Rupture Forecast, Version 3. (Adapted from E. H. Field et al., *Seismol. Res. Lett.* **88**, 1259, 2017.)

Deep-learning approaches

The application of AI techniques, such as artificial neural networks, to seismology dates back to the late 1980s, an era of much initial excitement around machine learning. The recent rise of deep neural networks (DNNs; see Physics Today, December 2024, page 12) has revolutionized seismology. Because of the availability of extensive seismic datasets, DNNs have permeated nearly every subfield of seismology. When coupled with improved algorithms and greater computing power, seismological deep learning can discern complex patterns and relationships.[4]

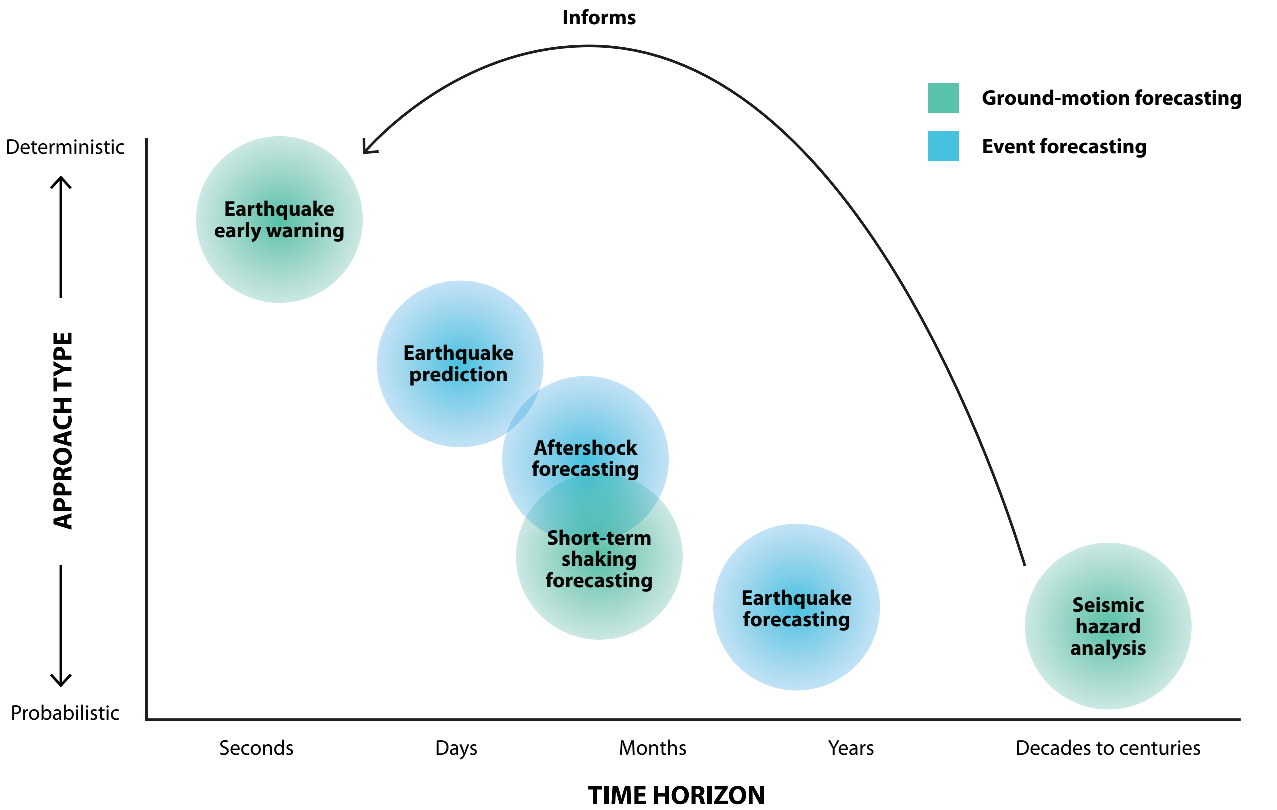


Figure 2. Seismic hazard characterization methods span a range of time horizons. Ground-motion forecasting approaches (green) include earthquake early warning (EEW), short-term shaking forecasting, and seismic hazard analysis (SHA). Event forecasting approaches (blue) include earthquake prediction, aftershock forecasting, and earthquake forecasting. SHA, which quantifies the strength of earthquake shaking likely to occur in the future, is used to identify regions with high seismic hazard and inform the development of EEW systems. Methods that overlap on the graph can be used together in an integrated approach. Wave propagation, used in EEW, and long-term plate boundary strain rates and historical seismicity patterns, used in SHA, are well-understood physics with high predictability. In contrast, the physics behind short- to medium-term forecasting is not as well understood, which results in lower predictability for those approaches.

Convolutional neural networks are a class of DNNs that are primarily used for extracting features from grid-like data through the use of filters. Recurrent neural networks, on the other hand, are designed to process sequential data by maintaining an internal state that captures information from previous steps in the sequence. That allows them to model temporal dependencies and make predictions based on historical context. Deep-learning models have surpassed both classical and early machine-learning approaches in many seismological tasks—particularly in signal detection and phase picking (measuring the arrival time of seismic waves). That has led to the creation of more-comprehensive earthquake catalogs that include many more, previously undetected small events, as shown in figure 3. The more dense information in those catalogs has already provided higher-resolution imaging of active faults and has the potential to improve forecasting accuracy.[5]

The exceptional ability of neural networks to model complex relationships opens new avenues for data-driven modeling of seismicity. Neural temporal point-process (NTPP) models use recurrent neural networks to forecast the time evolution of sequences of events. For that reason, they are a natural choice to explore as a more flexible forecasting strategy than traditional statistical-based point-processing models. A key shift in the modeling approach is the move from relying on sparse seismicity indicators (used in early machine-learning forecasting models) to using the information of all individual earthquakes in earthquake catalogs.[6]

Applications of NTPPs for earthquake rate forecasting[7] have thus far shown marginal improvement over ETAS models: NTPPs are more efficient and flexible, and the multimodularity of neural networks allows for incorporation of more information.[8] NTPP models require large training sets, however, which limits their applicability. The structured yet sparse nature of earthquake catalogs is an obstacle to training deep-learning models effectively. Incorporating spatiotemporal information from earthquake catalogs into the model-building process is also difficult. A recent trend in AI-based earthquake forecasting leverages the statistical power of ETAS models while incorporating the spatiotemporal sequence-forecasting capabilities of neural networks.[9,10] That allows the model to combine historical seismicity patterns and the established statistical principles of ETAS.

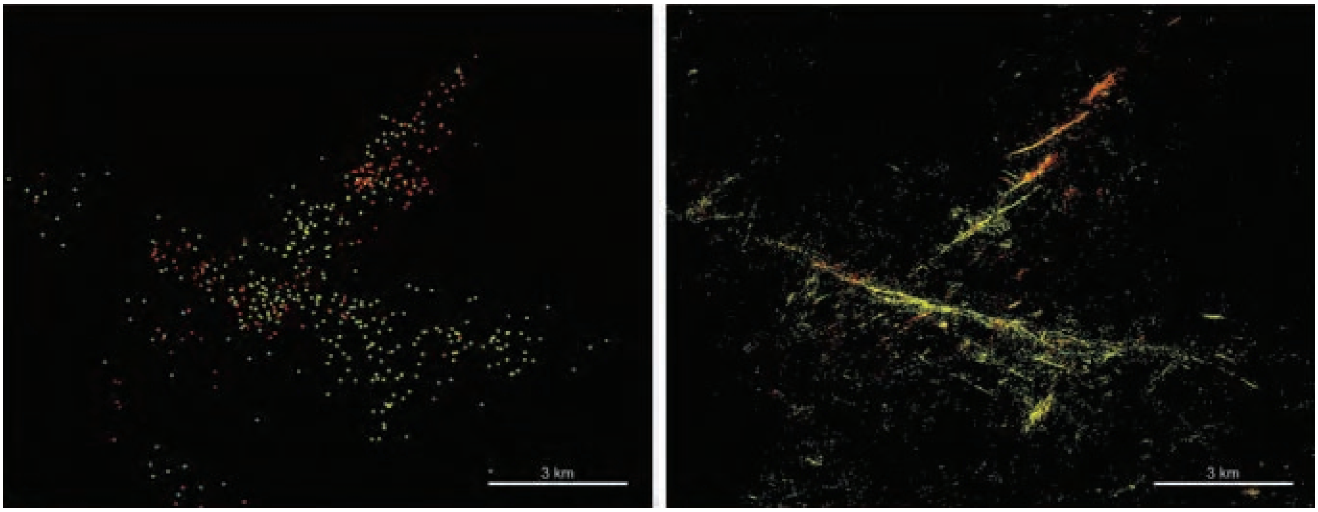


Figure 3. Earthquake detection from seismological data has been vastly improved by the application of deep-learning algorithms. Earthquakes from the 2016 magnitude 5.8 swarm near Pawnee, Oklahoma, are represented as individual points, color coded by time of occurrence, with yellow representing earlier quakes and red representing later ones. The US Geological Survey Advanced National Seismic System Comprehensive Earthquake Catalog **(left)** contains earthquakes that were directly measured by standard seismological methods. A deep-learning-based earthquake catalog[18] **(right)** illustrates the order-of-magnitude improvement to earthquake detection enabled by the application of AI to data processing. (Figure courtesy of Yongsoo Park.)

What AI can—and can't—do

Machine learning offers powerful tools for analyzing complex data. But a combination of the inherent nature of earthquakes, limited knowledge of Earth's interior conditions, and the constraints of current AI models poses challenges for using AI for earthquake forecasting.

Data requirements. One of the biggest difficulties is the nature of the data themselves. Deep-learning models, which gain the ability to predict by recognizing patterns, need massive amounts of data to train effectively. That poses a fundamental problem in earthquake forecasting, since major earthquakes are, thankfully, rare and may occur only once a century in a given location. The lack of historical data makes it difficult to train deep-learning models to predict major events. Even for smaller earthquakes, the data are often incomplete, especially in areas with limited seismic monitoring that detects only larger earthquakes. Though deep-learning-based earthquake monitoring has improved detection, only a few decades of high-quality digital data, even in well-monitored regions, are available. The lack of complete earthquake catalogs limits the ability to build effective forecasting models.

To overcome the problem of limited training data, researchers use such techniques as generating synthetic data from known physics and computer simulations. It's crucial, however, that artificial data mirror the complexity of real earthquakes. Another strategy is to leverage transfer learning, in which a model trained on a large dataset from one geographic area is then fine-tuned using a smaller dataset from a region of interest. That approach could help improve models in areas with limited data.

Generalization of models to new regions. Another hurdle to the development of effective earthquake-forecasting models using AI is the diverse nature of earthquakes across regions. The frequency, magnitude, and patterns of seismic events vary significantly in different tectonic regimes, which makes developing universal models extremely difficult. A promising technique involves domain adaptation, in which a model trained in one region is translated to another region. But the best approach may be to develop models trained on data from multiple regions to enhance their ability to learn more general patterns and reduce the risk of overfitting to region-specific characteristics. It could be achieved by incorporating more physics-based features rather than relying solely on data-driven approaches that are region specific.

Model interpretability and transparency. A key challenge to using AI in earthquake forecasting is the black box problem: Deep-learning models can be incredibly complex and opaque, which makes it difficult to understand how they reach their predictions. That lack of interpretability is not only an obstacle for scientists trying to understand the underlying physical mechanisms of earthquakes, but it also hinders the public trust that is crucial for operational earthquake forecasting. Furthermore, without transparency, it becomes difficult to diagnose errors, identify model limitations, and understand the reasons behind incorrect predictions or biases.

Methods of explainable AI, commonly known as XAI, are being developed to shed light on the decision-making processes of AI models. Techniques such as feature-importance analysis can reveal which factors are most influential in a prediction and potentially aid in the identification of the primary

(Image from Tokyo University Library.)

From deterministic prediction to probabilistic forecasting

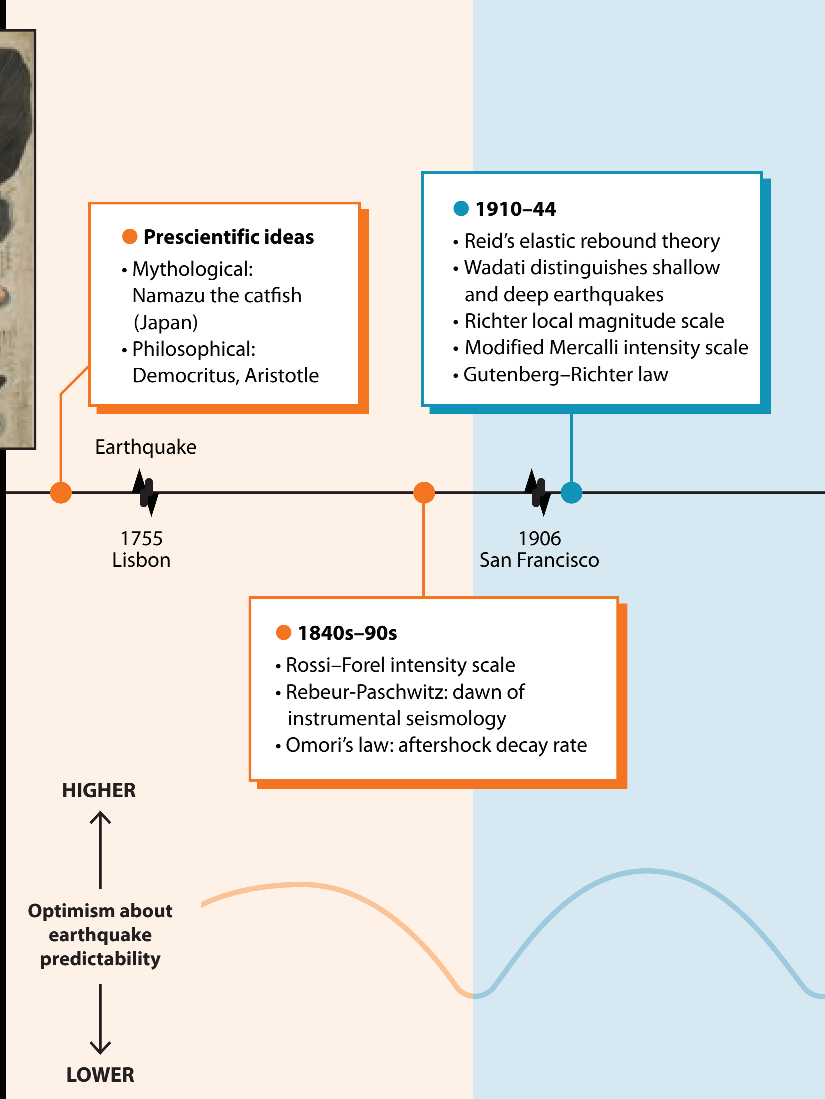
The history of earthquake science has seen repeated phases of growing insights punctuated by large earthquakes that highlight gaps in the community's understanding. Through that historical progression, earthquake science has transitioned from seeking deterministic prediction to embracing probabilistic forecasting frameworks that acknowledge the inherent complexity of seismic processes.

This timeline illustrates the evolution of earthquake prediction science across six major eras.

Timeline not to scale.

EARLY OBSERVATION ERA

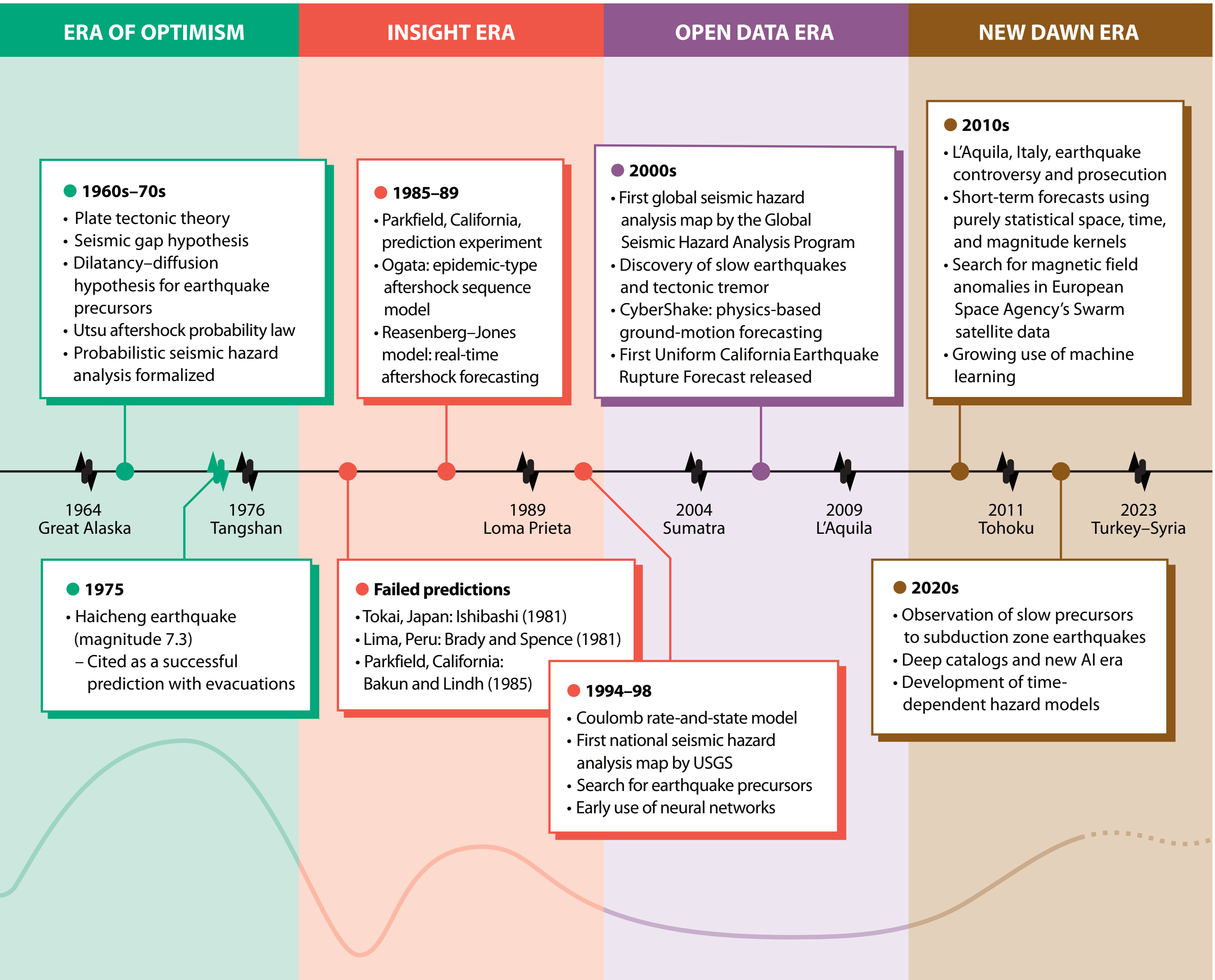
FOUNDATION ERA



Prescientific ideas about earthquakes include mythologies that are found in many regions. In Japan, for example, earthquakes were attributed to a giant underground catfish named Namazu (shown in the image above). Greek philosophers put forth ideas for how wind and water might cause earthquakes.

The early observation era (ancient times to 1890s) began with the creation of systems to characterize earthquake intensity and the development of tools to measure shaking. It culminated with Fusakichi Omori's groundbreaking law that describes aftershock decay patterns.

The foundation era (1900s–50s) was launched by systematic multidisciplinary studies of the 1906 San Francisco earthquake that advanced understanding of fault mechanics and its role in earthquake generation. At the end of that phase, the Gutenberg–Richter law (1944) established the exponential relationship between earthquake frequency and magnitude.



The era of optimism (1960s–70s) saw further improvement to scientific understanding of earthquakes with the widespread acceptance of plate tectonic theory. The dilatancy–diffusion hypothesis put forth mechanisms of expansion and fluid flow in faults as earthquake precursors and brought hope that geophysical observations could lead to predictions. The era reached its peak with the successful evacuation before the 1975 earthquake in Haicheng, China, only to be challenged by the country's devastating unpredicted 1976 Tangshan earthquake.

The insight era (1980s–90s) saw the emergence of probabilistic forecasting—epidemic-type aftershock sequence models and public aftershock forecasts in California—after several deterministic predictions failed. Scientists tried to monitor an earthquake they predicted would occur in Parkfield, California, before 1993, but the next major quake in the region wasn't until 2004. The Coulomb rate-and-state model better established the physics underlying earthquakes by relating crustal stress, fault friction, and earthquake nucleation.

The open data era (2000s) featured international collaboration. Better instrumentation led to the discovery of slow earthquakes and tectonic tremors in subduction zones. The seismology community was rattled, though, by the 2009 L'Aquila earthquake in central Italy and subsequent legal prosecution of scientists for forecasts that were judged to be misleading. The controversy prompted Italy to develop an improved aftershock forecasting system.

The new dawn era (2010s–present) has been characterized by advanced data integration, machine-learning applications, and expanded operational forecasting. The search for precursory signals extended to the use of satellites to measure magnetic anomalies and ionosphere disruptions before and during large earthquakes.

physical mechanisms driving a seismic sequence. Additionally, incorporating existing domain knowledge, such as established physical laws, into AI models can enhance their interpretability and ensure that their results are plausible. Hybrid AI models, which combine deep learning with traditional forecasting approaches, can also offer a path toward greater explainability.

Pitfall benchmarking. Rigorous testing and benchmarking are essential for establishing the reliability and skill of any earthquake-forecasting model. That validation involves both retrospective testing, which evaluates a model's performance on past data, and prospective (and pseudoprospective) testing, which measures its accuracy in predicting future seismic activity. Global community efforts, including the Collaboratory for the Study of Earthquake Predictability (CSEP)[11,12] and the Regional Earthquake Likelihood Models community forecasting experiment,[13] are working to facilitate those evaluations. And the Python library pyCSEP[14] allows researchers to efficiently apply standardized testing methods in their own research.

Despite the well-established standardized testing of operational earthquake forecasts, such testing has not been applied to most AI-based forecasts; that lack of testing raises concerns about the validity of their findings and scientific rigor.[15] The use of generic ETAS parameters that may not be transferable across different tectonic regimes is another commonly observed issue.[16] To ensure reliable evaluation, models need to be testable, contain clearly defined parameters, and be evaluated against well-tuned and state-of-the-art baselines. That requires prospective testing over extended periods and across multiple regions.

The earthquake-forecasting community recognizes the need for standardized tests but has yet to reach a consensus on the minimum requirements. There are several contributing factors, including the limitations of current evaluation methods and the recognition that models may still provide valuable information even if they fail specific tests.[12] Community-driven efforts to share source codes and prospective forecasts, along with platforms like CSEP, are crucial steps toward establishing robust, standardized earthquake-forecasting benchmarking.[17] CSEP provides a valuable platform to evaluate model performance in retrospective and prospective modes, collect data, and compare results across various models.

Ethical considerations. Communication of earthquake forecasts, especially probabilistic ones, in a way that the public can understand and appropriately act on presents a significant ethical challenge. Unlike weather forecasts, which people may expect to provide precise predictions of time and location, earthquake forecasts are inherently uncertain. That can lead to confusion, anxiety, and potentially dangerous responses from the public.

It will require careful consideration of several factors to address the ethical implications of AI-based earthquake forecasting. Privacy concerns must be balanced with the need for data to develop accurate models, and potential biases in the data or forecasting algorithms must be identified and addressed to ensure equitable outcomes for all communities. Clear communication using plain language is essential to avoid misunderstandings and to ensure that the public can interpret forecasts accurately. Managing public expectations is crucial; it requires emphasis on the probabilistic nature of earthquake forecasting and its inherent uncertainties.

Forecasts should also include clear, actionable guidance on how to prepare for and mitigate earthquake risks. Maintaining public trust requires transparency about the limitations of AI models and the uncertainties associated with any forecast. Finally, effective communication must be sensitive to cultural differences and variations in risk perception to ensure that forecasts are accessible and relevant to diverse populations.

A data-driven future

Probabilistic earthquake forecasting, in contrast to deterministic earthquake prediction, is a rapidly evolving field. Advances in technology and data analysis, particularly the incorporation of AI techniques, are driving the development of more-sophisticated forecasting models. Advances in sensor technology and the expansion of dense seismic networks are providing new insight into the dynamics of Earth's crust. That wealth of data enables the creation of more detailed and nuanced forecasting models that better capture the complexities of earthquake processes. A data-centric approach to AI-based earthquake forecasting allows for the incorporation of potentially unknown earthquake physics into the modeling process.

The multimodality of deep-learning methods can enable simultaneous processing of diverse sensor data, such as seismic, electromagnetic, and geodetic information. The flexibility and data-fusion capabilities of AI models allow for the implementation and testing of different hypotheses and may facilitate a more comprehensive understanding of earthquake processes. As forecasting methods continue to evolve, they hold the potential to improve earthquake preparedness, response, and resilience, all of which will remain vital for the mitigation of earthquake risk.

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Focus on software, data acquisition, and instrumentation

The descriptions of the new products listed in this section are based on information supplied to us by the manufacturers. Physics Today can assume no responsibility for their accuracy. For more information about a particular product, visit the website at the end of its description. Please send all new product submissions to ptpub@aip.org.

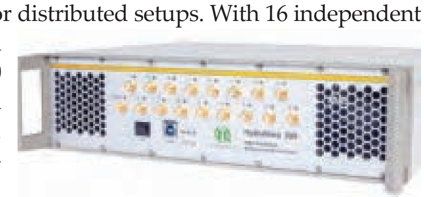
Andreas Mandelis

Superconducting magnet system

Oxford Instruments NanoScience has launched TeslatronPT Plus, a low-temperature, superconducting magnet measurement system. It integrates Lake Shore's measurement instrumentation onto an upgraded TeslatronPT cryomagnetic system with new automated operation and environmental control. The updated system uses an open architecture, which provides more flexibility than closed black-box systems, according to the company. It does not use proprietary measurement software or locked-in hardware and is designed to scale and adapt to evolving research needs. A browser interface allows for remote control. The TeslatronPT Plus enables critical characterization and investigation of fundamental materials physics, with measurement capabilities such as low and high resistance, Hall effect in both Hall bar and van der Pauw geometries, and I–V, or current–voltage, characterization. ***Oxford Instruments plc***, *Tubney Woods, Abingdon, Oxfordshire OX13 5QX, UK, https://nanoscience.oxinst.com*

Time-correlated single-photon counter

The HydraHarp 500 time-correlated single-photon counting unit from PicoQuant is suitable for advanced research in such areas as quantum communication, entanglement, and information; the characterization of single-photon sources; and time-resolved spectroscopy. Various trigger options support a wide range of detectors, including single-photon avalanche diodes and superconducting nanowire single-photon detectors. Versatile interfaces such as a USB 3.0 and an external field-programmable gate array ensure seamless integration and efficient data transfer; White Rabbit technology allows precise cross-device synchronization for distributed setups. With 16 independent channels, each with low dead time, and a common sync channel, the HydraHarp 500 enables true simultaneous multichannel data recording with no dead time between them. ***PicoQuant***, *Rudower Chaussee 29, 12489 Berlin, Germany, www.picoquant.com*



Compact linear translation stages

The V-141 linear motor stage family is the most compact, cost-effective addition to the PI (Physik Instrumente) line of high-performance direct-drive linear stages. With a footprint of just 80 × 80 mm for the 40 mm version, the V-141 is suitable for integration in applications where space is limited but high precision is required—for example, in OEM systems, laboratory automation, and microscopy, metrology, semiconductor, and photonics applications. The V-141 stages offer advanced capabilities for high-speed and high-precision positioning, scanning, and alignment applications. Available in three travel ranges—40, 60, and 100 mm—the stages feature bidirectional repeatability of 0.12 μm, straightness to 2 μm, and a maximum velocity of 1.1 m/s. The direct-drive linear motor technology eliminates the need for mechanical transmissions such as gears and screw drives, reducing maintenance and enabling smooth, wear-free motion with zero backlash. The V-141 supports *xy* and *xyz* configurations, with an optional integrated counterbalance on the *z*-axis, allowing for complex multiaxis motion systems. ***PI (Physik Instrumente) LP***, *16 Albert St, Auburn, MA 01501, www.pi-usa.us*

Modeling and simulation software

Version 6.3 of Comsol's Multiphysics software delivers improved performance, updates to the user interface, and new simulation capabilities for efficient physics modeling and simulation app development. Automated geometry preparation tools now yield higher-quality meshes for faster and more robust simulations. A new module enables detailed electric discharge and breakdown simulations in gases, liquids, and solids; that capability can aid in the design of consumer electronics, high-voltage systems, and more. GPU acceleration offers simulations and surrogate-model training 25 times as fast as previously possible. Version 6.3 brings new modeling capabilities for poroacoustics and fluid flow. It also delivers multiphysics capabilities for structural mechanics, including features for modeling the electromechanics of thin structures and moisture-induced swelling. An interactive Java environment supports model edits using the Comsol application programming interface. ***Comsol Inc***, *100 District Ave, Burlington, MA 01803, www.comsol.com*

Gas pump for high pressure and flow-rate applications

KNF's N 680.15 gas pump offers a maximum pressure of 12 bar relative and a strong flow rate of up to 140 L/min. Suitable for compression and hydrogen and gas recovery applications, the N 680.15 can tolerate high media and ambient temperatures of up to 40 °C and can handle hydrogen, biogas, natural gas, noble gases, and other challenging media. A cast-aluminum compressor housing, stainless steel heads, and cast-iron connecting rod impart maximum durability. A PTFE-coated diaphragm and stainless steel valves are available as standard options. Its durable construction and specialized head configuration allow for the pump's use in high-temperature applications. Excellent chemical resistance and leak tightness of up to 6×10^{-6} mbar L/s make the pump appropriate for helium-compression and gas-purification systems and for applications that involve dangerous or aggressive gases or high-value media. The gas pump has a powerful 230/400 V AC3 motor, with other voltages available as options for customization. ***KNF Neuberger Inc**, 2 Black Forest Rd, Trenton, NJ 08691, https://knf.com*

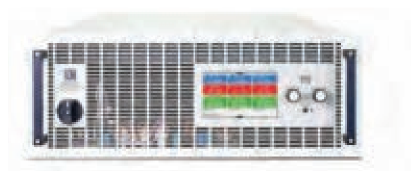
EBSD detector for materials characterization

Bruker's eWARP (Wide Area Pixelated) detector for electron backscatter diffraction (EBSD) features an innovative camera that combines direct electron detection and CMOS technologies. According to Bruker, eWarp's hybrid pixel sensor and high-speed signal-processing electronics designed to meet EBSD requirements increase signal efficiency and acquisition speed and significantly advance materials characterization in scanning electron microscopes. The sensor also enables the acquisition of EBSD maps with up to 14 400 patterns per second at electron-beam settings as low as 10 kV accelerating voltage and 12 nA probe current. At the core of eWARP is the patented CMOS device with on-sensor binning capability. When operated in binning mode, the sensor performs forescatter electron and backscatter electron imaging with up to 350 000 patterns per second. That capability is especially suitable for challenging applications that require high spatial resolution, low electron energy, or short exposure time. ***Bruker Nano GmbH**, Am Studio 2D, 12489 Berlin, Germany, www.bruker.com*

Electrical system testing technology

Keysight Technologies has developed an optically isolated differential probing technology to enhance performance testing for high-voltage applications such as electric vehicles, solar energy, and battery management systems. Validation of floating half-bridge and full-bridge architectures commonly used in power conversion, motor drives, and inverters requires measuring small differential signals riding on high common-mode voltages. Voltage source fluctuations relative to ground, noise interference, and safety concerns can make this challenging, but galvanically isolated differential probes let users measure floating circuits accurately and safely in high-voltage, noisy environments. According to Keysight, since its isolated differential probes provide common-mode rejection up to 10^{10} times greater than standard differential probes, they are suitable for high-voltage and high-side current measurements. With up to 1 GHz bandwidth and a ±2500 V differential voltage range, the probes enable accurate analysis of fast-switching devices such as wide-bandgap gallium nitride and silicon carbide semiconductors. ***Keysight Technologies Inc**, 1400 Fountaingrove Pkwy, Santa Rosa, CA 95403-1738, www.keysight.com*

Three-channel bidirectional power supplies



Delivering higher-power density and test capacity in one compact unit, the EA-PSB 20000 Triple series power supplies from Tektronix have potential uses for programmable power control in applications that require greater power capacity and efficiency. According to the company, the new series is the first triple-channel, bidirectional DC power supply capable of delivering high-density, parallel testing for components in complex systems. Each of the three independent, fully isolated channels can supply up to 10 kW of power, supporting a range of voltages from 0 to 60 V to 0 to 920 V and currents from 0 to 40 A to 0 to 340 A per channel. Featuring up to 96% energy recovery, the EA-PSB 20000 acts as a DC electronic load for energy recycling. The series lets users consolidate multiple testing setups into one, which reduces cost, space and equipment needs, and test time. It also features autoranging, which automatically adjusts the voltage or current to deliver full power across a wide operation range and allows a single unit to handle various voltage and current combinations. ***Tektronix Inc**, 13725 SW Karl Braun Dr, PO Box 500, Beaverton, OR 97077, www.tek.com* PT

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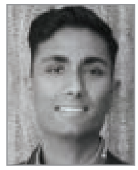

The enduring puzzle of static electricity

Ignaas Jimidar and Joshua Méndez Harper

Even though it lacks a complete explanation, the small-scale, everyday effect is being exploited for various applications.

Volcanic eruptions of ash instigate lightning discharges in the atmosphere. Flows of grain dust in agricultural silos trigger spontaneous explosions. Sandy dunes on Saturn's moon Titan that stretch for kilometers withstand the dense atmosphere's prevailing winds. In all those seemingly disparate contexts, vast numbers of tiny particles collide, rub against each other, and exchange tremendous amounts of electrostatic charge. But you don't need to see an eruption or an explosion to witness triboelectricity (the prefix "tribo" means "rub" in Greek). If you battle a spray of static-laden coffee grounds pouring out of a grinder in the morning, you can experience the effect firsthand. Figure 1 shows the aftermath: triboelectrically charged espresso grounds clinging to a coffee grinder.

Triboelectric charging occurs when two surfaces make contact or slide past one another—one surface becomes positively charged, while the other becomes negatively charged. Beyond coffee preparation, you've experienced contact and frictional electrification if your hair stands on end after you rub a balloon on your head or if you receive a sharp jolt after walking across a carpet and then touching a doorknob. But even though static electricity is an everyday phenomenon and has been studied for millennia, researchers still lack a fundamental understanding of why and how charge transfers between two or more interacting surfaces.

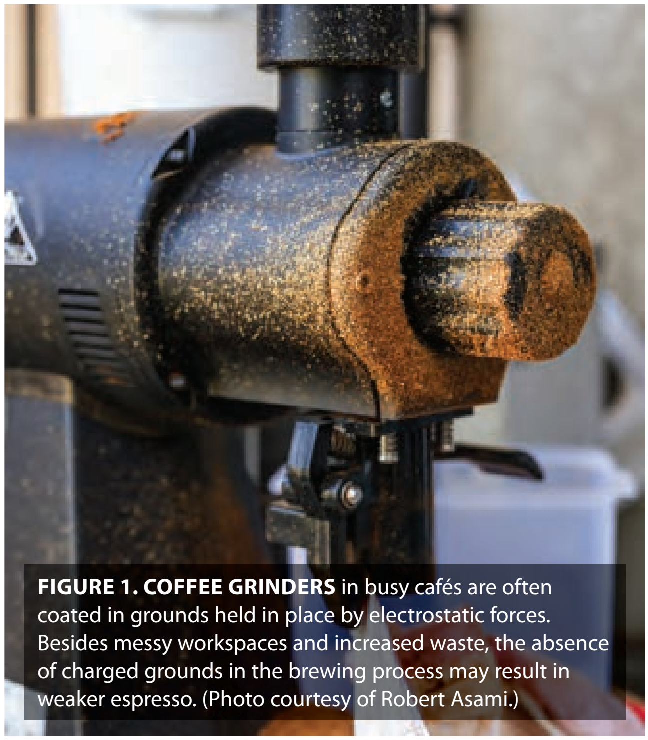

FIGURE 1. COFFEE GRINDERS in busy cafés are often coated in grounds held in place by electrostatic forces. Besides messy workspaces and increased waste, the absence of charged grounds in the brewing process may result in weaker espresso. (Photo courtesy of Robert Asami.)

The modeling (or lack thereof) of triboelectricity

For metal–metal contacts, theoretical and experimental evidence suggests that triboelectrification is driven by an electronic process in which charge flows from the metal with the lower work function to the one with the higher work function. A material's work function is the amount of energy needed to remove an electron from the surface and bring it to a point just outside the material, where the electron has zero kinetic energy. The situation is more complicated for insulators. Unlike metals, insulators lack free charge carriers and therefore do not have work functions. Although electron transfer has been implicated in metal–insulator contacts, some investigators have also argued that tribocharging arises from the transfer of ions or small bits of material.

In the absence of a physics-based model, researchers treat metal–insulator and insulator–insulator triboelectrification phenomenologically. That is, both metal and insulator materials get ordered in a list, known as a triboelectric series, according to the polarity of charge that they acquire when brought into contact with another material. The material that becomes positively charged is placed above the one that becomes negatively charged. Glass, for example, sits near the top of the list, and Teflon generally sits near the bottom. If a bit of Teflon tape is dragged across a glass rod, the tape will become negatively charged, and the glass rod will become positively charged.

Unfortunately, a lack of reproducibility diminishes the predictive power of a triboelectric series. Two experiments using the same sets of materials may yield two distinct orderings of the materials. Furthermore, triboelectric series cannot account for electrification between chemically identical surfaces. Charging has been observed when two pieces of of the same material repeatedly touched one another. The two pieces formed a triboelectric series: The surface of one gained a positive charge, and the surface of the other gained a negative charge. The finding hints that nanoscale morphological changes may be a crucial factor that affects the polarity acquired by an object.

Lastly, triboseries do not account for the effects of ambient conditions, such as temperature, relative humidity, pressure, and external electric fields, all of which have been shown to influence triboelectrification. Yet even though a detailed understanding of triboelectrification is lacking, its scaling relationships are known—and offer insights.

Small-scale interactions, big consequences

It's unsurprising that granular flows of volcanic ash plumes and foodstuffs in grain elevators display rich triboelectric effects. After all, systems consisting of large populations of particles collectively have extensive surface areas that allow for the particles to repeatedly transfer charge between each other. When charged, the constituent particles experience electrostatic forces. For particles with large diameters d and high mass densities, such forces are often negligible, because electrostatic forces scale with d^2, whereas body forces, such as gravity, scale with d^3.

When particle size and mass are small, however, electrostatic interactions can be several orders of magnitude stronger than body forces (see figure 2) and substantially affect particle–particle and particle–surface dynamics. Espresso aficionados might be intimately familiar with the transition to an electrostatically dominated regime. Although electrostatic forces are muted when coffee beans are coarse ground for French press or filter preparations, fine grinding for espresso has the tendency to produce coffee grounds that cling and scatter uncontrollably because of electrostatic forces.

Be it the result of electrons, ions, or bits of material, the charge transfer between interacting particles occurs at scales of nanometers to micrometers. In addition, electrostatic forces between particles act over relatively short ranges and decay proportionally to the square of the interparticle separation. Despite the limited range, electrostatic forces can have collective effects that manifest across much larger spatial scales, from millimeters to sometimes even kilometers.

The charging in volcanic plumes, for example, can drive fine ash particles to electrostatically cluster together. Although ash aggregates typically have diameters of at most a few millimeters, their clumping significantly changes the atmospheric residence time of ash. In some cases, fine ash particles may form rafts that allow them to settle slowly like feathers. In others, clumping may create dense, heavy aggregates that deposit more quickly. Aggregation ultimately helps regulate the effect that volcanic eruptions have on the amount of dust in a region and across the globe.

Designing charged materials

Despite a limited understanding of triboelectricity, researchers are increasingly shifting their roles from observers to designers. Even without a complete knowledge of the underlying mechanism, electrostatic interactions can be tuned in granular materials for beneficial applications. Researchers have, in some cases, shut off electrostatic attractions by tailoring particle surface chemistry or morphology to produce antistatic coatings. In other cases, the goal has been to exploit triboelectric charging to create structures from heterogeneous building blocks. In one proof-of-principle demonstration, two millimeter-sized beads of different polymer compositions were shaken over a conductive substrate material, and one polymer charged negatively and the other charged positively. After some time, the attraction led to the emergence of a checkerboard lattice.

The precise self-assembly of nanometer- to micrometer-sized particles has implications for the development of responsive materials, bioanalytical devices, efficient solar panels, and triboelectric nanogenerators. A granular-interfaced triboelectric nanogenerator can convert ambient kinetic energy into electricity. That could be one way to develop self-powered sensors for internet-of-things devices.

The diversity of research in triboelectric charging has led to tremendous progress over the past few decades. Consistent and reproducible triboelectric behavior, however, remains challenging to observe because of subtle variations in environmental conditions, surface chemistry, and local electric fields. All three variations cause large fluctuations in the magnitude and polarity of the generated charge. The unpredictability underscores the persistent absence of a unified model to describe the transfer and stability of charge at contacting interfaces. Although researchers can apply triboelectricity without a full understanding of the underlying mechanism, developing reliable triboelectric technologies will require solving one of the oldest unresolved problems in physics.

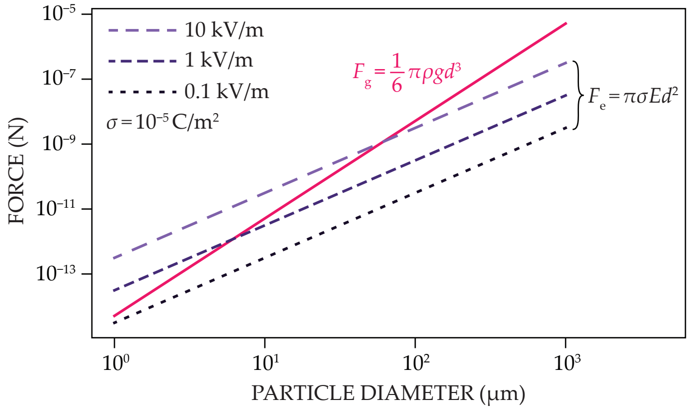

FIGURE 2. COMPETITION BETWEEN GRAVITATIONAL FORCES F_g AND ELECTROSTATIC FORCES F_e determine the behaviors of many granular materials. In this plot, a particle with a fixed density ρ of 1000 kg/m^3 and a charge density σ equal to the theoretical maximum in air is exposed to an electric field E of 0.1–10 kV/m. Particles with a large diameter d experience gravitational forces that easily exceed electrostatic forces (g is the standard acceleration of gravity). As d decreases, electrostatic forces can surpass gravitational forces by a couple orders of magnitude. The shift in force balance has important implications for the aggregation, behavior, and mobility of fine particles in natural and engineered systems.

Additional resources

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► D. J. Lacks, R. M. Sankaran, "Contact electrification of insulating materials," *J. Phys. D Appl. Phys.* **44**, 453001 (2011).
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PT

BACK SCATTER

Illuminating atmospheric aerosols

This green laser light was shined into the skies over Leipzig, Germany, as part of an effort to build a profile of atmospheric particulates. The MARTHA (Multiwavelength Atmospheric Raman Lidar for Temperature, Humidity, and Aerosol Profiling) instrument at Leipzig's Leibniz Institute for Tropospheric Research collects returning radiation that has bounced off aerosol particles and measures the polarization and scattering properties. Lidar data is used, along with physical particulate counts, in weather, climate, and environmental modeling. But the method has limitations: In high atmospheric layers, it confounds volcanic sulphates with smoke, and in low layers, it confounds smoke with urban pollution. To address the classification difficulties, MARTHA was updated in 2022 to also collect fluorescence backscatter, radiation emitted by particles that absorb the laser light.

Benedikt Gast and his team put the upgraded MARTHA to the test in the spring and summer of 2023, when plumes of sooty aerosols from Canadian forest fires were moving through Europe. The researchers found that by analyzing the fluorescence data, they were able to identify various types of smoke. The observations revealed thin layers of wildfire smoke at high altitudes. The layers, otherwise undetectable by conventional lidar, suggest that the upper atmosphere over Europe is more polluted than previously thought, particularly during the summer wildfire season.

Because pure water does not fluoresce, MARTHA can distinguish between dry aerosols and small water particles in clouds. That capability may enable future studies of cloud formation. (B. Gast et al., *Atmos. Chem. Phys.* **25**, 3995, 2025; photo courtesy of Tilo Arnhold, TROPOS.) —MC

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