PHYSICS TODAY

June 2022 • volume 75, number 6

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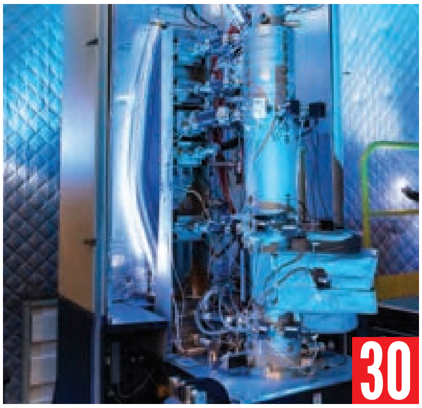

PHYSICS TODAY

June 2022 | volume 75 number 6

FEATURES

ON THE COVER: This school in Kharkiv, Ukraine, was hit by Russian missiles in March. Much of V. N. Karazin Kharkiv National University and other parts of the city have also been demolished. Even as some scientists leave Ukraine for temporary posts elsewhere, people the world over are thinking about how to rebuild science in the country when peace returns. In Russia, meanwhile, scientists are increasingly isolated as their international colleagues weigh showing condemnation and preserving communication. For more on how the war is affecting scientists and science, see **page 22**. (Photo by iStock.com/OLeksandr_Kr.)

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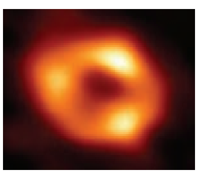

EHT COLLABORATION

Sagittarius A*

Three years after sharing a historic image of the Messier 87 galaxy's supermassive black hole, the Event Horizon Telescope collaboration unveiled last month the portrait of its second subject: Sagittarius A*, the 4-million-solar-mass black hole at the center of the Milky Way.
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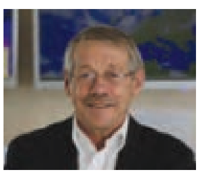

KARL GABL

Karl Gabl

When Simone Moro and other elite mountaineers need to decide whether to risk the elements and ascend to a summit, they rely on the predictions of 75-year-old Austrian meteorologist Karl Gabl. Vedrana Simičević profiles the alpine forecaster who Moro has said "is never wrong."
physicstoday.org/Jun2022b

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Australian science

Scientists in Australia were paying close attention to last month's general election. Many have expressed concern over a government minister's decision to block the national research council from funding multiple peer-reviewed proposals. Benjamin Plackett describes the rift between academics and the government.
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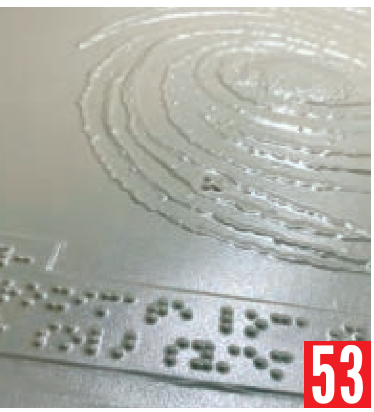
DEPARTMENTS



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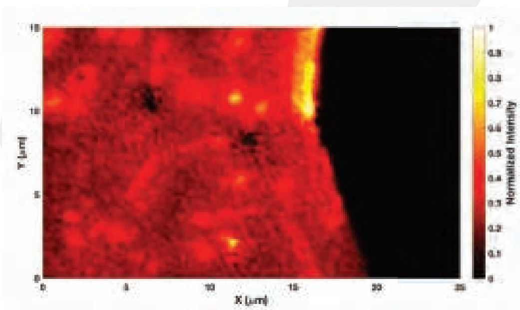
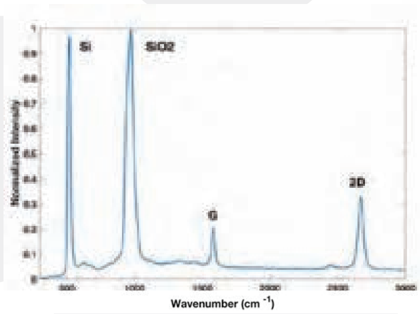
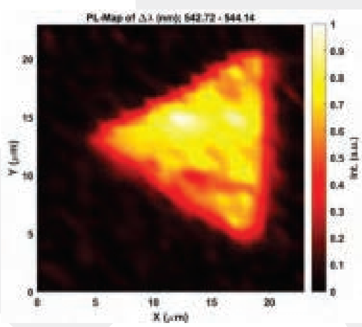
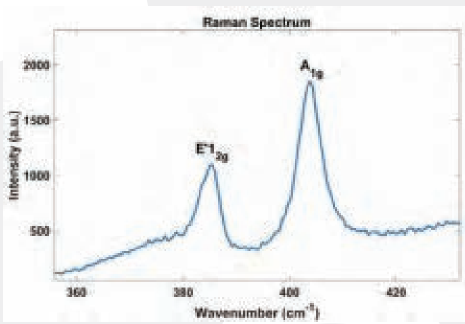




Single layer MoS2 Raman map*





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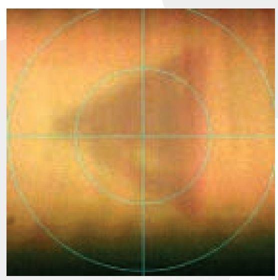

* Data courtesy of Furkan Ağlarcı, Çağlar Samaner, Serkan Ateş @ İzmir Institute of Technology, Turkey & Feridun Ay, Nihan Kosku Perkgöz @ Eskişehir Technical University, Turkey

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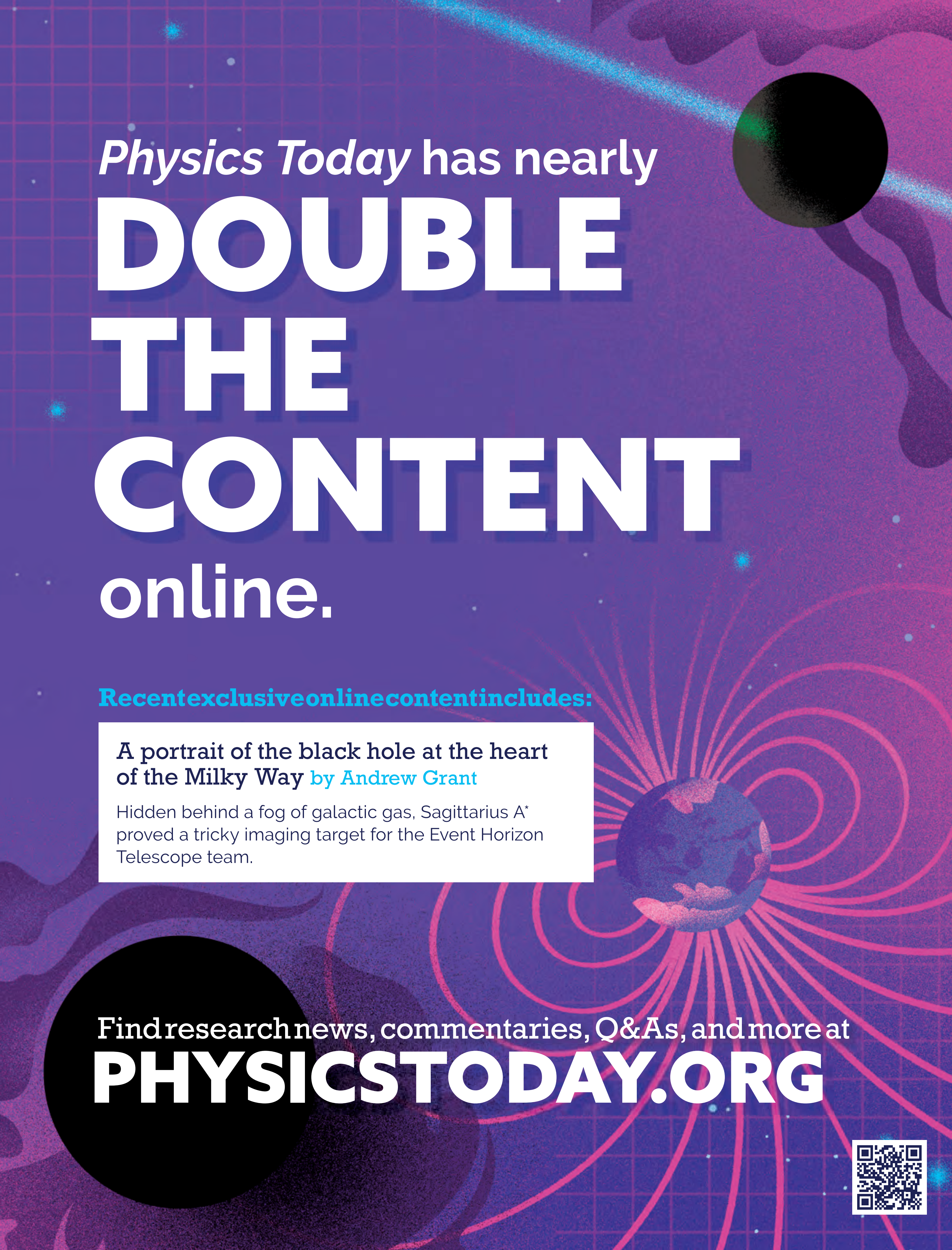
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Commentary

Breaking the spell of scientific isolation in the developing world

Scientific work in a developing country is fraught with all kinds of difficulties that many readers in richer countries won't even hear of in their lifetimes. I am currently a physics professor in Pakistan, and my peers and I face many challenges because of the country's economic position and political caprice.

Such difficulties manifest in different forms. Supplies and equipment come with additional overheads related to freight costs and customs and import duties. Travel advisories and the prospect of leaving behind families to visit presumably adverse environments discourage equipment manufacturers from traveling. Obtaining visas can be slow, and travel, of course, remains expensive. There are also the challenges of sanctions, political turmoil, cultural taboos, language barriers, lack of access to literature, literacy gaps, long power outages, and outright absences of electricity and the internet.

Still, against the backdrop of those difficulties, committed scientists living in developing countries vie to produce new knowledge and participate in the global expedition of scientific discovery. Against the odds, they strive to build new instruments, explain confounding natural processes, and find new ways to tackle diseases—and in the process, attempt to bring down the barriers that have held their populations back in the first place. And that is while they want to be true equals in the global scientific mission.

But lack of contact with peers, little funding, and unattractiveness to foreign scholars to visit perceivably uncomfortable or dangerous environments can quickly downgrade the drive for excellence into a mere desire to cling to mediocrity. The Nobel laureate Abdus Salam said that he had to leave his country, Pakistan, to remain a physicist.[1]

Thanks to the opportunities ushered in by the digital revolution, however, there is hope that the vicious circle of scientific ghettoization can be broken and scientific pursuit can catch up with the enormous strides made toward cultural globalization.

THE AUTHOR (squatting), science communicators, and children from the village of Bua in the Narowal District of Pakistan pose in front of the Khwarizmi Science Society's Large Hadron Collider Interactive Tunnel during one stop on its tour around the country. The society re-created the original LHC tunnel in collaboration with CERN's Media Lab in 2019.

In a commentary published in Physics Today (April 2016, page 10), the Canadian physicist Barry Sanders encourages his readers to wholeheartedly accept invitations to speak in the developing world. He enumerates many benefits for the invitee, such as the opportunity to experience new cultures, recruit and identify potential students and postdocs, and inspire budding scientists. Such benefits to the invitee are truly priceless. But as a host in the developing world, I'll say that the interactions can be true game changers for those of us in the inviting countries as well.

Physically seeing, meeting, listening to, and talking with world-renowned educators and scientists can have a lasting impression on our students' scientific worldview. Eminent scientists can have large fan clubs in the hosting countries, thanks to digital dissemination and popular accounts of their scientific work, and our students and early-career scientists always love to meet members of the community they already admire. For several years I helped organize the Abdus Salam Memorial Lecture Series, which brings scientists of global preeminence to speak about contemporary physics at my university in Lahore.

The encounters can also be purely digital, an experience that has become mainstream since the onset of COVID-19. For example, my university's mathematics department routinely organizes talks as part of the digital John Conway Spirited Mathematics Seminar Series, which brings the best mathematicians from around the world to speak in a virtual setting with anyone who would like to attend.

Such interactions open the door to new scientific questions and expose students to fascinating areas of research or exciting problems to calculate. Stirring conversations can solidify into long-term studentships and academic collaborations. Several of Sanders's students and postdocs have been scouted from his trips to "far-off" countries. Some of those students have now become outstanding educators and researchers in their home countries and help in the transnational pollination of scientific ideas.

Not only do international visitors present their research in specialized conferences, but they also provide the service of popularizing scientific knowledge. In my view, it's far more productive to intersperse research presentations with expository tutorials and public lectures, as people's appetites for advanced technical details can be far exceeded by their innate desire to be motivated and to be inspired. The Khwarizmi Science Society is a grassroots scientific movement I have been working with for the past 25 years. The society organizes the Lahore Science Mela, a festival that attracts thousands of students, children, and citizens to a temporary scientific wonderland. One of the highlights has been the Large Hadron Collider Interactive Tunnel, built by the society in collaboration with CERN's Media Lab. The lab's João Pequenão flew in from Geneva and directed the enactment of a theatrical performance that used the tunnel to teach visitors about particle physics, antimatter, the Higgs field, and gravity. His brief stay in Lahore has sparked the society's plans to tour remote towns and conduct road shows for thousands of eager schoolchildren.

Through introductory workshop-style interactions, visitors can even lay the foundation for new disciplines inside host countries. The International Iran Conferences on Quantum Information have brought together experts from around the world and played a vital role in bolstering Iran's position in the field of quantum information and computation. Vietnam's International Centre for Interdisciplinary Science and Education, which organizes workshops on diverse topics, draws international visitors and has helped the country emerge as a regional powerhouse of physics and mathematics. The African School of Fundamental Physics and Applications orchestrates fundamental training programs in African countries and holds conferences where international experts converge and contribute to elevating scientific understanding.

Some institutions, such as the Abdus Salam International Centre for Theoretical Physics and the World Academy of Sciences, have made it part of their purview to connect scientists from the developing and the developed worlds. But the most potent form of advertisement is the individual scientist in a developing country who extends and strengthens existing connections with Western mentors and invites them to become the seeds of change.

At times, partners between hemispheres have built entire institutions. At present I am dean of the Syed Babar Ali School of Science and Engineering at the Lahore University of Management Sciences. The design of the school, which is a startup experiment inside a university, owes its form to an international advisory board consisting of members from academia and industry. No one urges James Wescoat, the current chair of the board and a professor at MIT, to spend time advising the school's nearly 100 faculty members, all trained at the best universities in the world, on their academic programs and the investments they should make. It's only the inner calling of Wescoat and the other board members, who do not hesitate to visit our school in Lahore every spring, that pushes them to shape the future course of a thriving scientific ecosystem.

The global scientific enterprise can become an embodiment of international cooperation and can stand in the way of hegemony, imperialism, and war. That will require humanity to achieve its best virtue, which is that of sacrifice—namely, sacrificing time to ensure everyone is an equal in the global scientific mission.

Reference

1. A. Salam, in *One Hundred Reasons to Be a Scientist*, Abdus Salam International Centre for Theoretical Physics (2004), p. 29.

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LETTERS

Once a physicist . . .

I appreciated Charles Day's introduction to Physics Today's most recent careers issue (October 2021, page 8). I am always delighted to see attention drawn to the wide range of satisfying careers that can be entered with a physics degree.

The "Spotlight on Hidden Physicists" series in Sigma Pi Sigma's *Radiations* magazine is very special to me as a matter of inclusion and personal perspective. I vividly recall reading letters in Physics Today around the time of the cancellation of the Superconducting Super Collider in

1993. Much was made of how the cancellation was (or wasn't) the demise of US physics and how difficult it was for new PhD physicists to find proper jobs at the time. Industrial and other "hidden" physics jobs were not given much respect, and I don't recall many letters that discussed the struggles of those with bachelor's degrees in physics during that time.

A few years later, I had the privilege of being elected to the National Council for the Society of Physics Students and Sigma Pi Sigma. Under the leadership of Gary White, the director from 2001 to 2012, I participated in developing the broad outline of the Hidden Physicists program. One of our goals was to combat the prevalent misconception that the only thing a physics degree was useful for was a career in academic or government research.

That attitude is a great insult to the majority of physics degree holders, because only a relative few wind up in the business of publishing physics articles. Every year the country produces many more students with bachelor's degrees in physics than with PhDs. For example, data from the 2019–20 academic year show that 9296 students received bachelor's degrees in physics, while 1830 earned PhDs in the subject.[1] For the classes of 2019 and 2020, only about a third of physics bachelors pursued graduate degrees in physics or astronomy, and not all PhD graduates in those years ended up in "publish or perish" jobs.[2]

I espouse the view that completing any degree in physics alters a person's worldview and influences them for the rest of their life, whether they wind up with a PhD in physics or a PhD in medieval literature (a path one of my students followed).

Yes, it is a viewpoint akin to that of Aslan's in *The Lion, the Witch and the Wardrobe* by C. S. Lewis: "Once a king or queen in Narnia, always a king or queen." I concede that not everyone will be so inclusive. I strongly contend that someone who regularly uses their physics background is still a physicist, even if they are not publishing physics papers. That includes someone like the editor-in-chief of Physics Today, who must rely on a strong background in physics to be effective. So Charles, I recognize you as a physicist, and in your role at Physics Today, you were perhaps the most visible "hidden" physicist that I could imagine!

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1. S. Nicholson, P. J. Mulvey, *Roster of Physics Departments with Enrollment and Degree Data, 2020: Results from the 2020 Survey of Enrollments and Degrees*, AIP Statistical Research Center (September 2021).
2. AIP Statistical Research Center, *Initial Employment—Physics Bachelors and PhDs: Classes of 2019 and 2020* (March 2022).

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The weak mixing angle

I thoroughly enjoyed reading Konrad Kleinknecht's excellent summary of Jack Steinberger's life and physics career (Physics Today, September 2021, page 59). I was unaware of several of Steinberger's achievements. In my opinion, he deserved additional Nobel Prizes for some of them, such as his calculation of the two-photon decay rate and lifetime of the neutral pion and discovery of K_L^0 leptonic decay's *CP*-violating charge asymmetry.

I would like to point out, however, that the Weinberg angle, θ_W, referred to in the obituary is also called the "weak mixing angle." It was invented by Sheldon Glashow in his famous 1961 paper, "Partial-symmetries of weak interactions." It is the angle that diagonalizes the 2 × 2 matrix of the neutral gauge bosons, giving the Z boson and the photon as the mass eigenstates in the model based on the gauge group $SU(2) \times U(1)$. With that model, Glashow proposed to unify electromagnetic and weak gauge interactions.

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Correction

April 2022, page 16—The pressure of the hydrogen isotopes in the capsule is 350 Gbar (about 350 billion atmospheres), not 350 GPa. PT

W-boson mass hints at physics beyond the standard model

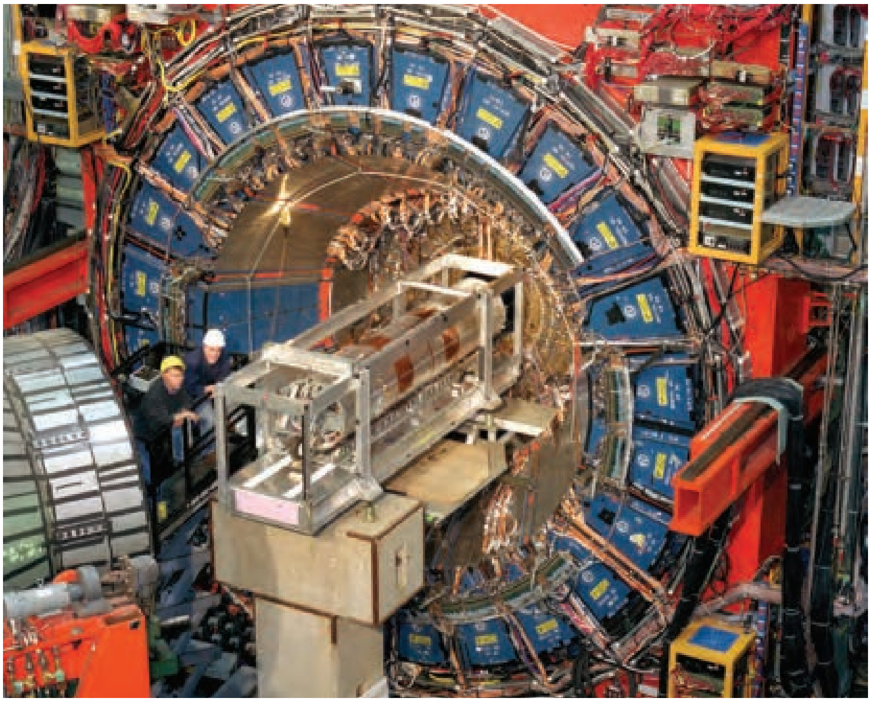

FIGURE 1. THE COLLIDER DETECTOR at Fermilab's now-defunct Tevatron accelerator measured the positions and momenta of electrons and muons produced in proton–antiproton collisions as they passed through 30 240 high-voltage wires. The detector provided data for the highest-precision measurement of the W-boson mass to date. (Courtesy of Reidar Hahn/Fermilab.)

Nearly a decade of collisions and a decade of analysis yield the fundamental particle's mass with the highest precision to date.

The standard model of particle physics must be incomplete. It doesn't explain gravity or dark matter, among other phenomena. But the model does an excellent job describing the other basic building blocks and forces of nature, and measurements that violate it are hard to find.

That's why it was big news last year when the Muon $g-2$ collaboration at Fermilab found that the muon's magnetic moment anomaly differs from the standard-model value by 4.2 standard deviations (see Physics Today, June 2021, page 14). Although a substantial difference, it fell short of the 5 standard deviations that are canonically required to claim a discovery.

In April the Collider Detector at Fermilab (CDF) collaboration published a result that surpasses that threshold and challenges the standard model. Using the now-shut-down Tevatron collider, the 400-person collaboration measured a W-boson mass that is 7 standard deviations higher than predicted and more precise than all previous measurements combined.[1] If independently confirmed, the result points to physics beyond the standard model.

W is for weak

Alongside the Z boson, the positively and negatively charged W bosons are the mediators of the weak nuclear force; their role is analogous to the photon's in the electromagnetic interaction. The weak force is responsible for beta decay, and without it the Sun wouldn't burn. Emitting or exchanging a W boson is also the only way quarks can change their flavor. The W-boson mass is tightly constrained by many other parameters, particularly the masses of the Z boson, Higgs boson, and top quark. Those interdependencies make the W-boson mass a strong test of whether the standard model is self-consistent.

The W boson's existence and properties were predicted in the 1960s and confirmed experimentally at CERN in 1983. Although the standard model doesn't give the mass of the W boson (or any other particle) directly, if one knows the experimental values of enough related particle masses, then predictions become possible. In the past, for example, W-boson-mass measurements enabled predictions for the masses of the top quark, which was eventually measured by Fermilab in 1995, and the Higgs boson, which was measured at the Large Hadron Collider (LHC) in 2012 (see the article by Joe Lykken and Maria Spiropulu, Physics Today, December 2013, page 28).

The observation of the Higgs boson was the final piece of the standard-model puzzle. It also presented the opportunity to check if the W-boson mass agreed with the model. The Z-boson mass was already known precisely—the world average is 91 187.6 ± 2.1 MeV—and with the Higgs mass as a final input, the standard model could offer a concrete number: a W-boson mass of 80 357 ± 6 MeV, with the precision limited by the mass inputs and the number of terms used in the perturbative calculations.[2]

Previous experimental values for the W-boson mass have more or less agreed with predictions.[3] For example, combined previous measurements from the Large Electron–Positron Collider and earlier Tevatron measurements yielded a value of 80 385 ± 15 MeV. Similarly, in 2017 the ATLAS Collaboration at the LHC found a mass of 80 370 ± 19 MeV. But none of those measurements rivaled the precision offered by the standard model. A precise measurement of the W-

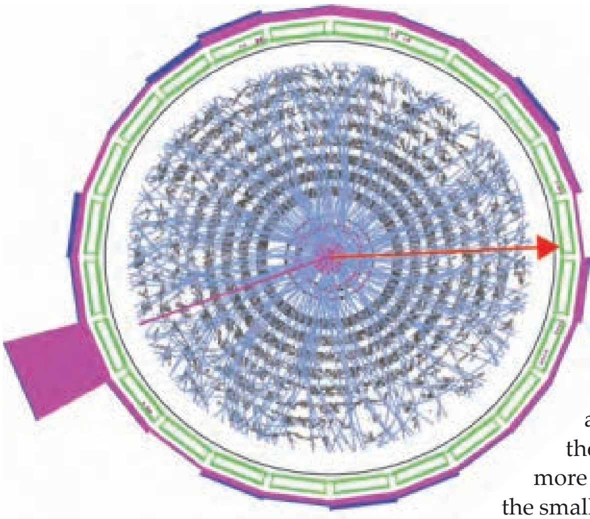

FIGURE 2. ELECTRON AND NEUTRINO PATHS (pink line and red arrow, respectively) from W-boson decay are picked out of the chaos of pion and kaon signals (blue curves). Particle positions—except those of the neutrino, which are inferred from momentum conservation—come from the electrical signals (black dots) of the cylindrical collections of high-voltage wires in the detector in figure 1, which are shown here in cross section. Calorimeters (outermost pink and blue rings) measure energy; the wedge of the lower-left azimuth shows a peak signal from the electron. The momentum distributions of carefully selected and measured electrons and muons can be fitted with a theoretical model to find the W-boson mass. (Courtesy of Ashutosh Kotwal.)

boson mass was one of the CDF collaboration's main goals for the Tevatron's second run.

Decades in the making

The Tevatron in Batavia, Illinois, propelled protons and antiprotons in a four-mile loop and was the most powerful particle accelerator in the world for about two decades until it was unseated by the LHC in 2009. Its first run, from 1992 to 1996, included the discovery of the top quark. Its second run extended from 2001 to 2011, after which the Tevatron was permanently shut down (see Physics Today, March 2011, page 33). Over that operating lifetime, researchers developed and refined techniques for precisely calibrating the CDF, shown in figure 1. They also improved their criteria for selecting data.

The CDF collaboration published a W-boson mass measurement in 2007 and another in 2012 with improved precision, mentioned previously.[4] Those results relied on data collected in the early years of the Tevatron's second run. For the new result, drawn from the full data set collected between 2002 and 2011, the researchers selected more than 4 million W bosons produced via quark–antiquark annihilation, a sample four times as large as that used for the 2012 analysis. In part because of the large sample size, the researchers attained a precision that's a factor of two better than previous studies at any collider. Although the LHC has already measured far more W-boson events than Fermilab, the Tevatron benefitted from lower collision energies, which limit particles' momenta to ranges easier to model theoretically.

Although including more data generally offers improved precision, the CDF researchers found it more advantageous to select only the small fraction of the total produced W bosons that could be measured precisely. The W boson decays into a neutrino paired with either an electron or a muon. Electrons and muons above a certain energy threshold and within a particular momentum range were more likely to be from pure W-decay events. Those and other criteria helped researchers select unambiguous W-boson candidates with low backgrounds.

The CDF tracked the electrons and muons as they passed through 30 240 high-voltage wires around the collision site, as shown in figure 2. One of many ways the CDF collaborators improved the accuracy of their results was by obtaining precise, micrometer-scale information about the positions of the wires. For example, if the straight paths of cosmic rays didn't show up as straight in the detector, the information about the wire positions must've been wrong and was corrected.

The researchers then measured the electron and muon momentum distributions, which are related to the mass of the W boson. Neutrinos are impossible to detect at hadron colliders, but their momenta, also needed for the mass measurement, could be deduced from momentum conservation: Before the collision, the momentum perpendicular to the beam is zero, so after the collision, the sum of all resulting particles' transverse momenta must be zero.

Then began a decade of rooting out sources of errors with 15 new or improved analyses and techniques. The CDF team members offset each electron and muon momentum distribution data set by an encrypted, randomly selected value between −50 MeV and 50 MeV to avoid the potential for subjective bias in fitting. They fit their data with a custom Monte Carlo simulation that models the movements of the electrons and muons through the detector. Compared with the 2012 result, the simulation had an improved precision, in part because of new information about the proton structure and knowledge extracted from the CDF data about how W bosons interact with other particles.

Weighty implications

In November 2020, the team decrypted the offset and unveiled the W-boson mass measurement, which was the most precise to date. "We were so focused on the precision and robustness of our analysis that the value itself was more like a wonderful shock," says Ashutosh Kotwal of Duke University, who initiated and led the analysis.

The researchers obtained a W-boson mass of 80 433.5 ± 9.4 MeV, well above the value from the standard model (see figure 3) and five of the eight previous measurements, although it falls within the uncertainty of some. The CDF team also measured the Z-boson mass, which did agree with the world average. That step wasn't taken in previous measurements of the W-boson mass and was one of many demonstrations of internal consistency.

The observation, if confirmed by independent measurements, could indicate unknown particles or forces. "Now we have to try and understand whether the theory is missing something or whether the measurement could be off or too optimistic about its uncertainty," says Martijn Mulders of CERN, who wasn't involved in the new study. Jonathan Lee Feng of the University of California, Irvine, who also wasn't part of the CDF collaboration, agrees that the result isn't definitive. But he adds, "it is highly significant and written by people and a collaboration with excellent reputations who have performed this analysis over 10 years."

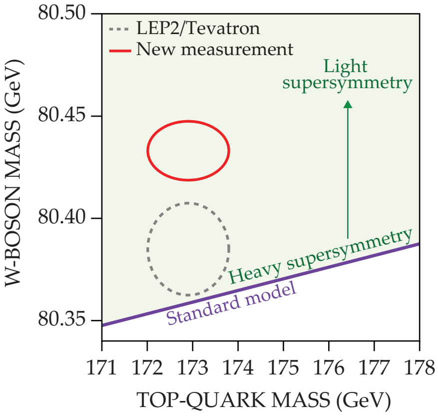

FIGURE 3. THE W BOSON is correlated to other masses in the standard model of particle physics. Using the measured Higgs-boson mass, the model predicts W-boson and top-quark masses to take values anywhere on the purple line. Experimental W-boson masses vary in how well they agree with the prediction, as shown by the 68% confidence level of the new Tevatron result (red) and the combined Large Electron–Positron Collider and earlier Tevatron measurements (dashed gray). The gap between theory and experiment could be bridged by many extensions to the standard model. For example, supersymmetry can shift the predicted masses to any value in the green region given the right parameters. (Adapted from ref. 1.)

With the Tevatron closed for business, the CDF collaboration is necessarily done collecting data. "We will engage in discussions with our colleagues on other experiments to see if we can come up with more ideas for improvement," says Kotwal. "In parallel, we hope that the ideas we have published can help other experiments perform a similarly precise measurement of the W-boson mass."

The LHC went offline in 2018 but will resume measurements this summer with higher beam energy and collision rates and with better detectors. Future W-boson measurements could also happen at proposed electron–positron colliders, such as the International Linear Collider in Japan, the Future Circular Collider at CERN, and the Circular Electron Positron Collider in China (see PHYSICS TODAY, September 2020, page 26).

Possible explanations for a larger W-boson mass come from extensions to the standard model—such as a composite Higgs boson, additional Higgs-like particles, dark-matter particles, or supersymmetry. Such extensions would increase the expected W-boson mass through new interactions, but despite extensive searches, no indications of those particles or interactions have been found so far. And although those extensions could reconcile the standard model with a larger W-boson mass, getting them to do so without causing inconsistencies with other predictions may prove nontrivial.

Heather M. Hill

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Entropy and order work together in an artificial spin ice

The very factor that propels most of the universe toward disorder pushes an array of nanomagnets into a visibly ordered state.

Students of thermodynamics learn that closed systems tend toward states of increasing entropy, which is often considered synonymous with decreasing order. But in some systems, entropy and order can be allies, not opponents: The systems tend toward greater order as—and precisely because—their entropy increases.

The phenomenon isn't as paradoxical as it sounds. The secret is to partition the system's degrees of freedom into two subsets, so that ordering in one subset increases the entropy of the other—and thus of the system as a whole. The trick is well known in soft-matter physics, where entropy-driven order shows up in contexts such as colloidal crystallization: When an ensemble of particles assembles from a disordered dispersion into an ordered lattice, each one can have more room to move around.

The mechanical motion of colloidal particles involves continuous degrees of freedom, which can be complicated to model and difficult to precisely measure. Now Yale University's Peter Schiffer, Los Alamos National Laboratory's Cristiano Nisoli, and their colleagues have shown that entropy-driven order can also occur in an array of nanomagnets called an artificial spin ice—a system whose degrees of freedom are solely discrete.[1]

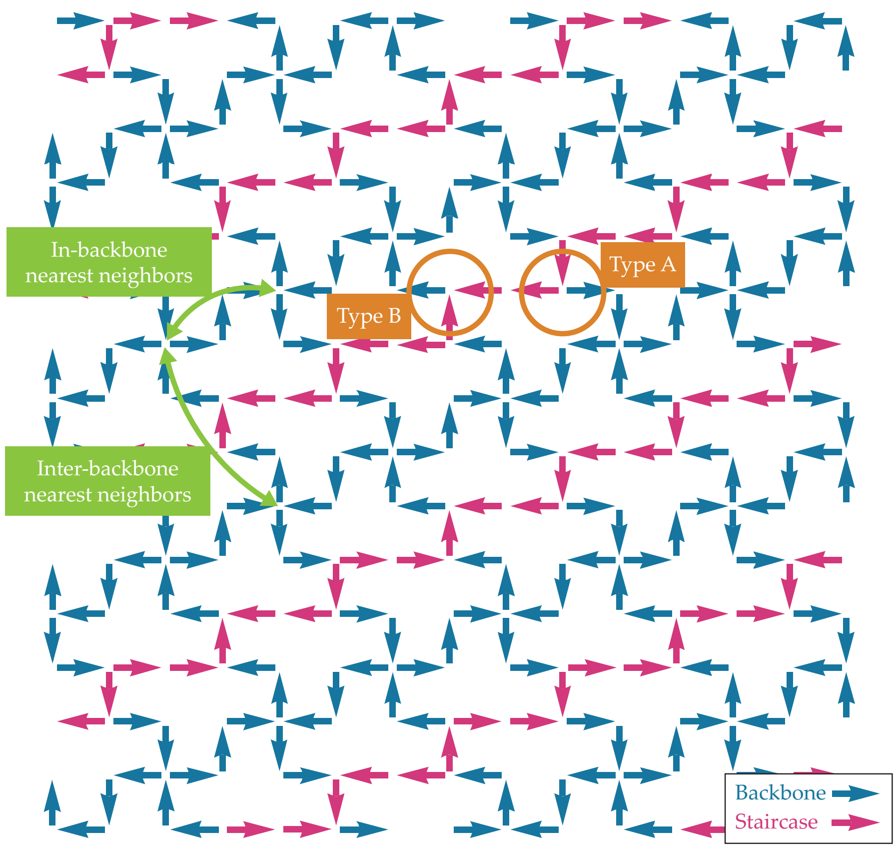

FIGURE 1. TETRIS ICE, an array of nanomagnets outlining a tessellation of T-shaped tetroids, is a vertex-frustrated system. Although the lowest-energy state for the three-way vertices is the one labeled "type A," a global arrangement of moments must have some vertices in the higher-energy "type B" state. Because of the many ways of arranging the type-A and type-B vertices, the lattice—and in particular, the set of staircase moments, shown in pink—has a large residual entropy. The staircase entropy drives the backbone moments, shown in blue, to adopt a large-scale alternating pattern, not just among in-backbone nearest neighbors but also among inter-backbone nearest neighbors. (Adapted from ref. 3.)

Ice degeneracy

Artificial spin ices are designed to mimic natural spin ices, which, in turn, take their name from water ice. The salient common feature of all three classes of systems is that the internal interactions can be frustrated to prevent the system as a whole from having a unique low-energy ground state. Instead, they can relax into any one of a vast number of nearly energy-degenerate configurations.

In water ice, each H_2O molecule sits at a tetrahedral vertex in one of six possible orientations: Each of the two hydrogen atoms can point toward any one of the four neighboring molecules. Because no two H atoms can point toward each other, positioning one molecule restricts the possible orientations of its neighbors, but not enough to fully fix the global configuration. An ice crystal therefore has residual entropy, even at absolute zero.

Natural spin ices are compounds with a similar tetrahedral lattice structure, but with magnetic spins in place of H-atom positions. The system seeks to lower its energy by balancing the spins pointing toward and away from each vertex. But that criterion isn't enough to guide the spins toward a single ground state.

With water ice and natural spin ices, researchers are limited to studying the structures that nature provides. But with artificial spin ices, they're free to create any lattice structure they want. (See the article by Ian Gilbert, Cristiano Nisoli, and Peter Schiffer, Physics Today, July 2016, page 54.) They can therefore design systems where residual entropy not only is present but gives rise to unusual emergent phenomena.

Vertex frustration

Schiffer, Nisoli, and colleagues' spin ice of choice in the new work, which they call "tetris ice," is shown in figure 1. Each of the blue and pink arrows marks the position of an oblong nanomagnet whose

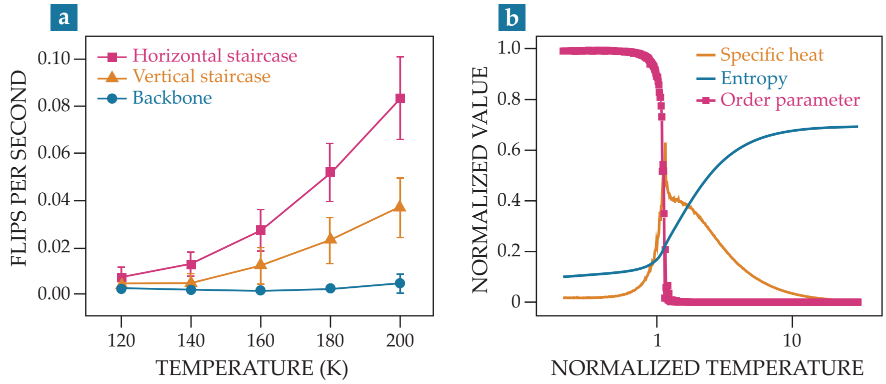

FIGURE 2. ENTROPY-DRIVEN ORDER in tetris ice can be studied in quantitative detail. **(a)** Imaging of the system over time shows that the staircase moments, where the lattice entropy is concentrated, change their magnetization much more frequently than the backbone moments, which are driven toward order. **(b)** A Monte Carlo simulation exhibits an order–disorder phase transition, despite the system's residual entropy at low temperature. (Adapted from ref. 1.)

magnetization is free to point in either of two directions along its length. Like natural spin ices, artificial spin ices can lower their energy by equalizing the number of moments pointing into and out of each vertex. If a vertex has more than one moment pointing in (or out), the lowest-energy state is the one that maximizes those moments' angular separation.

A vertex where four magnets meet has a clear lowest-energy state—with alternating moments pointing in and out—that's adopted in one of two possible configurations by all of the four-way vertices in the figure. A three-way vertex, on the other hand, can't have equal numbers of moments pointing in and out. Its lowest-energy state, labeled "type A" in the figure, is the one where the collinear moments either both point in or both point out. The "type B" state, with one of the collinear moments pointing in and one pointing out, is slightly higher in energy.

The important property of the tetris-ice lattice, as Nisoli and colleagues pointed out in a theory paper in 2013, is that it's vertex-frustrated: There's no way to arrange the moments so that every vertex is in its lowest energy state.[2] In practice, nearly all of the higher-energy vertices are type B three-way vertices. But the system has many ways to allocate its three-way vertices to type B and type A.

The sections of the lattice shown in blue, which the researchers call "backbones," have no three-way vertices, so each one can (and usually does) settle into its lowest-energy state, with the four-way vertices alternating in configuration. If that alternating pattern extends across multiple backbones—that is, if both in-backbone nearest neighbors and inter-backbone nearest neighbors have alternating configurations—then the staircases in between, shown in pink, have many ways to arrange their type B vertices that are all fairly low in energy. But when the backbones break the antiferromagnetic pattern, so that inter-backbone nearest neighbors have the same configuration, then the intervening staircase is limited to just one low-energy state.

Nisoli and his theory colleagues teamed up with Schiffer's group to study the system experimentally. For magnets a few hundred nanometers long, the energy barrier to spontaneously reversing magnetization is close to the room-temperature thermal energy. Furthermore, it's possible to quickly and reliably probe the magnet's states using x-ray magnetic circular-dichroism photoemission electron microscopy, so the experimenters can watch and record the system's configuration as it evolves over time.

In a 2016 paper, the joint team observed that tetris ice could be well described as a series of quasi-one-dimensional backbones and staircases, and they described the staircase behavior in terms of the 1D Ising model.[3] After that, the system sat on the back burner until 2020, when the COVID-19 lab closure prompted the researchers to reexamine old data in search of new understanding.

Data and theory

Many questions remained about the

tetris-ice system. With the backbones separated by staircases, which had so many available energy-degenerate configurations, can the backbones correlate with one another, and if so, by what mechanism? On the other hand, if tetris ice is really a composite of isolated 1D chains, that would seem to imply that it, like the 1D Ising model, could never undergo an order–disorder phase transition at any finite temperature.

Hilal Saglam, then a postdoc in Schiffer's group and now at Princeton University, took charge of sorting through the accumulated data. She found that although the backbone moments were more sluggish to flip than the staircase moments (as shown in figure 2a), the backbones did tend to organize into ordered antiferromagnetic domains—not just in one dimension but in two.

Nisoli's team proposed the ordering mechanism. Whenever two neighboring backbones broke the antiferromagnetic pattern, the staircase in between didn't pay an energy penalty, but it did pay an entropy penalty because of the fewer available low-energy configurations. The system's free energy—energy minus entropy times temperature—is therefore higher for the disordered-backbone state. Because systems tend to lower their free energies, the staircases' entropy drives the backbones toward order.

The smoking gun for that explanation would be to start with all the backbones completely out of antiferromagnetic order—with all pairs of inter-backbone nearest neighbors having the same moment configuration—and show that they still evolve toward order. Reversing the magnetization of an entire backbone would seemingly take a coordinated effort. Would the force of entropy-driven order be enough to accomplish it?

Unfortunately, experimental spin-ice tools, although adept at measuring a system's configuration, aren't up to the task of initializing the nanomagnets in such a specific state. The scenario the researchers had in mind could be studied only by simulation. Nisoli's postdoc Ayhan Duzgun (now at Intel) developed and refined a Monte Carlo model to match the experimental behavior. Along the way, he confirmed that the tetris-ice dynamics really were governed entirely by the vertex energies, not by any long-range interactions.

With the Monte Carlo simulations, Duzgun explored the system's phase diagram. As shown in figure 2b, it exhibits the hallmarks of an order–disorder phase transition—a spike in the specific heat and a jump in the antiferromagnetic order parameter—that would be impossible in a 1D system. As expected, the entropy never goes to zero, even at low temperature. And sure enough, when the lattice was initialized in a disordered-backbone state, it evolved toward order.

New designs

With their discovery of entropy-driven order in tetris ice, Schiffer, Nisoli, and colleagues now have a foothold to explore other systems in which it might also be lurking. "We're interested in these artificial spin ices to generate new unexpected phenomena that might be harder to find in real materials," explains Schiffer. Because the structure of artificial spin ice is fully under the researchers' control—and limited only by their imagination—they can tune the behavior to be as simple or as complex as they like. One item on their to-do list is to try to generate entropy-driven order in a lattice with more types of geometrically distinct vertices.

The long-term hope is that artificial spin ices could lead to new clues about other systems in which order arises spontaneously in ways that aren't fully understood, up to and including the nanomachinery of life. Even now, artificial spin ices are being explored as platforms for information storage and new modes of computing that may mimic the workings of the human brain. Nisoli can easily imagine entropy-driven order's relevance: "In information theory, entropy represents the uncertainty of an outcome," he says. "But here, it drives a correlation among bits. It makes the outcome more certain."

Johanna Miller

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Photonic waveguides shed their cladding

The slimmed-down conduits avoid cross talk between adjacent channels by using materials that support different wave modes.

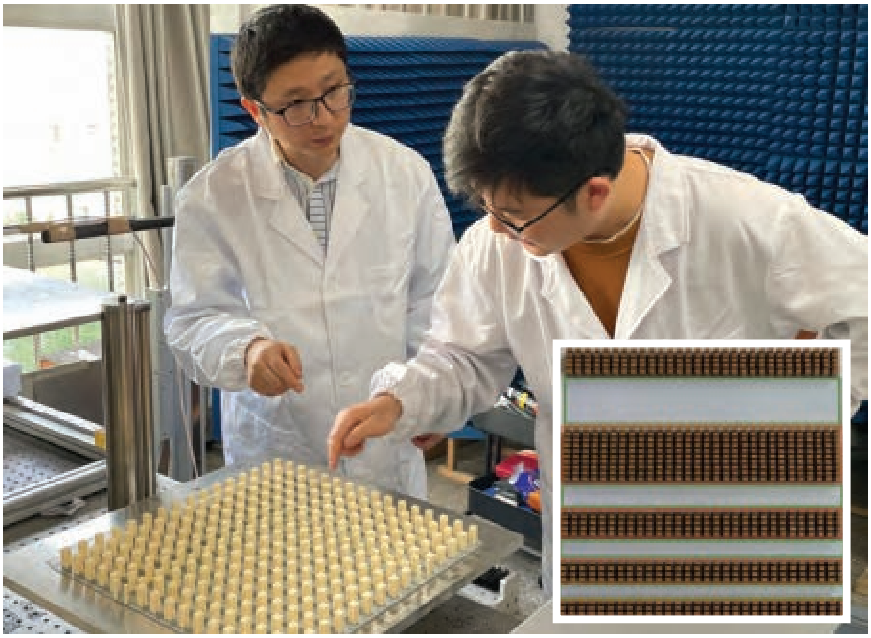

FIGURE 1. A PHOTONIC CRYSTAL made of dielectric posts surrounded by air transmits different wave modes than either material alone. Yun Lai (left) and his postdoc Hongchen Chu (right) are shown here with one such metamaterial. Alternating regions of air and photonic crystal forms a waveguide array with no separation between adjacent channels (inset). The photonic crystal, which has 3.6 × 2.4 mm posts, and the air host disjoint sets of wave modes, so light doesn't cross the boundary between them. (Photo courtesy of Cong Wang; inset adapted from ref. 1.)

Fiber-optic cables form the backbone of worldwide communication systems. By carrying light rather than electrical pulses, the cables transmit information faster and more efficiently than copper wires. The devices those cables connect still use electrical wires, though, so optical signals have to be converted at either end of their journey. Replacing device electronics with photonic analogues would both improve information-transfer capabilities and avoid resistive heating.

In a traditional fiber-optic cable, a core—usually a glass fiber about 10–100 μm wide—is surrounded by cladding that has a lower refractive index than the core and confines light using total internal reflection. That's fine for long-distance travel, where space isn't at a premium. But if photonic circuits are to replace electronic ones, cables will have to be shrunk down and packed onto chips to make integrated photonic circuits. The cladding is wasted space, and it places a fundamental limit on how tightly packed the cores can be: Light leaks through if the separating layer is thinner than $\lambda/2$, where λ is the wavelength of the light.

A team of researchers led by Yun Lai, Ruwen Peng, and Mu Wang at Nanjing University in China has now devised a waveguide array whose light-carrying channels don't require a separation layer.[1] Experiments and simulations demonstrate that the zero-separation waveguide array (ZSWA) confines light to individual channels and efficiently directs it around sharp corners—a critical capability for use in integrated photonic circuits.

Setting boundaries

Fiber optics based on total internal reflection are just one of the existing methods for guiding light along a desired path. But the various options all involve surrounding a light-carrying channel with a material that excludes transport: a photonic-bandgap crystal, a topological insulator, or even a metal. Researchers have worked toward shrinking the excluding layer to make increasingly compact photonic circuits, but some sort of barrier between conduits has remained necessary.

In the ZSWA design, adjacent waveguides are made from different materials (see figure 1 inset). Light can travel in either material, and the interface between the two materials blocks light transmission, keeping it on its intended path. Since every layer serves as a waveguide, no space is wasted on barriers.

To create a reflecting interface, the researchers sought materials with disjoint spatial dispersions. That means if light of a particular frequency has wavevector **k** in one material, the possible values for k_x—the wavevector's component parallel to the interface—in that material must not overlap with the allowable values k'_x in the other material.

The idea of disjoint spatial dispersions can be understood by considering the equal-frequency contours (EFCs) in figure 2a. Each one shows the allowable wavevectors for light at a given frequency in a particular material. Homogeneous materials, such as the core and cladding used in fiber-optic cables, have isotropic EFCs. The contour radii depend on the materials' refractive indexes. Any light in the core whose wavevector lies to the right of the dashed vertical line is confined to the core because there are no modes in the cladding with the same value of k_x; that light undergoes total internal reflection.

Fiber-optic cables produce confinement only in the core—light can't be confined to the cladding. For two materials to exclude light from each other, their EFCs would have to be entirely disjoint, as in figure 2b. With no overlap between the allowable values of k_x for the given frequency, light can't pass between the materials through an interface along the x direction. And because the restriction holds for every **k**, it's angle independent, unlike total internal reflection, which has a minimum incident angle.

But what materials behave in such a way? Lai came to the project with experience designing materials with unusual EFCs. In 2016, he and his coworkers at

Soochow University in Suzhou, China, and Hong Kong University of Science and Technology constructed a photonic metamaterial with an EFC shifted such that the material's boundary with air produced no reflection regardless of the incoming wave's direction.[2] When Lai moved to Nanjing University in 2018 and established his own microwave lab, he started brainstorming what other phenomena could be induced by shifted EFCs.

After his move, Lai started collaborating with new coworkers Peng and Wang, both of whom had experience working with waveguides and plasmonics. Eventually they arrived at the idea of creating cladding-free waveguide systems. "Our collaboration shows that discussions with experts from different backgrounds are very beneficial and could easily generate new inspiration," says Lai. "It was less likely that I would have come up with this counterintuitive idea alone."

Guiding light

For their two waveguide materials, the researchers used air and a photonic crystal made from a grid of rectangular dielectric rods. Parallel to the waveguide direction, the rods were 3.6 mm long and 2.4 mm apart; perpendicular to it, they were 2.4 mm long and 1.2 mm apart.

The asymmetry was necessary to create the EFC shown in figure 2b. If the photonic crystal was symmetric, its EFC would have two additional ovals, one above and one below the air's circular EFC. The materials would then have available modes with the same values of k_x, and light would be able to pass through their boundary. The asymmetric crystal and the air have no shared values of k_x, so light can't pass through waveguide interfaces. The materials do have modes with the same value of k_y, though, which is necessary for light to enter and exit the waveguides at their ends.

Since Lai's lab is set up for microwave experiments, and because millimeter-scale photonic structures are generally easier to build than nanometer-scale ones, the researchers developed their proof-of-principle device to work at frequencies around 15 GHz. But to underscore that the same principle will apply for frequencies of practical interest, they selected rods with a dielectric constant ε of 12 to match that of silicon at the 100–300 THz frequencies used for telecommunications.

Hongchen Chu, Lai's postdoc, experimentally tested the ZSWA shown in the figure 1 inset, which had channel widths ranging from 10 mm to 30 mm. He sent waves into each channel and tracked their propagation with a two-dimensional microwave scanner. In each case, the light stayed in its intended waveguide—air or photonic crystal—and exited through that waveguide's output port at the other end.

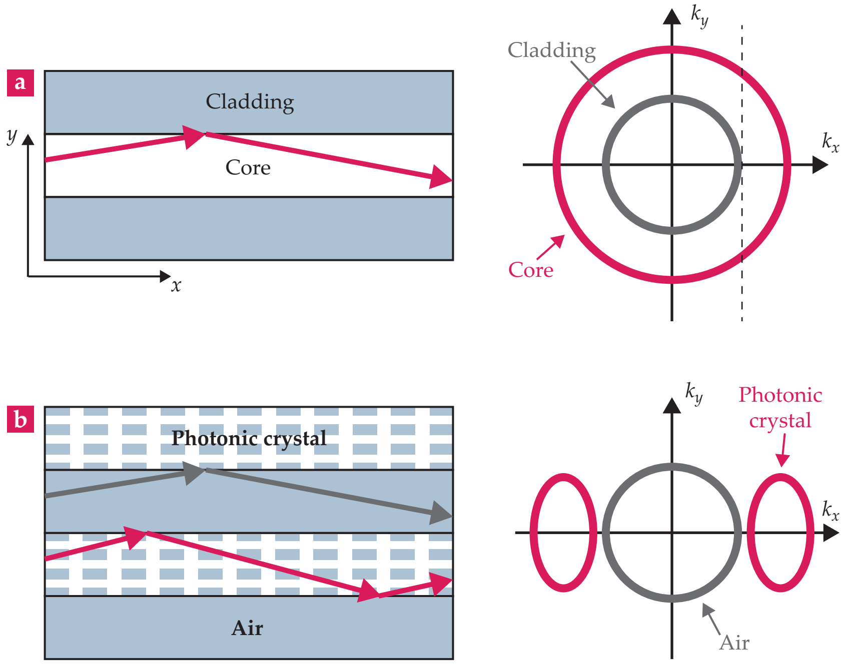

FIGURE 2. MATERIAL BOUNDARIES can direct transmitted light. **(a)** The core of a fiber-optic cable confines light by total internal reflection off the boundary with the cladding. The equal-frequency contours on the right, which show the modes (k_x, k_y) available in each material at a single frequency, illustrate the same restriction: Core modes to the right of the dashed line are confined because their component in the direction of travel, k_x, is beyond the maximum allowed in the cladding. **(b)** If the equal-frequency contours for two materials have no common values for k_x, which is possible when one of them is an asymmetric photonic crystal, light can't pass between them. (Adapted from ref. 1.)

To be of practical use in photonic circuits, the ZSWA channels must be able to not only confine light to a straight path but also direct it along a defined route. PhD student Tongtong Song realized he could steer the microwaves using arrangements of supercells—three-by-five blocks of the dielectric rods. Each metamaterial supercell had two edges through which waves could enter and exit, akin to the ends of the waveguides in the array, and two edges that blocked light, as at the waveguide boundaries.

Light moving through suitably arranged blocks and areas of empty space was steered around 90° and 180° turns. Initially some of the light leaked out as it turned the corners, but the researchers suppressed the loss by adding dielectric rods at the weak points. The same technique reduced backscatter as the waves traversed 180° turns. Scanner measurements showed overall transmission rates of about 95% through the turning paths, compared with nearly 100% for straight paths.

Challenges to shrinking down ZSWAs remain. When the channels in the device get narrow, for example, modes in next-nearest-neighbor channels begin to couple. Because practical optical chips have additional complications compared with the 2D microwave ones, Lai hopes to bring in collaborators who are more familiar with optical-chip fabrication.

"There's still a lot of work to do," says Lai. "But I don't see any insurmountable obstacles in applying this concept to optical chips and other communication systems, which we plan to achieve in the near future."

Christine Middleton

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In Ukraine, science will need rebuilding postwar; in Russia, its isolation could endure

The impulse to help Ukrainian scientists is widespread. But balancing sanctions against Russia while keeping open bridges of communication is tricky and controversial.

> *By unleashing war, Russia has condemned itself to international isolation, to the position of a pariah state. This means that we scientists will no longer be able to do our work properly: Scientific research is unthinkable without extensive cooperation with colleagues from other countries. . . . We demand the immediate cessation of all military actions against Ukraine.*

So reads, in part, a statement signed by several thousand Russian scientists and science journalists in the days following their country's invasion of Ukraine on 24 February. Numerous other statements from the science community, including ones by Russian expatriate scientists, have condemned the war. Meanwhile, one with signatures of the heads of hundreds of Russian academic and research institutions expresses support for the war and Russian president Vladimir Putin ("Now more than ever, we must demonstrate confidence and resilience in the face of economic and information attacks, effectively rally around our President").

In early March, Russian missiles heavily damaged the Kharkiv Institute of Physics and Technology and its neutron source (see "Prominent Ukrainian physics institute imperiled by Russian attacks," Physics Today online, 7 March 2022). By mid-April the war had displaced millions of Ukrainians. Among them were about 15 000 PhD scientists, or one-sixth of the country's total, many of whom have left the country, according to Vaughan Turekian, executive director for policy and global affairs at the US National Academies of Sciences, Engineering, and Medicine (NASEM).

YAROSLAV MATLAK

IRYNA ZHURAVLYOVA

DORMITORIES at the School of Physics and Technology (left) and the Central Scientific Library (right) at V. N. Karazin Kharkiv National University in Ukraine are among the casualties of repeated shelling by Russia.

Around the world, ordinary citizens are taking in Ukrainian refugees and helping them settle in for stays of undetermined duration, donating money, providing childcare, and otherwise rallying to help. Scientists, too, are finding ways to help their colleagues in trouble—from offering jobs and distance courses to looking ahead to rebuilding science in Ukraine. (See "Q&A: Oleksandra Romanyshyn on helping Ukrainian scientists," Physics Today online, 22 April 2022.)

Meanwhile, scientists and scientific institutions are struggling with how to navigate interactions with colleagues affiliated with Russian institutions. "I believe that scientific collaboration should transcend geopolitics and that open scientific collaborations can serve as good examples of how international cooperation can benefit the global society," says David Reitze, director of the Laser Interferometer Gravitational-Wave Observatory, or LIGO, an international project that includes a few scientists in Russia. Yet, he adds, "it would be impossible for me to knowingly collaborate with scientists who support Putin's naked act of aggression against Ukraine and the Ukrainian people."

"You always hit innocent people with sanctions," says Helmut Dosch, chair of the board of directors of DESY, the German Electron Synchrotron Laboratory in Hamburg. Still, the day after Russia invaded Ukraine, DESY suspended cooperation with Russian institutions. "We wanted to radiate a clear signal," says Dosch. Such a move is new for DESY, he adds. "We have never before frozen scientific cooperation for political reasons." Dosch also returned the honorary doctorate he received in 2010 from the Kurchatov Institute in Moscow.

Dosch stresses that he and DESY are keeping contacts with individual scientists in Russia who have expressed opposition to the "aggressive war." Such contacts must be handled carefully to protect the scientists, he says. "We assume the secret service is watching. If a scientist is accused of treason, they could disappear for good." It's complicated, he adds, "but we try to keep communication channels open."

Offers outnumber takers

Early on 24 February, Mykola Semenyakin was wakened by his phone. His parents in Kyiv were calling him in Moscow to tell him that Russia had attacked Ukraine. Within an hour, Semenyakin had bought plane tickets, and that night he flew to the Netherlands. His decision to study in Russia had been hard because of the 2014 annexation of Crimea and the start of the conflict in Donbas, he says. "That made it controversial. But I thought the scientific cooperation with good people might be okay." With the hot war, he continues, "it's impossible. It wouldn't be ethical for me to work there while people in Ukraine are dying from Russia's attacks."

Semenyakin had been months away from completing his PhD in mathematical physics at the Skolkovo Institute of Science and Technology (Skoltech), which was founded a decade ago with help from MIT and other Western institutions. (See Physics Today, January 2013, page 20.) He is on track to finish his PhD this summer, now with Carlo Beenakker at the University of Leiden, with whom he connected through friends. Semenyakin says he'd like to recognize his Russian adviser, "but the issue of affiliations is tricky. I prefer not to have Skoltech on my thesis."

Institutions around the world—in Europe and North America, and as far away as Australia and Japan—are offering Ukrainian physicists and other scholars temporary posts, typically for 3 to 12 months. The Polish Academy of Sciences, for example, placed 67 Ukrainian scientists at its various institutes within a day. NASEM is piggybacking on the Polish academy's program, says Turekian; by mid-April NASEM had raised

UKRAINIAN SCHOLARS are joining the Leibniz Institute for Solid State and Materials Research Dresden, in Germany. Of the several dozen, 19 newcomers received six-month scholarships after the 24 February invasion of their country; others had their contracts extended. Women are disproportionately represented because men aged 18 to 60 cannot leave Ukraine.

$2.5 million and placed 200 Ukrainian scientists around Poland. The Perimeter Institute in Waterloo, Ontario, Canada, is offering positions for master's and doctoral studies and postdoctoral and visiting scientists.

After Russia annexed Crimea, the Kyiv branch of the Moscow Institute of Physics and Technology severed its ties with Russia and reinvented itself as Kyiv Academic University. It strengthened collaborations with institutions in Europe. Since the invasion in February, some 19 students and scientists, mostly physicists, have gone to the Leibniz Institute for Solid State and Materials Research Dresden, says Jeroen van den Brink, director of the German institute's theoretical solid-state physics division. The institute also extended contracts for Ukrainians who were already there.

But many scientists either cannot or do not want to leave Ukraine. Men between the ages of 18 and 60 are barred from leaving the country. And women may have family or other reasons not to leave, notes Alexander Kordyuk, director of Kyiv Academic University. "The number of offers greatly exceeds the number of our students and researchers who can and want to leave Ukraine," he says.

Some institutions also welcome refugees from Russia. A statement by FAIR, the Facility for Antiproton and Ion Research in Darmstadt, Germany, for example, says it's keeping its "doors open to researchers from Russia who face political persecution."

Leonid Rybnikov, a Russian professor of mathematics at the Higher School of Economics in Moscow, landed a temporary post at the Institute of Higher Scientific Studies near Paris. He was arrested in Moscow on 1 March for writing slogans against the war and Putin and spent two weeks in jail. Now, he says, "for the same offense, you can go to prison for several years."

Scientific sanctions

On 25 February, the day after the invasion, MIT ended its relationship with Skoltech. The same day, Germany's Alliance of Science Organisations released a statement recommending that "academic cooperation with state institutions and business enterprises in Russia be frozen." On 2 March, Germany's largest research funding agency, the German Research Foundation, suspended funding for German–Russian projects; over the past three years, the funding agency has invested some €110 million ($116 million) in more than 300 such projects. For now, data, samples, and equipment may not be exchanged, and German scientists and their Russian counterparts cannot hold joint events.

On 1 March, the Polish Ministry of Education and Science quit the Joint Institute for Nuclear Research in Dubna, near Moscow, of which Poland was a founding member in 1956. "I was a member of the nuclear physics program advisory committee at Dubna," says Adam Maj, who heads the division of nuclear physics and strong interactions at the Polish Academy of Sciences' Institute of Nuclear Physics in Kraków, Poland. "I withdrew." Other Polish scientists on Dubna committees and scientific boards did too, he says.

Some 40 to 50 Polish nuclear physicists had strong ties with Dubna and will have to reorient, Maj says, and 5 neutrino physicists in Kraków involved in the Baikal Deep Underwater Neutrino Telescope in southern Siberia will look to join different projects outside of Russia. "People are not happy to change experiments," he says. "At first, opinions were split, but increasingly, people see that it's not possible to work with Russia for now."

The Large Hadron Collider (LHC) at CERN is coming back on line after a three-year shutdown; beams of protons circulated on 22 April, and experiments are set to start in June. Despite the excitement about new LHC experiments, the war in Ukraine and sanctions on Russia are "the biggest concern at the moment," says Joachim Mnich, CERN's director for research and computing.

About 140 scientists from institutions in Ukraine are involved in CERN, of which the country is an associate member. Some 1000 scientists from Russian institutions work at CERN, with roughly half of them spending at least half their time on site. At a special meeting on 8 March, the CERN Council suspended the observer status of the Russian Federation; observers—the others are the US and Japan—can attend council meetings where discussions on the LHC take place, but they do not have voting rights. The council also ruled out future joint projects involving Russian institutions. But the thorny issues of ongoing projects and publications are still in discussion.

TAIGA COLLABORATION

TAIGA, the Tunka Advanced Instrument for Cosmic Ray Physics and Gamma Astronomy, is being built in Siberia. The partners from outside of Russia have suspended their participation in the project in response to Russia's invasion of Ukraine.

Scientists affiliated with Russian institutes make up about 7% of the workforce on the LHC and its experiments, Mnich says. "In some key areas, it would not be easy to replace the Russian contributions." For example, he says, the photon spectrometer in the ALICE detector "is entirely the responsibility of Russian institutes. It would be hard to train others to operate it."

Scientists in Russia are also responsible for parts of the high-granularity calorimeter for the upgrade of the CMS experiment; the scintillator for the calorimeter is supposed to be milled in Ukraine, and institutions in Belarus (under sanctions for supporting Russia's invasion of Ukraine) and the US also are contributing to it. "The CERN Council has not yet suspended such ongoing collaborations," says Mnich. "For now, we try to continue, but with sanctions, the difficulties in exchanging goods and money hinder progress."

Suspending ongoing collaborations at CERN would mean a loss in expertise and in financial and in-kind contributions, likely causing delays and cost hikes. Russian scientists at CERN could lose their residence permits and salaries. And for those who have spoken out against the war, returning to Russia would be dangerous. CERN is evaluating implications and possible solutions to the fallout of a full suspension, says Mnich. The council is expected to decide how to proceed at its June meeting.

Meanwhile, publishing has become fraught. A preprint posted on arXiv.org on 26 April lists the authors as the "CMS Collaboration" instead of including the full list of authors (around 2350 names), some of whom have Russian affiliations. Other LHC experiments are taking the same tack, and decisions on how authors are listed in final publications are still to come. Some members of the collaborations don't want Russian affiliations included on a publication, but for scientists with such associations, it could be risky to omit them.

For their part, publishers are mostly staying out of the fray. Ukrainian journals are an exception; they are rejecting authors with Russian affiliations.

Michael Thoennessen, editor-in-chief of the American Physical Society journals, says APS has not changed its publishing policies. "We continue to be committed to maintain open dialog and promote cooperation between scientists," he says. "We have no plans to impose sanctions or restrict scientific information." But, he adds, APS will list authors as they request—including with a home address or no affiliation. "The caveat is that all authors have to agree."

Collaboration versus condemnation

As a major partner in FAIR, Russia was responsible for providing magnets for the facility's accelerator. Having suspended Russia's participation, FAIR is seeking other sources for magnets. The change "will imply some delays and additional costs," says FAIR spokesperson Ingo Peter.

Razmik Mirzoyan is an astrophysicist at the Max Planck Institute for Physics in Munich, Germany. He has been a leader in TAIGA, the Tunka Advanced Instrument for Cosmic Ray Physics and Gamma Astronomy, since the project's start in 2013. Most of the collaboration's roughly 90 scientists are at Russian institutes, with a handful in Germany and Italy. The design consists of four telescopes and 120 large photomultiplier-based stations distributed over about 7 square kilometers near Lake Baikal. The instruments measure the direction and energy of impinging ultrahigh-energy cosmic rays, from teraelectron volts to hundreds of petaelectron volts.

Two of TAIGA's telescopes are operational. An imaging camera, mirrors, and other parts for the third telescope were due to arrive from Germany in late February or early March, but with the sanctions, Mirzoyan assumes the shipment was stalled. He is unaware of the exact status because on 9 March, he called a video meeting and put the collaboration on hold. "With people dying and everyone around me doing things to help refugees from Ukraine, continuing the cooperation as if nothing had happened seemed unnatural," Mirzoyan says. "It's a pity for us—and a greater pity for our colleagues in Russia."

Achim Stahl is working with a team of about a dozen physicists—experimentalists at the University of Aachen and the Jülich Research Center in Germany and theorists at two Russian institutions—who are looking for electric dipole moments in protons and deuterons. Funding for visits and networking from the German Research Foundation is frozen, and the agency recommends that the collaboration cease joint publications, says Stahl. "But they said it was our decision." For now, he says, "we won't publish or submit joint talks, but we will continue to email each other and keep our personal contacts. It's a balance between keeping open bridges of communication and not wanting to help a country that is aggressively invading another country."

At the individual level, some scientists in the West continue to work with their Russian colleagues. That's easiest for theorists, who can interact by email, telephone, and video. A physicist at the University of British Columbia in Vancouver, Canada, who requested anonymity to protect Russian colleagues, says that he and a half-dozen theorists scattered around the US, Europe, and Russia still meet regularly on Zoom to discuss quantum gravity and quantum cosmology. "We assume the FSB [Russian federal secret service] is listening, so people have become more careful about what they say," he says. "As long as Russian scientists can access the internet, we can work together."

But other scientists are uncomfortable working with people who keep their Russian affiliations. Oleksandr Gamayun is a Ukrainian condensed-matter theorist who has been at the University of Warsaw as a research fellow since 2021. He has long-standing close collaborations with Russian colleagues from when they were postdocs in the UK. "I know these people well," he says. "I would love to keep working with them. But because of their Russian affiliations, it's hard. In my eyes, the affiliation is a representative of the regime. I hope they will move abroad." Their joint work is on hold, he says, but "after peace, I wouldn't have trouble reestablishing the connection."

Alex Buchel is a Ukrainian string theorist who has been at the Perimeter Institute for nearly 20 years. "I have colleagues in Ukraine. They can't do science right now," he says. "They are looking for bulletproof vests." Last fall he gave an online colloquium in Moscow, but he says that he wouldn't give a talk in Russia now. "And if I receive an application from a Russian postdoc or student, I don't look at it. I don't want to have to second guess about their views." To work with someone in Russia, he says, or to publish their papers, "there should be a litmus test. Someone who wants to benefit from funding, collaboration, and publishing must stand and say they do not support the war." Mirzoyan agrees: "I came to the conclusion that one of the ugliest things in society is when people keep silent."

Rybnikov, the Russian mathematician currently in France, is looking for jobs in English-speaking countries. He is pessimistic about the future of science in Russia: "I expect that Russia will stop most international programs in mathematics and other sciences, and you can't do science in a vacuum. It will work both ways—other countries will also stop working with Russia."

"It's very difficult to do physics when this criminal war is continuing," says a theoretical physicist in Moscow who requested anonymity. Many Russian scientists, especially students, consider emigration to be "the most reasonable choice now," he says. Other scientists, both inside and outside of Russia, also worry about the effects on science of Russia's isolation. Alex Levchenko is a Ukrainian theoretical physicist at the University of Wisconsin–Madison. "The damage in Ukraine, including to science, is impossible to grasp," he says. But because of the sanctions, international condemnation, and exodus of talent, "Russian science will inevitably suffer longer term." The ripple effects will reach the rest of the community, he adds. "It's negative for all sides."

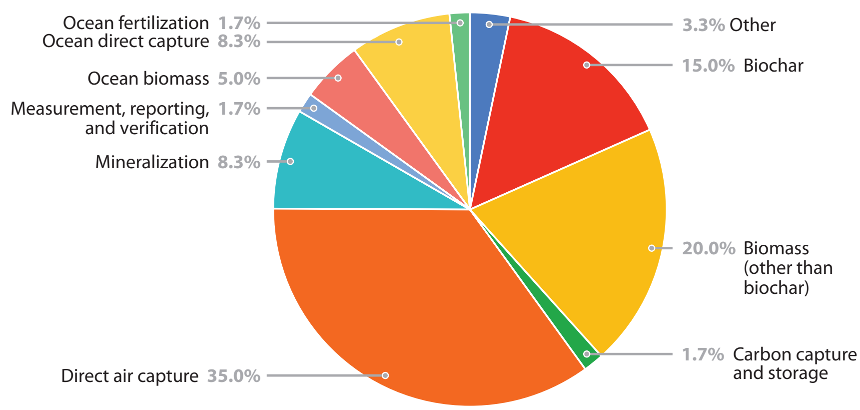
Toni Feder

Carbon dioxide removal is suddenly obtaining credibility and support

The question about carbon extraction is no longer if it will be needed, but whether it can be scaled up quickly enough.

As the likelihood of the world failing to decarbonize rapidly enough to avoid the worst effects of climate change grows, the interest in atmospheric carbon dioxide removal (CDR) has exploded.

April was an eventful month in CDR: A new privately backed nearly $1 billion funding mechanism was unveiled. More than a dozen aspiring CDR startups received $1 million prizes to help further develop their technologies. And the United Nations' Intergovernmental Panel on Climate Change (IPCC) confirmed the necessity of CDR to achieve carbon neutrality by midcentury. The US Department of Energy continued finalizing plans on how it will spend the billions of dollars for direct air capture (DAC) that lawmakers appropriated in November.



ADAPTED FROM ROBERT HÖGLUND

TECHNOLOGIES PROPOSED by the 60 teams that were selected as finalists for the XPrize carbon-removal "milestone" prizes. Fifteen of the teams were awarded $1 million prizes. Up to four prizes, worth a combined $80 million, are to be awarded in 2025. Organizers say the milestone winners won't necessarily be favored in that contest.

In its latest assessment report, released on 4 April, the IPCC for the first time unequivocally declared that CO_2 removal must be part of the solution to limiting the increase in global temperature to 2 °C above its preindustrial level, the ceiling established by the 2015 Paris Agreement. Though the amount of CDR needed will depend on the extent that CO_2 emissions can be mitigated, the IPCC estimated that 5–10 gigatons will have to be extracted each year by midcentury to prevent the world from overheating.

The need for CDR is twofold: to offset continuing emissions from sources that will be very difficult to eliminate—agriculture, aviation, long-haul trucking, and ships—and to extract legacy CO_2 emissions to bring concentrations back to acceptable levels, says Jay Fuhrman, a postdoc at the DOE-funded Joint Global Change Research Institute who was a contributor to the IPCC assessment's CDR modeling. The US would need to remove about 1 gigaton of CO_2 per year by 2050—about the level of emissions from the nation's hard-to-abate sectors—to reach net-zero carbon emissions, says Jennifer Wilcox, DOE principal deputy assistant secretary for fossil energy and carbon management.

The magnitude of that challenge is hard to overstate. "We are at thousands of tons [of annual CDR globally] today. We've got to get six more zeros in less than 30 years," says Wilcox.

The Infrastructure Investment and Jobs Act enacted by President Biden in November 2021 appropriated $3.5 billion for DAC demonstrations. In DAC, CO_2 is extracted through mechanical and chemical means. Additional billions of dollars were allocated for demonstrations of carbon capture and storage from power plants and industrial facilities (see Physics Today, January 2022, page 22).

The measure directed DOE to begin soliciting proposals for four DAC demonstration "hubs" within six months. Interviewed in late April, Wilcox declined to say exactly how DOE will comply with the congressional directive but said the department may issue a notice of intent or a funding-opportunity announcement.

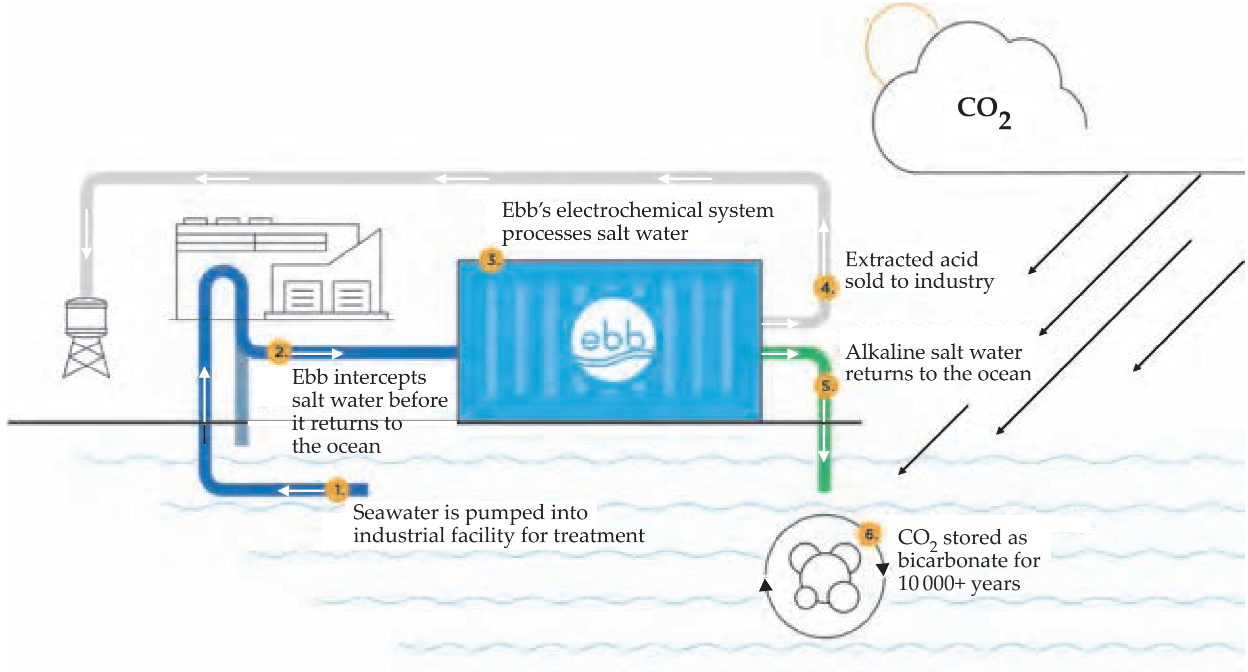
Lawmakers specified that in addition to extracting at least 1 million tons of CO_2 annually, each hub is to have a dedicated CO_2-transport infrastructure, subsurface storage resources, and other carbon-sequestration infrastructure. Wilcox notes there are methods to store CO_2 that don't require the energy expenditures needed to achieve the high-purity product that's appropriate for injection to geological formations. Exposing the captured gas to alkaline-rich rock or mine tailings or using it to stimulate algae growth could be accomplished at CO_2 concentrations of 15–30%, for example. She cites the Tamarack nickel mine in Minnesota, which the partners Rio Tinto and Talon Metals are developing to also permanently store hundreds of millions of tons of CO_2. In February, DOE awarded the project $2.2 million in R&D support.

Asbestos tailings scattered across the country are highly reactive to CO_2, Wilcox says. Gigatons of permanent storage could also be gained in the production of synthetic aggregates such as carbonate rock, which can replace the sand and gravel used in concrete.

"Not all roads lead to pipelines and storage deep underground, although we want to see those pathways move forward too," she says.

Wilcox says that DAC with storage is the only CDR method so far that can accurately and verifiably show how much CO_2 is permanently removed and stored. That means DAC companies are eligible to receive a tax credit that is based on the number of tons captured and utilized or put underground. No CDR company has yet removed and stored the minimum of 25 000 tons of CO_2 to qualify for the credit. But Oxy Low Carbon Ventures plans to open a DAC plant with an annual capacity of 1 million tons, based on technology from Canada's Carbon Engineering. Other CDR methods lack that same degree of verifiably accounting for the CO_2 they fix, the amount of energy expended in doing so, and the durability of storage.

Still, DOE offers support to other CDR options too. Through its "carbon-negative shot" launched last November, the agency invited all types of nascent technologies to apply for R&D funding and help in developing carbon-accounting tools. The initiative is looking to support gigaton-scale approaches that will capture and store CO_2 for less than $100 per ton, offer robust accounting of emissions over their full life cycle, and



EBB CARBON

EBB CARBON is eyeing desalination plants for its initial commercial carbon dioxide removal plants. It plans to open its first plant this summer at a pipeline located in the US that's used for research purposes.

provide verifiable storage for 100 years or more.

New funding models

Governments aren't the only source of funding for CDR. On 22 April, Elon Musk's $100 million XPrize competition for carbon removal announced its 15 "milestone" winners, each receiving $1 million. While most of the winning teams were US based, Europe, Kenya, the Philippines, and Australia also were represented. More significant, perhaps, were the number of participants the competition attracted. A field of 1133 teams was narrowed to 287 that met the eligibility criteria. Seventy expert reviewers then screened and ranked the proposals.

More than one-third of the 60 finalist teams proposed DAC solutions (see the chart on page 26). DAC captured six of the $1 million prizes. Biochar—biomass heated in the absence of oxygen to form a carbon-dense material to be spread onto soils—and other biomass solutions were advanced by five of the winners, while ocean-based capture took three and rock mineralization one.

The first-place XPrize winner and up to three runners-up will be selected in 2025 and will split $80 million. Prize officials say the milestone winners aren't necessarily favored in that competition.

Also in April, the payments company Stripe announced the formation of Frontier, an advance market commitment to buy $925 million of permanent carbon-removal services over the next eight years. The founding contributors are Alphabet, Shopify, Meta, McKinsey & Company, and Stripe customers who donate a small portion of their transaction costs to CDR contenders. Frontier's concept, first employed a decade ago to speed development of pneumococcal vaccines for low-income countries, is to provide a binding commitment to buy a product that doesn't yet exist once it becomes available. Instead of taking an equity stake in startups, Frontier will pay CDR companies by the tonnage of CO_2 they remove, guaranteeing revenues for those that are judged by reviewers to have viable technologies—regardless of their initial cost per ton removed.

"Frontier is focused on accelerating the scale of carbon-removal solutions that we think can be a meaningful part of the 5–10 billion tons of carbon removal the world needs by 2050," says Hannah Bebbington, head of strategy for Stripe Climate, a Frontier organizer. "[Advanced market commitments] can help create market certainty that entrepreneurs and investors can use to confidently build new technologies over a long period of time."

Frontier will select CDR technologies that can store carbon for greater than 1000 years, cost less than $100 per ton of CO_2 removed, offer a path to more than 500 million tons of CO_2 removal per year, have transparent monitoring and verification capabilities, and be safe and environmentally sound. Frontier also will look for CDR methods that don't require arable land.

Frontier members don't get a price or volume guarantee with their purchase. Instead, Frontier will facilitate purchases from emerging CDR technologies that meet its target criteria as volume becomes available. The goal is to support a wide portfolio of technologies at large scale by 2050.

Frontier estimates that fewer than 10 000 tons of carbon have been removed by DAC to date. "As this market grows, a whole carbon-removal economy will need to grow with it, including robust measurement, reporting, and verification infrastructure and a network of storage sites around the world," says Bebbington.

Another philanthropic CDR-support effort is expected to be announced soon by the First Movers Coalition, a public–private partnership between the US Departments of State, Commerce, and Energy; the World Economic Forum; and nearly three dozen international corporations. Those firms have already pledged to buy clean technologies in advance of a market for them in hard-to-abate industries such as steel, cement, air travel, and shipping. The Bill Gates–founded

Breakthrough Energy is collaborating with the coalition.

Varun Sivaram, senior director for clean energy and innovation in the office of John Kerry, the presidential climate envoy, said in mid-April that the coalition would announce a CDR-specific initiative and new members within weeks. "These companies are making a truly meaningful commitment by creating an early market that can help technologies scale and literally change the world," Sivaram said. "It's far more impactful than a company reducing their own emissions or buying offsets."

The Swedish company Milkywire has set up the Climate Transformation Fund, which invests in carbon-removal technologies. Its largest contributor is Klarna, a Stockholm-based financial technology firm, which has raised \$2 million for the fund over the last two years through an internal tax on its carbon emissions. Robert Höglund, who manages the fund, credits XPrize in part for the rapid growth of nascent CDR technologies and startups. Still, fewer than 40 firms have yet produced sales—half of those employing biochar.

Question of durability

Höglund's fund has invested in two biochar companies: the Cambodia-based Husk, which produces the carbon-rich material from rice husks, and MashMakes, an Indian firm whose feedstock is crop residues. As with some other biomass CDR solutions such as reforestation, biochar provides less permanent storage than DAC. Höglund says available evidence shows a durability of more than 100 years, depending on such variables as soil acidity and temperature. But some biochar will oxidize in as little as 10 years, says Wilcox, who explored the technology in depth as a member of a National Academies of Sciences, Engineering, and Medicine review committee. "Is that carbon removal? Absolutely not. That won't impact climate in a positive way." Yet she acknowledges biochar's side benefits of improving the carbon content of soils and reducing the need for fertilizers.

The Milkywire fund has backed California-based Heirloom, a partner in one of the \$1 million XPrize winning teams. The company hopes to soak up CO_2 with calcium carbonate, then heat the rock to release the concentrated gas for geological storage. The carbonate would then be chemically regenerated. As with other DAC processes, the heat and electricity required should come from renewable sources to produce negative emissions. Fossil-fuel-powered DAC could produce more CO_2 than it removes.

One of a handful of DAC firms to attract significant investment to date is Climeworks, the Swiss company that last year in Iceland opened the world's largest capture plant. Carbfix, its partner in the venture, injects the CO_2 underground. The plant's annual capacity is 4000 tons. In April, Climeworks reported it had raised \$650 million in an equity funding round, which it described as the largest investment ever in a DAC company.

DOE in April awarded a combined \$14 million to five teams for front-end engineering design studies of DAC that utilize carbon-free energy sources. AirCapture is a partner in two of those projects, both of which propose to adsorb CO_2 from air blown by fans across chemical contactors. The concentrated gas is then desorbed using low-temperature steam. A nuclear plant supplies the steam for one of the projects. A fertilizer plant is the heat source in the other.

AirCapture's refrigerator-sized machines can remove 100 tons per year, says CEO Matt Atwood. The plan for the other project is to use captured CO_2 from the fertilizer plant to produce formic acid, which is used industrially and can also be a hydrogen carrier or a precursor to synthetic fuels. The CO_2 produced with nuclear energy will be shipped offsite for geological storage.

Although plenty of potential geological storage is available in the US, and the US Geological Survey has produced detailed maps of the formations, the Environmental Protection Agency has approved just two wells for CO_2 injection nationwide. Beyond requiring assurances that the gas won't escape, regulators must consider the potential for induced seismicity from injection operations.

On 5 May, DOE acted to begin distributing the \$2.5 billion that was included in the infrastructure act for expanding the nation's geological CO_2 storage capacity. The agency's notice of intent begins the process for distributing \$2.25 billion over five years in cost-shared funding for an unspecified number of projects capable of storing at least 50 million tons of CO_2—equivalent to the annual emissions from roughly 10 million gasoline-powered cars. In addition, DOE issued two funding opportunities, totaling \$91 million, to help increase the number of available CO_2 storage sites and to advance carbon-management technologies.

Atwood says his company hasn't decided whether to apply to participate in Frontier. "But it's very encouraging to see companies coming together and saying we need to get on the learning curve and that we're willing to pay a high price for CO_2 to help these companies scale and get their cost down."

Ben Tarbell, CEO of ocean-capture company Ebb Carbon, is also encouraged by the new funding models. "For a long time, most of the attention has been on compliance," based on the expectation of regulation, he says. "What's happened recently is a number of subnational entities, corporations, cities, and universities have stood up and said we're going to do what's right here and commit to neutrality and pay for the waste we're dumping."

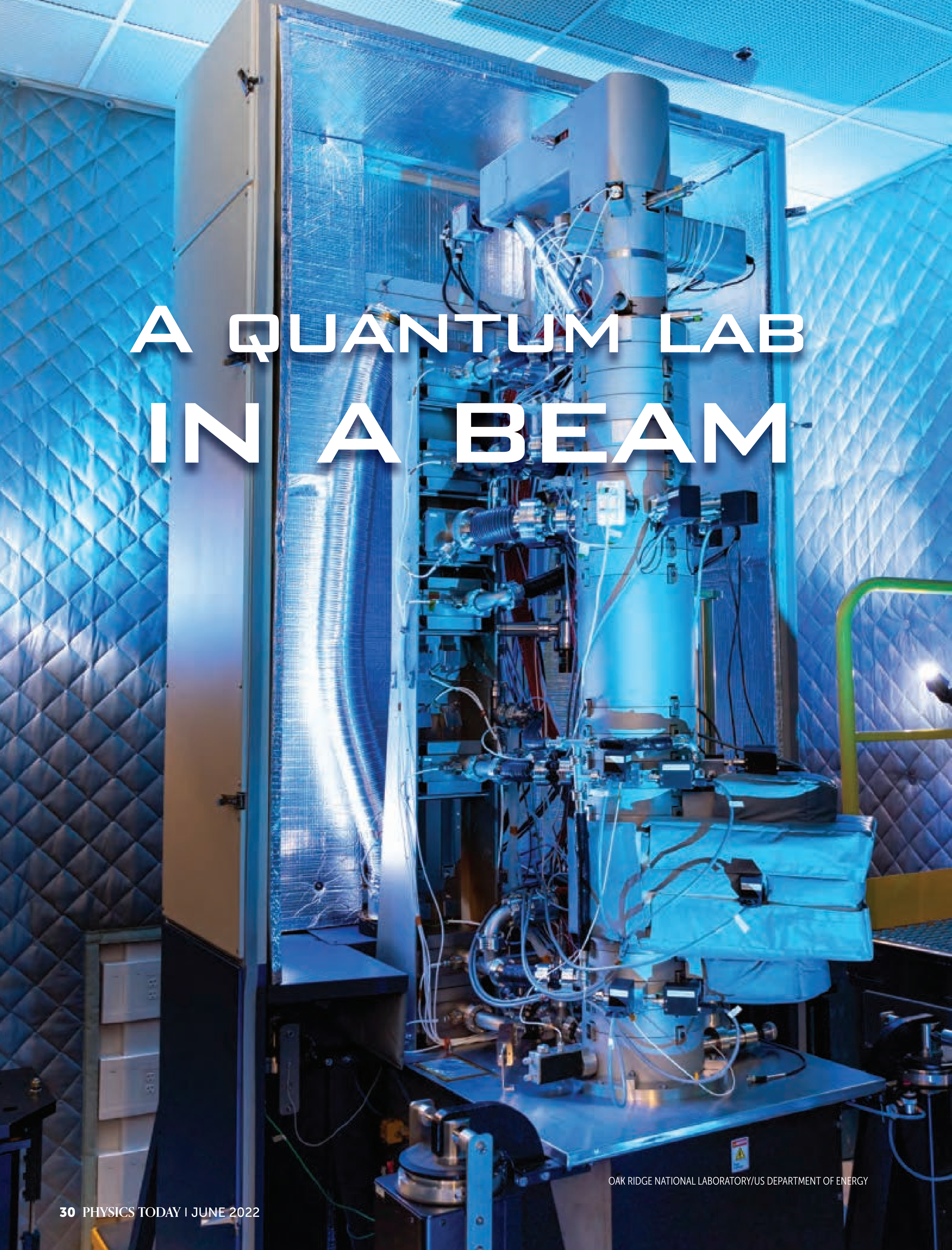
Ebb Carbon's electrochemical process raises the alkalinity of the water it processes and returns to the sea, reducing the ocean acidification that has come with climate change. A by-product is hydrochloric acid, which is used in steelmaking, food and chemical processing, and other industries. Tarbell says the company's business plan doesn't depend on revenues from acid sales; he's counting on corporate and government carbon-emissions pledges instead.

Lennart Joos has reviewed ocean-capture proposals for Frontier. The organization, he says, will be backing "moonshot ideas that still have to manifest themselves" in a working plant. Joos tried unsuccessfully for several years to attract investors to his own ocean CDR technology. "Investors would all tell me that they want a pilot plant before they give you money," he says.

But Joos warns that the concentration of investments in a small number of successful CDR companies will be to the detriment of many other good CDR concepts. "Climeworks has now raised more than \$800 million, and their capacity is 4000 tons a year. It's not too hard to make a joke out of that," he says. "Imagine how many smaller ideas you could fund with that amount of money."

David Kramer PT

A QUANTUM LAB IN A BEAM



OAK RIDGE NATIONAL LABORATORY/US DEPARTMENT OF ENERGY

Sergei Kalinin is a professor in the department of materials science and engineering at the University of Tennessee in Knoxville. Starting in 2023, he will be the Weston Fulton Professor. **Stephen Jesse** and **Andrew Lupini** are researchers at the Center for Nanophase Materials Sciences at Oak Ridge National Laboratory in Tennessee.

Sergei V. Kalinin, Stephen Jesse, and Andrew R. Lupini

Advances in electron microscopy have revolutionized atomic-scale imaging, characterization, and manipulation of materials.

The history of science is filled with questions about the nature of matter, its constituent elements, how properties emerge from the elements' arrangements, and how the arrangements can guide or be guided by energy flows. The answers to those questions have progressed from philosophical proposals of atomic theory to practical demonstrations of atoms' existence to modern quantum theory. And, importantly, the answers have been based on experimental measurements.

Recently, electron-microscopy techniques have given resounding answers to such questions as the following: Can we see atoms? What do they do? How do their interactions give rise to properties, forms, and functions? The fields of condensed-matter physics and materials science are now transitioning toward more directly practical goals—namely, understanding why atoms do what they do and controlling their behavior.

The origins of modern atomistic theory can be traced to ancient Greece, where the concept of indestructible and indivisible atoms was developed. Solids were assumed to be formed by atoms with multiple hooks and openings to ensure strong bonding (see figure 1), and liquids by slippery atoms that could easily move with respect to each other. Although the theory was simplistic from the point of view of modern science, Democritus correctly ascribed the properties of matter to the interactions between individual components. He rather adroitly noted that our macroscopic world is built up of fundamental building blocks: "By convention sweet and by convention bitter, by convention hot, by convention cold, by convention colour; but in reality atoms and void."[1]

In Democritus's time, however, atomic theory remained but one of many competing worldviews, and it was developed on a philosophical rather than experimental basis. Some Persian scientists hinted at the atomic model in their works from the 12th to 14th centuries, the golden age that also gave the world much of the basis for algebra, medicine, chemistry, astronomy, and geography. (See the box on page 34 for an example.) Still, the theory lacked an experimental foundation.

From hypothesis to visualization

The birth of modern atomic theory dates to around 1800 with the work of John Dalton. It was based on experimental observations, including the constant ratios of elements in compounds and the physical properties of gases. Skepticism remained strong for several decades after Dalton published his findings; in 1871, for example, Edmund Mills scathingly concluded that "the atomic theory has no experimental basis, is untrue to nature generally, and consists in the main of a materialistic fallacy."[2]

As Freeman Dyson famously said, though, "Science originated from the fusion of two old traditions, the tradition of philosophical thinking that began in ancient Greece and the tradition of skilled crafts that began even earlier and flourished in medieval Europe. Philosophy supplied the concepts for science, and skilled crafts provided the tools."[3] Indeed, the tools of science ultimately settled the debate. Albert Einstein's interpretation of the experimental observation of microscopic Brownian motion was a critical step in verifying the atomistic conjecture.

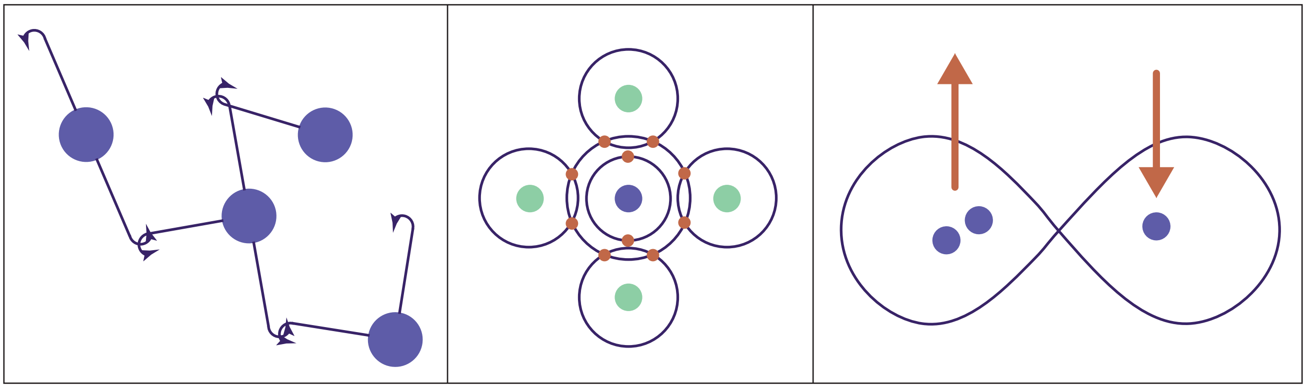


FIGURE 1. UNDERSTANDING OF ATOMS and atomic interactions has progressed from a basic hook-and-eye model through a simple electron–nucleus conception to a modern quantum picture.

Early 20th-century physics brought forth both conclusive evidence of matter's atomistic structure and insight into the atom's internal structure. A high point of that legendary time was the demonstration of x-ray scattering from periodic crystalline structures for which father-and-son collaborators William and Lawrence Bragg received the 1915 Nobel Prize in Physics. The structures' ideal periodicity allowed for the representation of solids in reciprocal space and molded the mindsets of subsequent generations of physicists.

With the existence of atoms established, at least indirectly, a question arose: Can atoms be seen one at a time? That question was answered around the middle of the 20th century, when the first images of atomic species were obtained in a field ion microscope that detected the electron-emission patterns from an anatomically sharp tip.[4] The same operating principle—applying an electric field to a sharp tip until it ejects electrons by field emission or tunneling—was behind the development of atom-probe tomography, scanning tunneling microscopy (STM), and electron microscopy (see figure 2).

Imagineers of atomic assembly

Progress in both experimental and theoretical atomic physics has stimulated exploration of the possibility of direct atomic visualization and fabrication. In his famous 1959 lecture "There's Plenty of Room at the Bottom," Richard Feynman pointed out both the need to make the electron microscope much more powerful and the vast potential for processing and storing information if single atoms could be controlled.[5] More recently, many have begun to appreciate the enormous potential that atomic-scale control can bring to information processing. Quantum information science seeks to leverage the quantized nature of matter and energy and the related phenomena of entanglement and superposition to solve previously intractable computational problems. Individual atoms can host quantum bits that, if properly arranged and encoded, could receive, process, and transmit quantum information in a coordinated and massively parallelized fashion.

One of Feynman's last quotations, "What I cannot create, I do not understand," clearly sets forth what may be the next big challenge for understanding the atomic world: deliberately creating structures, atom-by-atom, that exhibit predefined functionalities. In the 1980s Eric Drexler put forward a similar concept of atomic-scale machines based on sufficiently complex molecular structures.[6] Perhaps based on the work of John Von Neumann, the idea has firmly entered the world of popular science fiction, including Drexler's apocalyptic gray goo, Alastair Reynolds's nano-assemblers, and the television show *The Expanse*'s mysterious protomolecule. Despite appearing physically feasible, however, practical realization of such devices remains uncertain. Following Dyson's framework, the philosophy backing molecular machines and atom-by-atom assembly is in place, yet scientists still lack the necessary craft and tools.

Enter the scanning probe

The emergence of scanning probe microscopy in the 1980s provided a major boost for the field of nanoscale imaging and atomic-scale assembly. Together with the introduction of STM by Gerd Binnig and Heinrich Rohrer in 1981, it brought new visual insights to controversies in surface science. It also heralded the advent of tools capable of imaging atomic structures in real space using desktop-scale instrumentation.

The fundamental operating principle of STM is based on the quantum mechanical phenomenon of tunneling electrons. An extremely sharp tip is brought near a surface, and an applied voltage causes electrons to tunnel through the gap, thereby producing a measurable current that reflects the surface's shape and electronic properties. It effectively, if indirectly, puts quantum physics at one's fingertips. The development a few years later of atomic force microscopy (AFM), which uses a tip mounted on a bendable cantilever, and related methods for probing magnetic, electrical, transport, and electromechanical phenomena has opened the nanoworld for exploration.[7]

In 1989 Don Eigler demonstrated direct atomic manipulation using an STM probe by forming the letters *I*, *B*, and *M* in xenon atoms on a copper surface. His work had a profound impact on both the research community and the general population because it showed for the first time the ability to not only visualize but also control matter on the single-atom level—a direct response to Feynman's challenge.

For more than 20 years following Eigler's experiments, the field remained narrow because of the practical barriers to constructing and operating low-temperature STM machines and the lack of immediate practical applications. But quantum computing and quantum information systems are now at the forefront of scientific inquiry, and STM-based atom-by-atom manipulation is one of the few approaches that can create atomically precise structures. The Kane quantum computing architecture, for example, relies on single atoms precisely positioned inside isotopically purified silicon. Exciting progress has been made by several groups toward the fabrication and

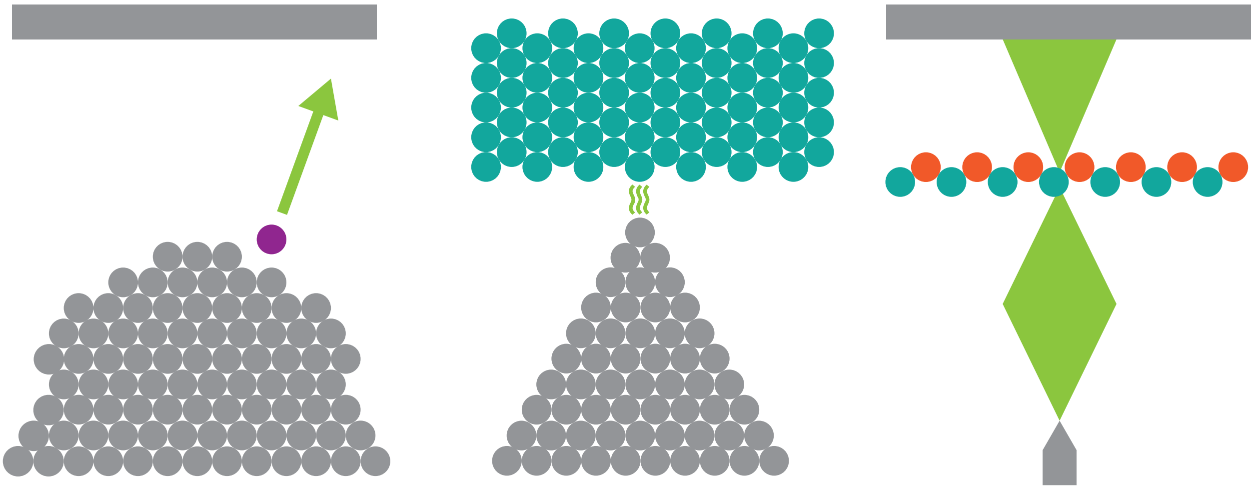


FIGURE 2. ATOMIC-RESOLUTION MICROSCOPY TECHNIQUES probe materials using various mechanisms. In field ion microscopy (left), the ancestor of atom-probe tomography, adsorbed gas molecules (spheres) become ionized and are attracted to a detector. In scanning tunneling microscopy (center), a sharp tip (gray) is scanned over a sample (teal), and the tunneling current is monitored to map a sample's surface. In scanning transmission electron microscopy (right), a focused electron beam (green) is transmitted through a thin sample.

production of such devices, in particular one developed by Michelle Simmons and coworkers at the University of New South Wales in Sydney, Australia, that uses single phosphorus atoms.

As impressive as the results described above are, atomic manipulation still takes place on a surface inside an ultrahigh-vacuum chamber. In the real world, atmospheric molecules and surface contamination would quickly overwhelm single-atom devices. The obvious answer is to encapsulate the resulting structures, but that process presents its own difficulties—it would necessitate complex surface chemistries and integration strategies. Hence, the question remains: Is it possible to visualize all the atoms in a material, probe their dynamics and functionality, and arrange them in desired patterns?

Scanning the beam

The key limitation of STM is the use of very low-energy electrons that are geometrically confined by the tip to length scales well below their characteristic wavelength. The alternative approach is to reduce the electrons' wavelength to visualize matter, akin to optical imaging. Transmission electron microscopy (TEM) was invented by Max Knoll and Ernst Ruska in the 1930s; Ruska won the Nobel Prize in Physics for their work in 1986. In the technique, a relatively large area of a sample is illuminated by a beam of electrons with near-parallel trajectories. A series of electromagnetic magnifying lenses enlarge the transmitted waves to form an image at a phosphor detector screen.

Scanning transmission electron microscopy (STEM) is closely related to TEM, and a single microscope can typically operate in both modes. The invention of STEM and scanning electron microscopy (SEM) can largely be attributed to Manfred von Ardenne's work in the 1930s; the modern form of STEM was optimized by Albert Crewe in the 1970s.

STEM can be thought of as an upside-down and highly focused version of TEM. The magnifying optics are primarily located before the sample, and they project an atomic-sized beam of electrons—the probe—onto a sample. An image is formed by recording the scattered intensity of the beam as it scans across a sample. The principal benefit of STEM over TEM for imaging is that the electrons scattered at high angles give an image that depends mainly on the atomic number Z. Thus a so-called Z-contrast image can be approximately interpreted as directly mapping nuclear positions in the samples. Several technological advances enabled the modern STEM instrument; see reference 8 for a review. Chief among them is aberration correction.

The question of what imaging resolution is ultimately achievable is one that is still debated today. Following the wisdom of optical microscopy, it seems natural that the illumination wavelength should be smaller than the size of the object to be resolved. Thus, the short de Broglie wavelength of high-energy electron beams—typically a few picometers—and the ability to accurately focus those beams using electric or magnetic fields position the electron microscope as a promising instrument to directly image single atoms. (Interestingly, Ruska and Knoll appear to have been unaware of the electron's wavelike nature at the time of their invention.)

In practice, however, a modern electron microscope's lenses will always suffer from aberrations, and those imperfections are the principal factor limiting the device's resolution. In the 1930s and 1940s, Otto Scherzer demonstrated that aberrations are unavoidable. But he also indicated several methods by which they could be mitigated. The most promising method used a series of electromagnetic fields with different symmetries to shape and modify the beam. Consequently, contemporary aberration correctors are complicated systems that add extra elements to the microscope column. The addition of such a device is why the column in the opening image is so tall.

Building an aberration corrector proved to be so complicated that for many years it was feared to be impossible. The lenses must each be precisely aligned and dynamically adjusted to compensate for varying conditions while also remaining extremely stable. During the imaging of single atoms, even a small instability from a stray field, a noisy power supply, or air-pressure variation could be disastrous. The sheer number of variables makes it difficult for a human to keep track of all the elements, so quantitative computer control and alignment are essential.

Aberration correctors were successfully developed in the 1990s and early 2000s. The devices have revolutionized the field of electron microscopy, and imaging of single atoms is now almost routine. In recognition of that advance, the Kavli Prize was jointly awarded in 2020 to two endeavors—one led by Ondrej Krivanek for STEM[9] and another by Knut Urban, Harald Rose, and Maximilian Haider for TEM.[10]

In addition to providing structural information about nuclear positions, beam electrons transmitted through a sample also interact with the sample's electrons. After the beam and sample electrons exchange energy, a magnetic prism in an electron spectrometer can disperse the outgoing beam onto a position-sensitive detector to give an electron-energy-loss spectrum (EELS), which provides information about the composition, bonding, and electrical structure of the material.

The energy resolution of an EELS is primarily limited by the energy spread of the electron beam. The spread can be reduced by removing electrons with too much or too little energy before they get to the sample. The removal process, known as electron monochromation, has been used since the early days of electron microscopy and has achieved impressive results. But it reduces the number of electrons in the beam, and because of significant experimental challenges, early implementations usually degraded the signal's spatial resolution.

A new generation of electron monochromators, in particular those pioneered by Krivanek and coworkers,[11,12] has mitigated those issues. When paired with aberration correctors, the devices enable microanalysis at previously unprecedented energies and spatial resolutions. Given that EELS reflects a material's vibrational and electronic properties, monochromation improvements are beginning to open a new vista of biological, chemical, and physics applications. Advanced measurements of atomic-scale structure and function are possible and continuously improving.

With those capabilities an aberration-corrected STEM device is essentially "a synchrotron in a microscope," as STEM pioneer Mick Brown eloquently described it in his 1997 paper of that name. In the years following its publication, the ability to perform atomic-resolution spectroscopy and obtain spectra from even single atoms was experimentally demonstrated.[13]

From imaging to knowledge

Advances in STEM resolution, functionality, and sensitivity over the past decade or so have transformed the technique from a mere imaging system to a quantitative tool. It can characterize atomic structures with picometer-level precision, watch structural evolution under external stimuli, and provide information on local functionalities using EELS. Developments in detector technology now allow recording of a diffraction pattern at every probe position.[14] It has thus become possible to record scattering information at atomic resolution to generate multidimensional data sets featuring both real- and reciprocal-space information.

The new data streams present challenges for recording and interpretation. Unlike bulk-scattering methods, in which information is averaged over mesoscopic volumes, STEM obtains distinct data from multiple spatially separate locations. It therefore requires mathematical tools capable of interpreting and compressing the information and relating it to macroscopic properties and functionalities. Although still relatively uncommon in condensed-matter physics, such approaches are regularly used in other fields, such as astronomy. If fully adopted, they can provide a wealth of information on a solid's chemical and physical functionalities, ranging from defect equilibria and solid-state reactions to the nature of ferroic, charge-ordering, and magnetic distortions. A variety of long-standing questions, including ones on the nature of ferroelectric relaxor and morphotropic materials, nanoscale phase separation, and dynamic phenomena, might now be open for exploration.

Advances in quantitative spectroscopy have opened the door to exploration and discovery of quantum phenomena through spectroscopic signatures in electron-energy-loss spectra, multidimensional scattering data sets, and structural images. Correlating and condensing the large, varied data streams into compressible, interpretable information necessitates linking materials functionalities to reduced descriptors. It also requires the inversion of experimental data, along with their associated uncertainties, to recover the physical functionality of interest.

Once such data-analysis methods become available, researchers will be able to explore the atomic-level origins of materials functionality. Of course, for many phenomena, such analysis is nontrivial. In phonon and plasmon measurements, for example, localized quasiparticles are considerably larger than the beam, so the interactions behind the resulting image are, at the beam's scale, nonlocal. Similarly, in multidimensional STEM, the measurement process will be strongly affected by the beam shape and aberrations.

All of those problems are surmountable. Still, working with the logic from Feynman's quote, there might be further development—namely, moving from understanding preexisting atomic configurations to intentionally building them atom by atom.

Hints of atoms in the 13th century

There is nothing unchangeable, everything is in motion
The particles attached together until all the lands and sky were created
When we started to know them, we gave them names and meaning
Once again, these familiar particles drown in the vortices
The particles split from one another and turned to another form again
I see the Sun appeared from the combination of hundreds of thousands of particles
The structure and order of hundreds of thousands of particles caused the formation of the world

هیچ چیزی ثابت و برجای نیست
جمله در تغییر وسیر وسرمدی است
ذره ها پیوسته شد با ذره ها
تا پدید آمد همه ارض و سماء
تا که ما آن جمله را بشناختیم
بهر هر یک اسم و معنی ساختیم
بار دیگر این ذرات آشنا
غرق می گـــــردند در گـــردابها
ذره ها از یکدگر بگسسته شـــد
باز بر شکل دگر پیوســـته شد
ذره ها بینم که از تر کیبشـــان
صد هـــزاران آفتـــاب آمد عیـان
صد هـــزاران نظـــم و آئین جـدا

—Jalāl ad-Dīn ar-Rūmī (translation by Mahshid Ahmadi)

From lab to fab

Prior to the advent of aberration correction, the preponderant way to achieve better resolution in TEM and STEM was to increase the accelerating voltage used in the microscope, thereby giving a shorter electron wavelength. The problem with that approach is that the amount of kinetic energy that can be directly transferred to a nucleus in a single collision increases, which increases the damage done to the sample. By providing an alternative, the aberration corrector has made STEM a technique of choice for materials science, condensed-matter physics, and high-resolution spectroscopy. And, importantly, it has set the community on the pathway to routine visualization of single atoms under a variety of conditions.

Over the past few years, advances in low-voltage aberration-corrected microscopy have led to many studies of beam-sensitive materials. They also opened for exploration the regime in which beam-induced material changes are minor and localized, often even on the atomic or single-chemical-bond level. In many cases, the changes occur sufficiently slowly that both the initial and the final state of the system can be visualized. Rather usefully, the rate of induced changes can be controlled by adjusting beam parameters, such as voltage and current. Those capabilities have led researchers to actively pursue direct atomic fabrication: The electron beam, in conjunction with image- or spectrum- based feedback, is proposed as a means to manipulate atoms and create atomic-scale structures;[15] see figure 3 for an example.

STEM- and STM-based atomic manipulation strategies each offer benefits. The electron beam in STEM can induce changes inside a material, whereas STM interacts with only the topmost layer of atoms and therefore necessitates clean, atomically flat surfaces. STEM also provides a more direct picture of atomic structure than STM does because it is sensitive to atomic nuclei, whereas STM provides maps of electron density. STM-based atomic fabrication requires surface-science strategies to passivate, depassivate, and protect surfaces. STEM can offer greater levels of environmental control around samples—gases and even liquids can be introduced to induce and control a range of material transformations. In practice, most STEM samples must be relatively thin films, typically less than 100 nm. That is the perfect experimental space, however, to investigate and exploit two-dimensional materials, such as graphene or ultrathin suspended layers of three-dimensional materials.

Unlike STM, STEM provides high-resolution imaging and spectroscopy over a wide range of temperatures and thus permits the use of temperature as a knob to allow or forbid certain transformations. Recent advances in STEM should allow one to operate anywhere between a few Kelvin, where quantum phenomena can be investigated, to over 1000 K, where defects and dopants can readily diffuse or be more easily moved by the beam.

To date, four distinct classes of manipulation have been demonstrated: control of single vacancies, atoms, and multiatom complexes in 2D materials; control of single heavy atoms inside 3D materials; phase changes, which are characterized by the ordering of vacancies or localized amorphous–crystalline transitions; and controlled addition or removal of material at local sites. Interesting opportunities may emerge in the context of stacked and twisted 2D materials (see the article by Pulickel Ajayan, Philip Kim, and Kaustav Banerjee, Physics Today, September 2016, page 38), where local beam-induced changes can give rise to the emergence of the moiré materials and open new vistas for the physics of proximity effects.

Remarkably, electron-beam modifications can be performed at length scales ranging from nanometers to angstroms, which span the range covered by conventional lithographic and fabrication methods and single-atom manipulation. Some modifications are analogous to those possible in larger-scale electron-beam fabrication or conventional lithography; the beam-directed repositioning of atoms is perhaps most comparable to using STM to move atoms[16,17] and assemble multi-atomic structures.[18]

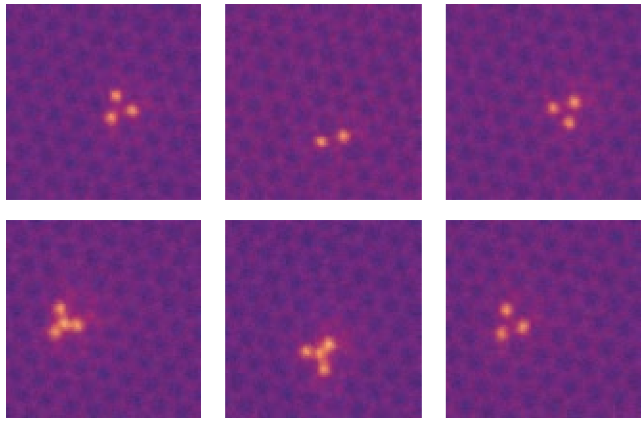


FIGURE 3. ATOMIC MANIPULATION can be achieved using an electron beam. Here, a cluster of silicon atoms in a graphene sheet is created and modified. (Adapted from ref. 18.)

A lab in a beam

In the near future, researchers may be able to modify materials atom by atom, explore and define their quantum properties, and realize a so-called quantum lab in a beam. That capability will represent a convergence of nanoscience techniques brought together primarily by STEM advances. The new capabilities will enable visualization of important electronic, magnetic, and optical properties with near-atomic resolution, and they will increase control of reactions, local environments, and chemistries. Combining those emerging capabilities with advances in machine learning that provide real-time feedback and analytics will allow for the extraction of physical functionalities from the collection of atomic variables—a revolution for nano- and atomic-scale science.

As lab-in-a-beam capabilities become more widespread, routine, and understood, they may even grow to include fabrication. "Fab in a beam" capacity could become a critical component in the development and process flow of quantum information science devices and applications (see figure 4).

Progress will require extensive integration across several disciplines. Although the realization of quantum devices and the exploration of quantum phenomena in atomically engineered systems are immediate targets for electron-beam manipulation, creation of such devices will require integration between STEM and semiconductor workflows.

As surface-chemistry control becomes more important, sample-preparation requirements will become more demanding. Many of the relevant technologies and limitations are well known and understood in related fields, but they have yet to be transferred to the electron-microscopy world. That transfer can be integrated with surface-science methods to deliver and control dopants. Ultimately, true atomic-scale fabrication may require combining and leveraging the different strengths of all three approaches: STM, STEM, and traditional nanofabrication.

Data and information-support infrastructures will also be necessary. Just as computer control was essential for aberration

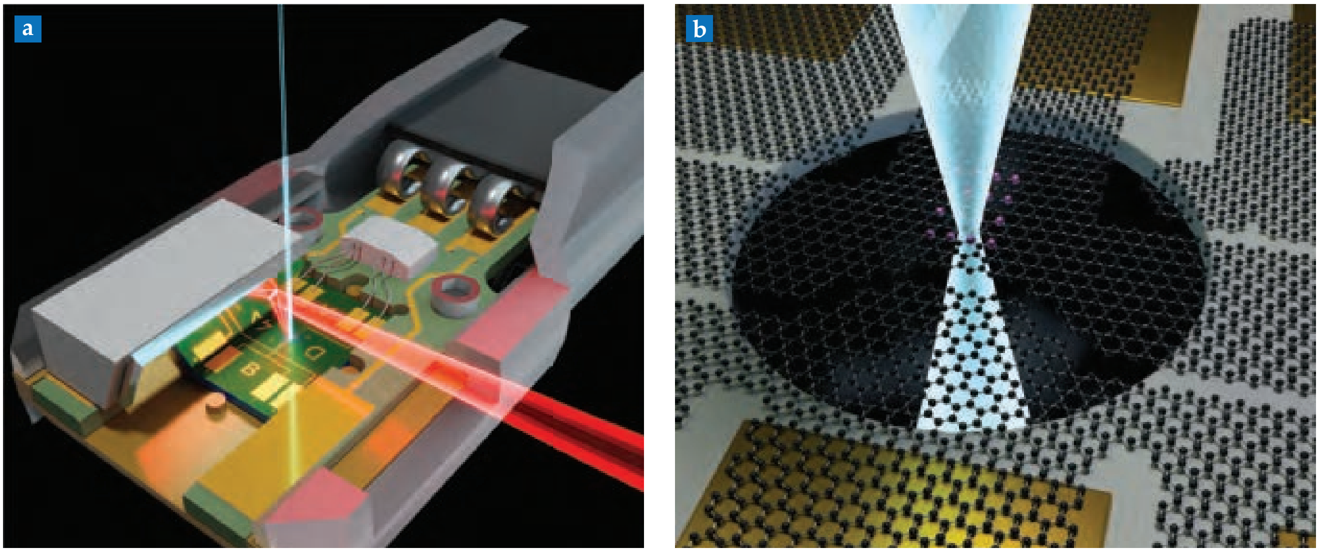


FIGURE 4. A LAB IN A BEAM incorporates many capabilities into one device. **(a)** At the microscale, lasers can heat, sculpt, analyze, or excite materials. **(b)** At the atomic scale, single atoms can be inserted and manipulated with an electron beam. Electrodes can be used to gate, control, or measure nanodevices.

correction, it will also likely be essential for lab-in-a-beam capabilities, including such developments as real-time beam control with automatic drift correction, low-dose imaging based on compressed sensing and nonlinear scans, and real-time image analysis and feedback based on deep learning. Data-transfer rates, the availability of central and graphics processing units, and real-time feedback then become key considerations for further instrumental design.

It is also interesting to speculate about whether electron-beam fabrication can be scaled up for practical applications. Such systems appear to have much lower intrinsic latencies than scanning probe manipulations. But even at tens or hundreds of manipulations per second per beam, they do not scale easily to industrial production.

At the same time, one doesn't need to make very many elements in a quantum system to have a real impact. Several good but easily accessible elements might be enough for many applications. In some cases, only about 50 error-free qubits would be expected to compete with the fastest classical computers. Similar to how enzyme-catalyzed chain reactions enable the duplication of biological signals, a combination of the atomic fabrication of seed elements and chemistry-based duplication may open the way to mass production.

Equally important is the development of fundamental theory for beam–solid interactions. Although the theory for electron scattering that underpins STEM image and EELS formation is well developed, beam-induced changes in solids remain relatively underexplored. An electron with precisely known energy can be delivered to a selected part of an atomic lattice with atomic-scale horizontal precision—although presently without equivalent vertical resolution—yet the type of changes it will induce are still unclear. The multistage process includes energy transfer between the electron and nuclei and, potentially, dynamic evolution of localized bonding, delocalized conductive subsystems, and core electronic excitations. The underlying mechanisms are difficult to model because they can span multiple orders of magnitude in energy and time. A lab in a beam would not only produce atomic-scale devices but also provide the ideal test bed to explore those mechanisms and learn how to make new quantum systems.

The opportunity to create quantum structures atom by atom, visualize them, and explore their functionality with the lab in a beam makes the field an exciting one to pursue. The more precisely we can build, the deeper our understanding can become.

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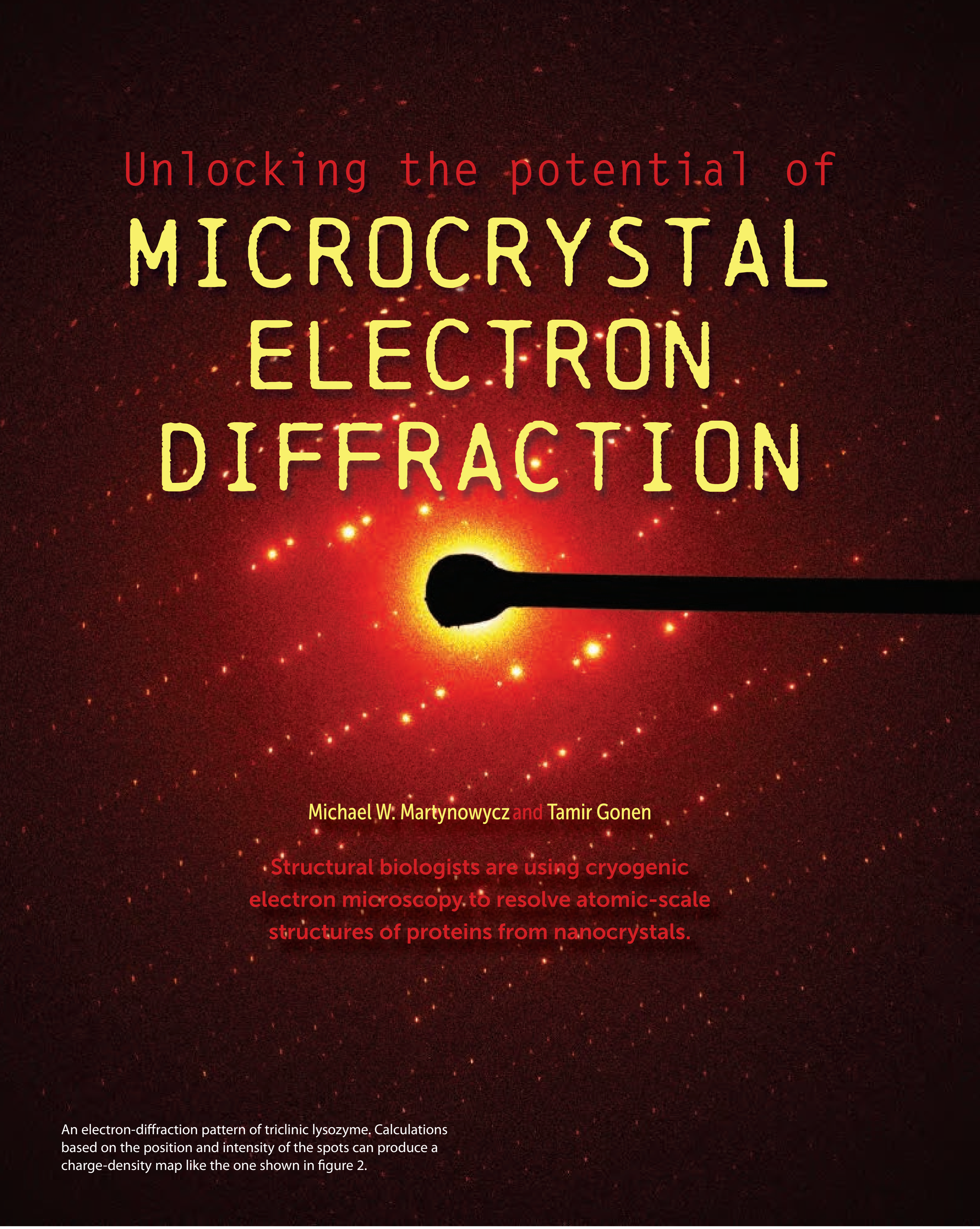
Unlocking the potential of MICROCRYSTAL ELECTRON DIFFRACTION

Michael W. Martynowycz and Tamir Gonen

Structural biologists are using cryogenic electron microscopy to resolve atomic-scale structures of proteins from nanocrystals.



An electron-diffraction pattern of triclinic lysozyme. Calculations based on the position and intensity of the spots can produce a charge-density map like the one shown in figure 2.

Mike Martynowycz is a research scientist and **Tamir Gonen** is a professor, both in the department of biological chemistry at UCLA.


Atoms stick together in different ways to make the molecules that compose everything we touch and see. Our bodies are made of cells. Cells, in turn, are made of lipids, proteins, nucleic acids, metabolites, and water. Every one of those molecules is made from the same handful of atoms. But although the components are the same, the molecules differ in how many atoms they have and how those atoms are arranged in space.

Proteins are tiny biological machines. They do work at the nanoscale by moving molecules around, forming or breaking bonds, and catalyzing reactions. Structural biologists strive to determine where all the atoms reside inside proteins. The most common method uses high-energy x rays for the job. Purified proteins grow into three-dimensional crystals that act as diffraction gratings when exposed to coherent radiation. Rotating the crystal in the x-ray beam produces diffraction spots that identify the atoms' locations inside the crystal.

But growing proteins into crystals large enough for x-ray diffraction is challenging. Indeed, the most important proteins for human health rarely grow into crystals large enough for x-ray diffraction experiments to work on them, or they are too sensitive to the radiation and break down before the data can be collected. Fortunately, a cryogenic electron microscopy (cryo-EM) method, known as microcrystal electron diffraction (MicroED),[1] can determine protein structures from crystals as small as one billionth the size of those used in traditional x-ray crystallography.

The method uses the same cryogenic electron microscopes that biologists rely on to image macromolecular complexes or to discern the 3D structure of entire cells—techniques known as single-particle imaging and tomography, respectively. MicroED promises to open structural biology to new classes of protein nanocrystals and glean novel details from the tiny proteins.

The structure-function relationship

Understanding what something does is powerful. It lets people know, for instance, how to fix things that are broken. Scientists refer to that understanding as the structure–function relationship. Structural biologists care about how the machinery in our bodies works and investigate how proteins operate by determining their atomic structure. Beyond many other critical functions, proteins can move sugar into cells, carry oxygen from lungs to muscles, and produce electrical signals in our brains.

The first step to determining a target protein's structure has been to grow crystals of it. Fortunately, many proteins can arrange into a repeating 3D pattern to make crystals. Such crystals are grown by isolating the pure protein and mixing it with various salts and additives that coerce the protein into small, ordered clumps that then grow outwardly into beautiful, faceted shapes, as shown in figure 1a. Those crystals are then interrogated by a beam of x rays.

At large synchrotron light sources, strong magnetic fields whip electrons around circular tracks at relativistic speeds. The accelerating electrons emit a broad spectrum of light. Such light sources are enormous, with circumferences typically on the scale of hundreds of meters. Stretching out from those rings are end stations, at which the electromagnetic spectrum is filtered and an emerging x-ray beam is used for experiments.

Protein crystals placed in the path of those beams diffract a small fraction of the x rays into detectors that record their pictures—tiny spots known as reflections, similar to the ones shown in the opening image. Calculations based on both the locations and intensities of the reflections build up a map of the positions of every atom inside the protein.

Although growing crystals is standard practice for x-ray diffraction, growing protein crystals large enough to be studied can take years or fail altogether. That bottleneck has led many structural biologists to search for other methods to determine a protein's structure.

Cryo-EM in retrospect

The 2017 Nobel Prize in Chemistry was awarded to Jacques Dubochet, Joachim Frank, and Richard Henderson for their development of cryo-EM of biomolecules in solution (see Physics Today, December 2017, page 22). Traditional light microscopes magnify small objects by focusing light through glass lenses—an achievement limited by the wavelength of visible

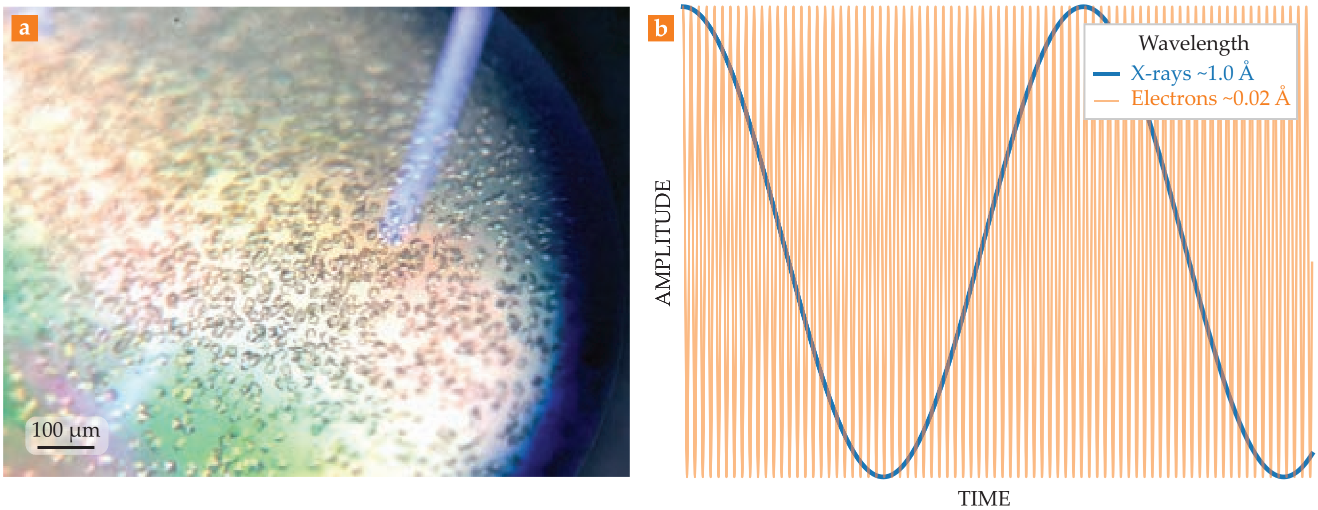


FIGURE 1. CRYSTALS and their diffraction. **(a)** Protein crystals of proteinase K, a serine protease, are seen through a light microscope. **(b)** The graph shows a comparison between the wavelengths of x rays (blue) and electrons (orange) typically used in diffraction experiments. With their much shorter wavelength, electrons can resolve much finer details of a biomaterial.

light. Electrons, by contrast, have a wavelength far lower than visible light—smaller even than typical x rays (see figure 1b). And because they carry both charge and mass, electrons can be accelerated to high velocity using electromagnetic lenses. The upshot: Electron microscopes produce images with details that are far finer than can be seen with a light microscope.

Even so, imaging biological material as small as an individual protein is difficult. High-energy electrons must propagate in a vacuum, which is incompatible with a liquid environment—the natural home for most proteins. And those electrons can damage biological materials. To circumvent those problems, researchers developed methods to freeze the sample quickly enough that the protein's liquid surroundings cannot crystallize. They leave the proteins embedded in a thin layer of vitrified, amorphous ice. The frozen, hydrated state exists at a liquid-nitrogen temperature of about −320 °F, an environment that *is* compatible with electron microscopy.

Early cryo-EM studies that preceded the development of rapid-freezing techniques typically focused on proteins that grew into large, 2D crystal arrays. Imaging them required embedding the protein crystals in another material, such as sugar, that could withstand the vacuum and damaging electron beam inside the microscope. The first demonstration of 2D electron crystallography showed that high-resolution diffraction patterns could be collected from thin protein crystals without the need to stain or fix them using a hydration stage.[2] That demonstration was followed by the first use of cryo-EM that froze protein crystals and preserved them in a native hydrated state for subsequent electron diffraction studies.[3]

In 1975 Richard Henderson and Nigel Unwin, both at the UK's Medical Research Council Laboratory of Molecular Biology, presented the first 3D structural models by electron crystallography using glucose-embedded 2D crystals of the purple membrane protein bacteriorhodopsin and bovine-liver catalase at 7 Å and 9 Å resolution, respectively.[4] They used both imaging and diffraction. Henderson and Unwin extracted phases from Fourier transforms of the images and combined those phases with amplitudes obtained from electron diffraction patterns. Together the phases and amplitudes were then used to reconstruct a 3D density map.[5] To pull off the achievement, they conducted their experiments with a transmission electron microscope operating at room temperature.

In 1984 Dubochet and collaborators developed a method to rapidly freeze biological specimens by plunging them into liquid ethane.[3] That procedure freezes the sample and water so quickly that the ice cannot form crystals; it becomes vitrified. The result is a frozen biological specimen that remains in its native hydrated state—an advance in sample-preparation technology that ultimately led to near-atomic-resolution models of bacteriorhodopsin from electron crystallography of cryogenically preserved 2D crystals.[6] Over the next couple of decades, researchers were able to achieve numerous milestones by using cryo-EM and electron crystallography.

In 2005, biologists resolved the first protein structure—that of aquaporin-0 from "double-layer" 2D crystals—at near-atomic resolution by using cryo-EM.[7] To discern the structure of that channel, one of us (Gonen) and collaborators relied on electron crystallography that used only diffraction patterns recorded at various tilt angles. A major advantage of crystallography that can discern single or multiple layers is that membrane proteins can be reconstituted in their native environment. The process allows researchers to study the proteins' functionality and their interactions in the lipid bilayer.

Diffraction from tiny 3D crystals

A similar approach revealed the structure of a 3D protein crystal.[8] The Gonen group collected images of diffraction patterns from crystals of lysozyme at various angles and determined the structure by molecular replacement (see the article by Qun Shen, Quan Hao, and Sol Gruner, PHYSICS TODAY, March 2006, page 46). The vitrified 3D crystals created small diffraction spots akin to x-ray diffraction experiments.

Gonen and others subsequently modified the approach to record data on a fast camera as the crystal was rotated in the electron beam.[9,10] Under those circumstances, the procedure was analogous to the standard rotation method in macro-

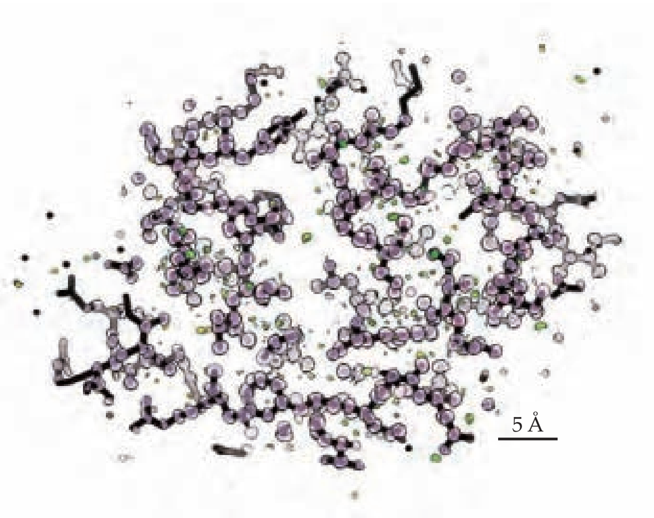


FIGURE 2. SUBATOMIC-RESOLUTION STRUCTURE of triclinic lysozyme. The charge-density map was determined *ab initio*. Pink spheres correspond to protein atoms (carbon, nitrogen, and oxygen, typically), and green spheres correspond to hydrogen atoms. Maps of this quality allow structural biologists to build accurate models of proteins that can aid drug discovery and design**.** (Adapted from reference 12.)

molecular x-ray crystallography, which made the data collection better and faster. Continuous rotation in MicroED experiments produced a higher-quality structure of the protein lysozyme from a single microcrystal. And the data could easily be processed using the same software as x-ray crystallography. MicroED data are rapidly collected by continuously rotating vitrified crystals under low-dose conditions in a cryogenically cooled electron microscope.[1]

Following the initial MicroED studies on lysozyme and catalase, which demonstrated the technique's potential for structural biology, researchers went on to resolve several other structures from 3D protein crystals, including various membrane proteins and ligand-bound complexes.[11] This past year the two of us and two colleagues demonstrated true atomic resolution from MicroED data on the lysozyme,[12] shown in figure 2. The demonstration sets the stage for future MicroED studies at subatomic resolution.

Electron crystallography is also a useful technique for resolving the structure of small inorganic and organic molecules. While MicroED researchers adopted the approach and technologies of 2D electron crystallography of proteins, other researchers were using electron diffraction to characterize nonvitrified, radiation-hardy molecules. The two worlds of structural biology and materials science collided in 2018, when two groups independently applied electron diffraction to small-molecule pharmaceutical compounds.[13,14]

In experiments by the two of us and several colleagues,[13] low-dose conditions were the norm. The conditions facilitated rapid diffraction-data collection and structure determination from beam-sensitive organic molecules. Preparation is relatively straightforward: Samples can be crushed or ground into a dry powder and directly placed on a standard electron microscopy grid for MicroED.

During data acquisition, the grid is exposed to the electron beam, and individual crystals can be selected for MicroED analysis. If the samples being assayed contain mixtures of compounds, the process lets researchers identify the different compounds directly from the mixture at atomic resolution.[13] That capability opens the field to many possibilities in the study of natural products and the characterization of pharmaceutical compounds.

What do electrons allow us to see?

Researchers analyzing MicroED data use the same software as those who analyze x-ray experiments. Both methods produce a map, from which an atomic model is built. Although the same software processes the data, the maps generated from the methods provide different information. Whereas x rays scatter from the electron cloud that surrounds an atom, electrons scatter from the atom's electrostatic potential, which is generated by the interacting positive and negative charges.[15]

Because each type of experiment uses different physical phenomena, the information contained in their maps differs. X-ray scattering gives an electron-density map, which reveals where the electrons are inside the crystal. And electron scattering produces a potential map.[16] That potential depends on both the element and its charge. The local environment can result in wildly different scattering amplitudes from a given atom, as shown in figure 3. Indeed, electron-diffraction experiments can reveal the state of electric charge for amino acids, ions, salts, and even solvent.

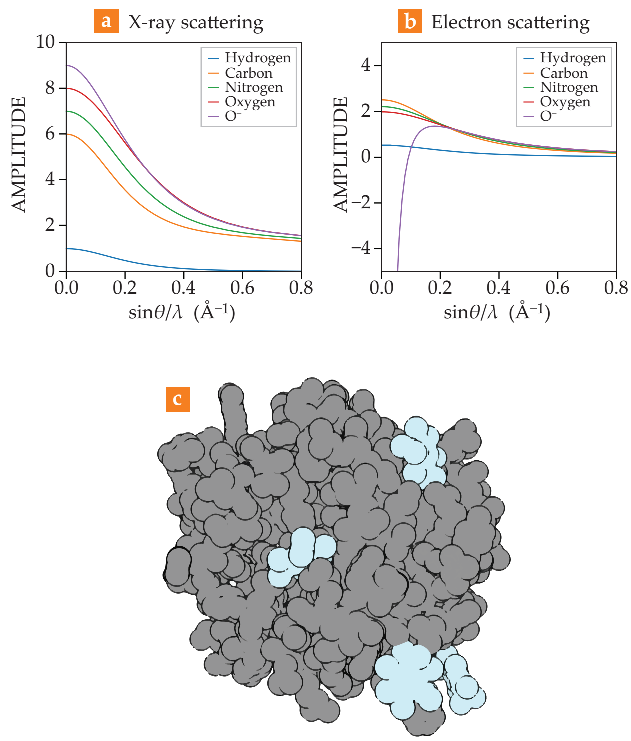


FIGURE 3. DIFFERENCES between **(a)** x-ray and **(b)** electron scattering from neutral and charged atoms. Whereas x rays scatter from an atom's electron cloud independently, electrons are scattered by the charge environment. Vast differences in scattering can be seen for charged atoms. **(c)** This structure of an enzyme (gray) bound to drugs (blue) was determined by microcrystal electron diffraction.[11] With those diffraction patterns, researchers can resolve biomolecular structures and screen new drugs and discern how they bind to different proteins.

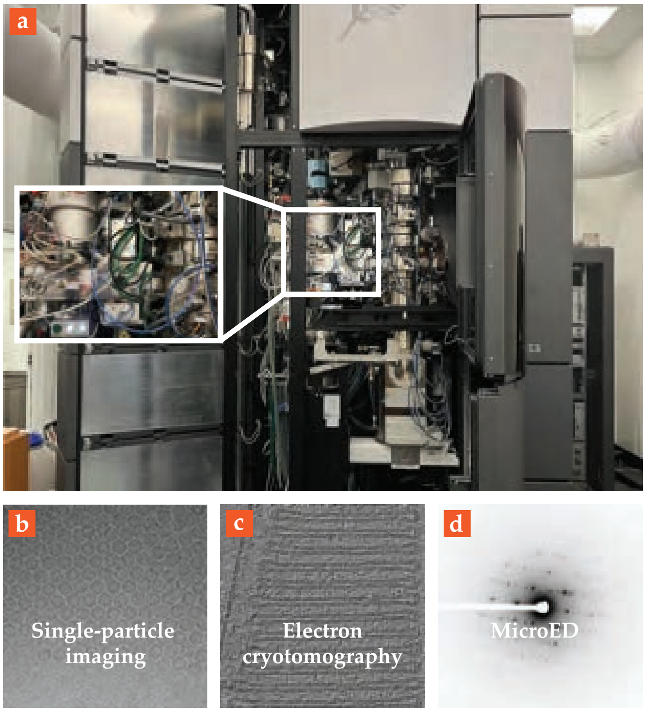


FIGURE 4. CRYOGENIC ELECTRON MICROSCOPY, in practice. **(a)** The internal components of a 300 kV microscope are shown, including (from top to bottom) an electron source, collimated electromagnetic lenses, a cryogenic sample chamber and stage (inset), and several camera systems. The same electron microscope can be used for all modalities of cryogenic electron microscopy. Examples of **(b)** single-particle analysis, **(c)** cryotomography, and **(d)** cryogenic electron diffraction are shown here. In the first two cases, the microscope operates in imaging mode, and a structure is calculated on the basis of the recorded pictures. In the last case, the microscope takes the crystal's diffraction patterns, from which the structure can be determined. (Panel b adapted from K. M. Yip et al., *Nature* **587**, 157, 2020. Panel c adapted from M. Pöge et al., *eLife* **10**, e72817, 2021.)

The majority of medications approved by the US Food and Drug Administration are molecules with fewer than 70 atoms bound together in a complex 3D shape. Those small-molecule drugs are typically composed of carbon, nitrogen, oxygen, and hydrogen. Hydrogens make up about 50% of the atoms in any given protein or drug. But it's difficult to resolve the locations of those hydrogens from diffraction patterns taken of proteins and drugs with synchrotron x-ray radiation. That's because hydrogens are so much lighter than other elements and have a small electron cloud.

Although those atoms can be seen in extremely high-quality data, most structural biology investigations cannot achieve the necessary resolution to accurately find them. Instead, the hydrogen atoms are placed automatically in positions where theoretical considerations suggest they should be located. Scattering using electrons may allow biologists to identify hydrogen atoms at more modest resolutions, because unlike x rays, electrons scatter strongly from hydrogen.

By deciphering where those hydrogens are in a structure,[12,17] the biologists will be able to model how the drug will bind to the protein receptor of interest. Better binding means that they may design drugs with higher efficacy and fewer side effects. Using MicroED, they can determine the structure of those drugs quickly. Biologists can determine the atomic-resolution structure of the drug bound to the target protein with higher throughput than if they were to attempt to crystallize the drug with the protein beforehand.[18] The electrostatic-potential map of the bound drug directly reveals how the binding works and how the charges interact. In that respect, MicroED aids the drug-discovery process—by identifying the drug's structure in order for researchers to understand its interaction with the protein.

Future of MicroED

The advent of MicroED for proteins and small molecules has created an incredible value for the transmission electron microscope as a structural-biology instrument. The same instrument can be used to take pictures of large proteins and complexes using single-particle and cryogenic electron tomography and to resolve atomic structures from tiny crystals using MicroED, as shown in figure 4. Using just a transmission electron microscope, researchers could feasibly produce an entire drug-discovery pipeline.

The ability to probe charge and visualize potential instead of electron-density maps is not unique to MicroED. It is a property of all electron-microscopy investigations. But reducing a sample to cryogenic temperatures has proven essential for probing the structure of biological materials. Indeed, MicroED opens a new world of structural-biology investigations: Locating hydrogen atoms, accurately modeling electric charge, and determining structures from nanocrystals all give the method an edge in many investigations. The resulting data can inform deep-learning algorithms for solving the protein-folding problem and improve their predictive abilities. (See Physics Today, October 2021, page 14.) Together, such capabilities could lead to rapid improvements in drug discovery. Using the method to determine the structures of molecules that cannot be resolved by any other means is just the beginning.

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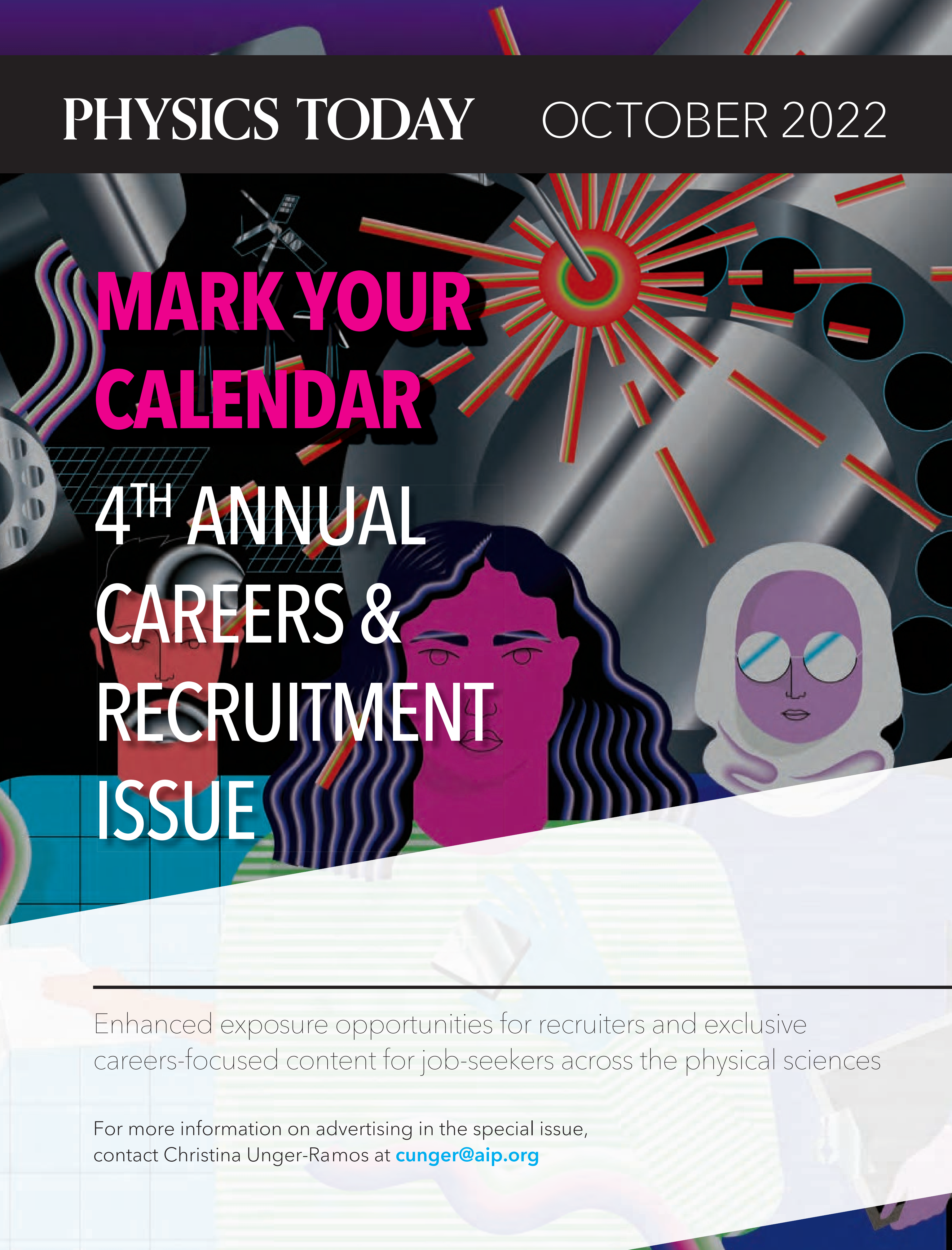
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FINDING THE RIGHT PROGRAM FOR YOU

Samantha Pedek, graduate student, University of Iowa; co-chair, Physics Congress 2022 Planning Committee

Find Your People and Grad Program at the 2022 Physics Congress

Join hundreds of physics undergrads, grad school reps, and physics luminaries

Samantha Pedek, 2022 Program Co-chair

Samantha Pedek

Networking is one of the most important aspects of being a young professional. We've all heard the spiel about how networking can have positive impacts on future educational and career-related opportunities, but many of us struggle with making the initial contact that can lead to lasting connections.

In 2016 I attended the Physics Congress (PhysCon), the largest gathering of undergraduate physics students in the United States. Every few years, PhysCon brings together students, alumni, and faculty members for three days of frontier physics, interactive professional development workshops, and networking. It is hosted by Sigma Pi Sigma, the physics honor society, and anyone interested in physics can attend.

Networking at PhysCon was unlike any other professional development experience I had as an undergraduate physics student. The sheer number of like-minded people was daunting—hundreds of physics and astronomy undergraduates, representatives from graduate schools and summer research programs, employers from all over the country, and well-established professionals at the height of their careers were all under one roof for three days.

The Physics Congress is a high-energy, hands-on weekend designed explicitly for undergraduate physics students. Photo courtesy of SPS National.

PhysCon has continued growing in attendance, scope, and opportunities, and you won't want to miss the next one! In celebration of the 100th anniversary of Sigma Pi Sigma, an extra-special PhysCon is planned for October 6–8, 2022 in Washington, DC. With a little preparation, you'll have the chance to narrow down your graduate school search, meet potential employers, and make lasting connections with people heading down similar career paths.

The most direct opportunity to meet with representatives from physics and astronomy grad programs and potential employers occurs during the Expo, which encompasses both a grad school fair and a career fair. During the Expo, attendees can visit booths to learn more about a program, company, or undergraduate research experience as well as get tips and advice on applying. When I attended, seeing the wide variety of vendors enabled me to start thinking about my life after col-

NETWORKING TIPS

Before you attend a networking event, craft and practice your **elevator pitch**—a 30-second narration of who you are professionally, what you've accomplished, and where you hope to go in the future.

If you're attending an in-person event as a prospective student or employee, **business cards** (or contact cards) show that you're serious about your future and make it easy for new contacts to connect with you.

BE AN SPS INTERN

The Society of Physics Students summer internship program offers 10-week, paid positions for undergraduate physics students in science research, education, communication, and policy with various organizations in the Washington, DC, area.

www.spsnational.org/programs/internships.

2019 Physics Congress attendees visit one of the many graduate school booths in the exhibit hall to learn about the program and check out physics demonstrations. Photo courtesy of SPS National.

lege, and I was blown away by the versatility that a degree in physics can provide.

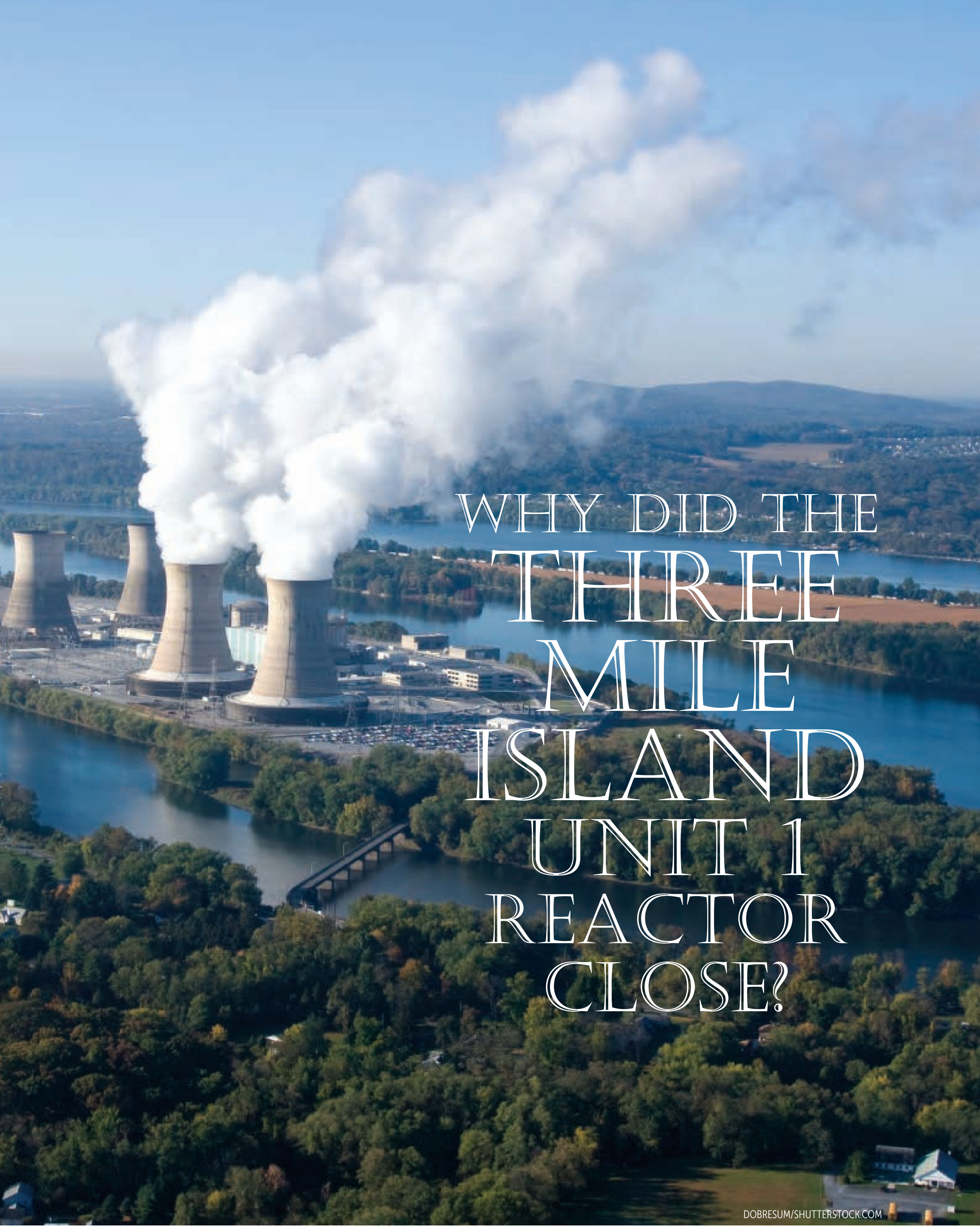
A more subtle opportunity to build your network as a young professional is to engage with attendees you don't already know, between events or at meals. Shuffling between workshops, plenaries, and banquets will be hundreds of people with lived experiences similar to yours. Be adventurous and sit at a meal or workshop table with strangers! You might find yourself next to a professor from a graduate school you're interested in, or even from a school you didn't realize you should be interested in. A quick conversation can leave a lasting impression.

A straightforward way to meet students and professionals is to go to the poster sessions, as a presenter or an attendee. These are excellent opportunities to have one-on-one interactions with others and to learn about new topics. Seeking out posters in subfields you're doing research in or interested in studying in grad school is a great way to form connections and learn about current research in the field. My favorite question to ask a presenter is "Can you tell me more about your research?" They likely have an answer prepared, which can be a bridge to more natural conversation.

The physics and astronomy community is quite small, so if you meet people at PhysCon, you're likely to run into them again. Almost a year after I attended PhysCon 2016, I was a Society of Physics Students intern. Of the 14 of us, over half had met previously, largely at PhysCon. Having that shared experience helped me connect with the other interns right from the start. We even looked back at old PhysCon photos and tried to spot one another in the background, which was wildly entertaining.

Attending PhysCon is the networking gift that keeps giving. I have met others who attended in different years and we're still able to bond over our shared experiences. You are bound to find someone with similar interests and goals in a sea of over a thousand physics students, mentors, and advisers. Preparation is the key to successful networking, so practice your elevator pitch, make business cards, and I'll see you in 2022! GSS

WHY DID THE THREE MILE ISLAND UNIT 1 REACTOR CLOSE?



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Hannah Pell works at EnergySolutions as a licensing engineer and serves on the TMI-2 Community Advisory Panel in Middletown, Pennsylvania. **Ryan Hearty** is a PhD candidate in the history of science and technology program at Johns Hopkins University in Baltimore, Maryland. **David Allard** directs the Bureau of Radiation Protection at the Pennsylvania Department of Environmental Protection in Harrisburg.

Hannah Pell, Ryan Hearty, and David Allard

Navigating the future of US commercial nuclear power requires understanding how regional energy markets, state regulations, and community activism influence the life span of nuclear plants.

On 30 May 2017, Exelon Generation (now Constellation Energy) announced its plan to shut down Unit 1 of the Three Mile Island (TMI) nuclear power plant, located on the eponymous stretch of land in the Susquehanna River in south-central Pennsylvania. That closure by the largest operator of nuclear plants in the US is the first step in a decommissioning process that's required by the Nuclear Regulatory Commission to be completed within a 60-year time frame. TMI had two pressurized water-reactor units; the iconic cooling towers, shown in the opening image, are a stark visual contrast to the rolling farmland surrounding them. After the infamous 1979 accident, Unit 2 was defueled and has remained in a monitored storage condition.[1] EnergySolutions acquired Unit 2 in December 2020 and is now managing the early stages of decommissioning it.

For the six years following the 1979 accident, the power plant's owner, Metropolitan Edison, worked to restart the Unit 1 reactor. But the company faced technical complications, legal challenges, and contentions among local activists,[2] fueled in part by mishandled communications (see Hannah Pell's piece "Three Mile Island and lessons in crisis communication," Physics Today online, 5 May 2020). The Unit 1 reactor was eventually restarted in 1985, changed ownership, and went on to supply electricity to more than 800 000 homes for decades thereafter. Despite the fact that the unit was licensed to operate until 2034, it was ultimately shut down on 20 September 2019.

In its *Annual Energy Outlook 2021* report,[3] the US Energy Information Administration projected that planned nuclear power plant retirements across the US fleet will result in less total nuclear electricity generation capacity in 2050 than in 2020. Figure 1 highlights that decline, and several reasons explain the decrease: historically low natural-gas prices, limited growth in electricity demand, state-level clean-energy initiatives, and increased competition from renewable energy. Commercial nuclear power has reached a crossroads, and navigating its future in the US will require an understanding of the regional factors that led to this point and the hidden costs and potential unintended consequences of such premature closures. What were those costs for TMI, and why did Unit 1 close more than a decade sooner than the end of its operating license?

One reason is that TMI and other nuclear power plants have struggled to compete in the regional electricity market controlled by the Pennsylvania–New Jersey–Maryland Interconnection, or PJM. Figure 2 shows the territory served by PJM. According to current Pennsylvania energy policies, nuclear power is not categorized as clean energy. And shale development, which uses the extremely productive technique of hydraulic fracturing, or "fracking," has driven down market prices for electricity over the past decade. Thus nuclear power is forced to economically compete with the historically low prices of natural gas and state-subsidized renewable energy sources that are protected from market volatility. Additionally, TMI's place in the particular labor and environmental politics of Pennsylvania complicated the legislative efforts to financially rescue the plant.

Our use of TMI as a case study of the challenges that nuclear power faces underscores the need for a narrowed focus on localized causes and effects of prematurely retired nuclear power plants. Regional energy markets, state-specific energy policies, and local interests significantly influence the life span of nuclear facilities. Although we are not pronuclear in the sense that we support the energy resource for its own sake, we believe that TMI's premature closure will negatively affect the broader goals of supplying cleaner energy and improving the well-being of Pennsylvania's citizens. There's no free lunch when providing reliable, affordable, and carbon-free energy, and a comprehensive cost analysis is crucial for navigating a just energy transition.

Cheap natural gas

Pennsylvania is an energy-exporting state and has a complex history with innovative energy technologies.[4] It's an epicenter of the fracking revolution. The oil and gas extraction technique has existed for more than a century, but advances over the past few decades in seismic imaging, financial arrangements for leases of large amounts of land, and refinement of directional drilling have allowed companies to tap into vast and previously unrecoverable oil and gas deposits in shale. The rich Marcellus and Utica shale formations encompass much of eastern Ohio; western, north-central, and northeastern Pennsylvania; southwestern New York; and West Virginia. New York banned shale development in 2014. Pennsylvania's state legislature, on the other hand, has largely supported shale development because of its economic benefits.

Shale development in the region has dramatically increased electricity sales from gas-fired plants on the PJM market. PJM Interconnection is a regional transmission organization that manages the distribution of 180 gigawatts of power generation across 13 states and Washington, DC. PJM partially manages electricity rates for consumers by overseeing wholesale energy markets, which include annual auctions that ensure which plants will supply future energy demands. According to PJM, competition has helped ensure a less expensive, more reliable, and cleaner supply of electricity.

The price for wholesale energy, however, has been driven so low in recent years that TMI was unable to compete in the PJM system. In its report of the 2018–19 auction results, PJM concludes that the low cost of natural gas contributed to higher-capacity market offers from other energy-production resources across the PJM system, particularly nuclear power. In 2019, gas-fired power plants surpassed nuclear power plants as the largest suppliers of in-state electric energy for the first time, and Pennsylvania is predicted to provide 40% of the total US gas production by 2040. Since 2014 TMI's Unit 1 reactor has been unable to participate in the PJM market auction because the price per megawatt it offered was too high; other, cheaper providers have met the predicted demand.

Although shale development has created a near-term boom in cheap natural gas and has provided thousands of jobs in Pennsylvania, it has also generated heated concerns. The pollution and health hazards of oil and gas activities, to say nothing of the long-term effects of increased greenhouse gas emissions, have mostly been dismissed by those who benefit from shale development, even as potential harms have been claimed by activists.[5] Like the questions of nuclear power's benefits and costs in the 1970s and 1980s, the so-called fracking debate is complicated and won't be easily resolved.[6] The point, however, is that Pennsylvania continues to support shale development because of the promise of low-cost natural gas and the economic growth it offers to local communities, many of which have endured financial stress over the past few decades. Meanwhile, TMI and other nuclear power plants struggle to remain financially viable in the PJM region.

Flawed regional markets

When TMI opened in the mid 1970s, utilities in Pennsylvania were vertically integrated, meaning that they controlled the gen-

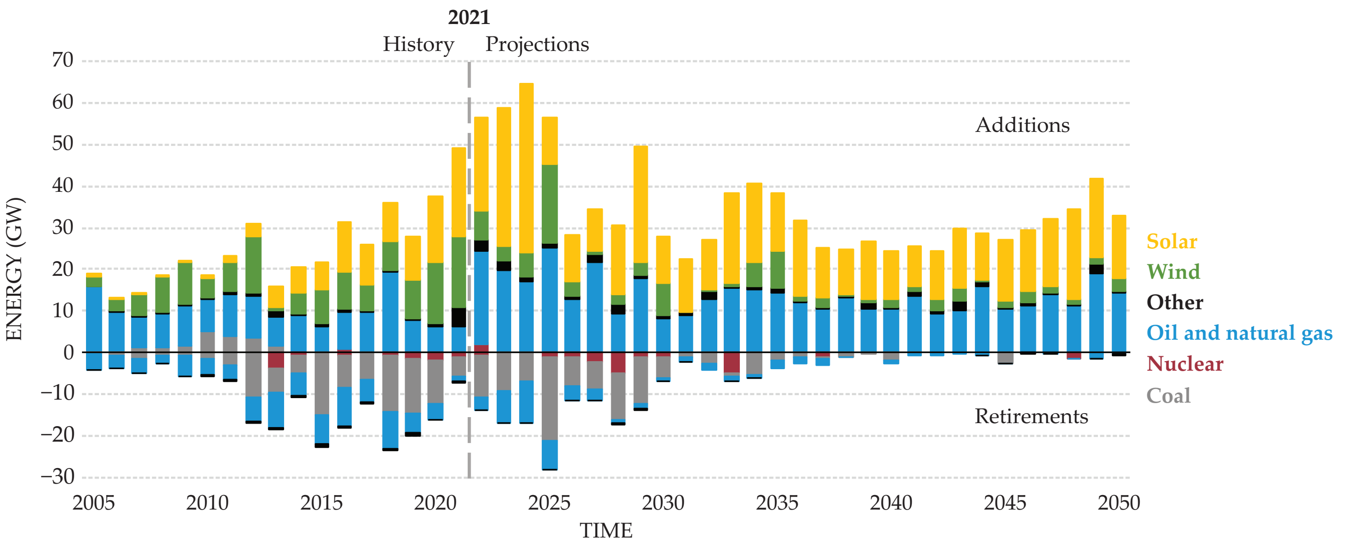

FIGURE 1. THIS TIMELINE of US electricity capacity shows how various generation sources have been added and retired over time. Nuclear power, in particular, has experienced a decreasing trend. (Courtesy of the US Energy Information Administration.)

eration, supply, and distribution of power to consumers. Ratepayers couldn't choose where their electricity came from. In 1996 the Pennsylvania legislature passed the Electricity Generation Customer Choice and Competition Act, which deregulated the state's wholesale energy market. The law fundamentally restructured the way in which electricity is consumed by separating supply from distribution. According to the act, it is in the public interest for ratepayers to choose their electricity providers, "as long as safe and affordable transmission and distribution service is available at levels of reliability that are currently enjoyed by the citizens and businesses of this Commonwealth." Today nearly all electricity production in Pennsylvania is generated by privately owned power plants.[7]

One of the principal reasons for the decision to shutter TMI's Unit 1 reactor, according to Exelon, was "market flaws" in the PJM Interconnection that "fail to recognize the environmental and resiliency benefits from TMI and other zero-carbon nuclear energy plants across the Commonwealth." Notably, Unit 1 wasn't the only nuclear plant in the PJM region whose electricity couldn't be sold in that system. Exelon's Byron and Dresden plants in Illinois also failed to clear the 2018 auction. The Beaver Valley plant located near Pittsburgh was also at risk for early closure by FirstEnergy Solutions (now Energy Harbor Corp), although it has since been rescued by legislative action.

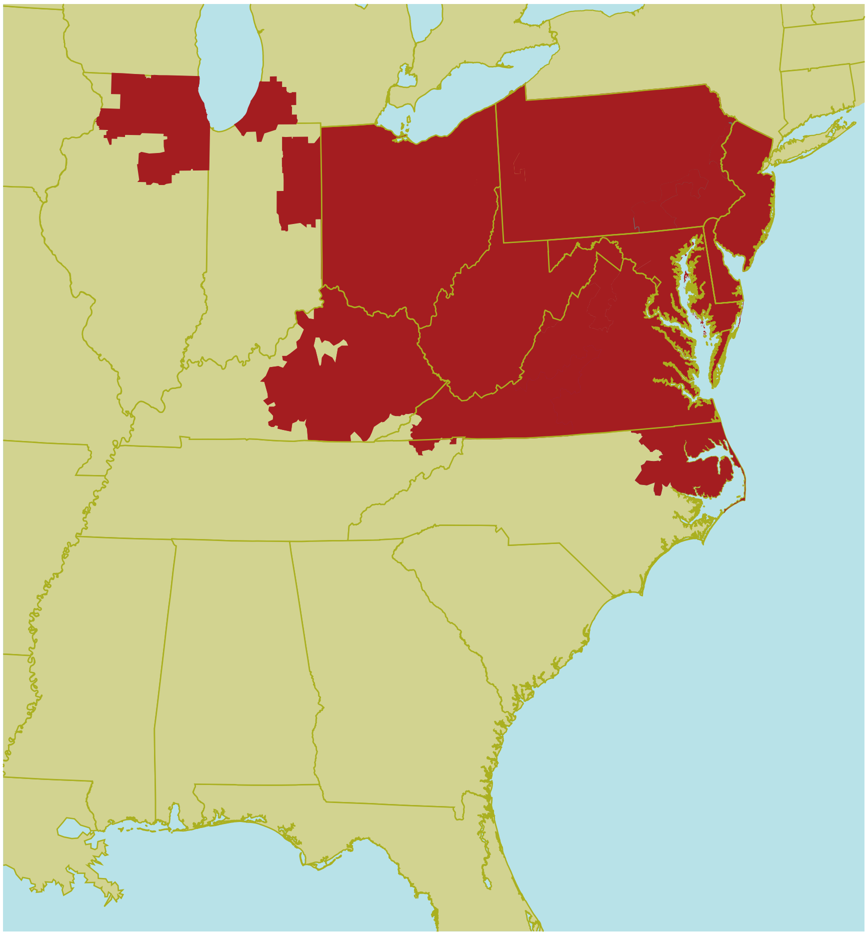

FIGURE 2. **THIS MAP** shows the territory served with electricity by the Pennsylvania–New Jersey–Maryland Interconnection. (Courtesy of PJM.)

Neighboring states, including New York, New Jersey, and Ohio, have created policies to financially support their nuclear power plants. (The nuclear subsidies bill in Ohio, however, was repealed after a bribery scandal behind the legislation was uncovered.) Pennsylvania, a state experiencing a much larger boom in shale development, has not.

Federal regulators, the Pennsylvania legislature, and PJM share responsibility for energy management in the state. Those groups have different interpretations on two important concepts that underlie the market rules and affect the fate of nuclear power plants: grid resiliency and renewable energy.

The resilience of the grid is a measure of its capacity to withstand disruptions that would cause widespread power outages. In 2017 the US Department of Energy proposed that the Federal Energy Regulatory Commission (FERC) impose a rule to require independent system operators and regional transmission organizations, including PJM, to account for grid resiliency in their pricing. The rule would have benefited nuclear power in particular given its significant baseload contribution to grid supply.

Because Pennsylvania was particularly vulnerable to plant closures—even in 2020 the state ranked third nationally for coal production and second for nuclear power—legislators in the state House and Senate voted overwhelmingly for resolutions urging FERC to adopt the pricing rule. But FERC unanimously rejected DOE's proposed rule and instead initiated a new proceeding asking independent system operators and regional transmission organizations to evaluate the resiliency and reliability of power-generation sources.

Stakeholders have debated whether nuclear power is "clean" and have concluded that plants such as TMI are ineligible for crucial state subsidies received by other power producers. The problem is that "clean" is not only a vague and relative metaphor but one that greatly affects how different power producers compete in the PJM market.

In 2004 the Pennsylvania legislature passed the Alternative Energy Portfolio Standards Act (AEPS), which mandates that a minimum percentage of all electricity sold must be produced from "renewable and environmentally beneficial sources." It established two tiers of eligible energy sources: A minimum of 8% of total electricity production must come from Tier I, which includes solar, wind, low-impact hydropower, geothermal, biomass, and fuel cells; and a minimum of 10% from Tier II, which includes waste coal, municipal waste, and other nonrenewables. Nuclear power was not included in either tier. Thus TMI and other plants missed out on the newly created alternative-energy credit system that increases the economic viability of various energy sources. (The 15-year timeline for companies to reach the standards ended in 2021, and local environmental groups are calling for updated legislation to increase the percentages outlined in the initial standards.)

Legislative and public (in)action

Exelon cited the lack of a clear state policy solution as another factor for its inability to reverse TMI's premature retirement. Some Pennsylvania lawmakers, motivated to keep the state's fleet of nuclear power plants running, tried and failed to correct what they viewed as disadvantages to nuclear power caused in part by assumptions about grid resiliency and definitions of clean energy. They have tended to draw attention to nuclear energy's reliability as a baseload source and have leveraged rhetoric about "good-paying jobs" to make their point.

In anticipation of TMI's Unit 1 potential closure in 2019, state representative Tom Mehaffie (R-106) sponsored a House bill named the Keep Powering Pennsylvania Act (HB 11). It proposed to amend the AEPS to include nuclear power as a Tier III energy source. The amendment would correct market flaws by ensuring that 50% of electricity purchased by companies would come from Tier III. State senator Ryan Aument (R-36)—cochair of the first-of-its-kind bicameral Nuclear Energy Caucus—sponsored a similar Senate bill.

At an 11 March 2019 event announcing the bill, Mehaffie (shown in figure 3) said that "the markets do not treat all clean sources of energy the same, and they do not penalize polluters. As state legislators, we need to take a step back, recognize this, and we need to truly take into account the cost of doing nothing." That cost, according to Mehaffie, was excessive to consumers: an estimated $788 million annually in higher electricity bills, which would amount to roughly $2.39 more per month per household, compared with the $500 million to cover the nuclear subsidies in Tier III proposed in HB 11. That would lower the additional monthly household cost to $1.77.

Opponents—including the oil and gas industry, some environmental groups, manufacturers, and consumer advocates—view nuclear power's lack of market competitiveness as a positive outcome. "We urge Pennsylvania legislators to shift their focus from preserving the aging energy sources of the past and instead look ahead toward real climate solutions that will advance a clean energy future in our Commonwealth," the Conservation Voters of Pennsylvania said in a March 2019 press release. Some swiftly framed the proposed subsidy as a bailout that was further perpetuated by a No Nuke Bailout mailing campaign funded by the American Petroleum Institute and a coalition of special-interest groups forming the Citizens Against Nuclear Bailouts. Meanwhile, PennFuture, a nonpartisan environmental advocacy group, published a report estimating the various ways in which the Pennsylvania state and local governments provided $3.8 billion in 2019 in fossil-fuel subsidies.[8]

Neither the House nor the Senate bill ever made it to the floor. "We, the legislature, let you down," Mehaffie said during a TMI closing event on 20 September. The bill was cosponsored by 20 state representatives, including David Hickernell (R-98), whose jurisdiction includes TMI. In an 8 May 2019 statement, he said, "If we had an industry that wanted to bring 16,000 jobs to Pennsylvania, as a Legislature we would bend over backward to make that happen. But we weren't willing to do anything to save family-sustaining jobs that are already here."

Given the high stakes of TMI's retirement, we might have expected local residents to protest the closing, or at least voice their opinions, especially given TMI's influence in the region. Its presence is symbolic not only of decades of local labor participation and energy production but of lingering unease from the 1979 accident; figure 4 shows the cooling towers following the accident. Many citizens, however, had no strong opinion either way. According to a March 2019 poll by the Center for Opinion Research at nearby Franklin and Marshall College, a little more than half—55%—of voters believed that nuclear energy should be one component of Pennsylvania's long-term energy strategy, and exactly 50% favored the proposal to add nuclear power to the AEPS.[9] Ultimately, the public was indifferent—neither for nor against its premature closure. As PennLive reported on the day it was shuttered: "Three Mile Island closes with a whimper, and a whisp."

Weighing local labor loss

Exelon officials were not the only ones drawing attention to the loss of jobs that resulted from TMI's closing. At a 23 May 2018 hearing called "Value of Nuclear Power to Pennsylvania Labor," state senator Aument asked, "If the situation were reversed and we had an opportunity in this Commonwealth to attract

FIGURE 3. TOM MEHAFFIE, a Pennsylvania state representative, unveils the Keep Powering Pennsylvania Act in Harrisburg in March 2019. (Courtesy of Marie Cusick, StateImpact Pennsylvania.)

FIGURE 4. THE COOLING TOWERS of Three Mile Island are shown here following the 1979 partial meltdown at Unit 2 (right). Unit 1 (left) was restarted in 1985. (Courtesy of NRC File Photo, CC BY-NC-ND 2.0.)

3 000 jobs for a manufacturing facility, . . . could you imagine the effort underway in this building today to put in place economic incentives, tax credits, to attract these jobs to Pennsylvania?" Although Aument and other Pennsylvania legislators tried to galvanize support to keep TMI open, preventing the loss of jobs failed to attract the same public support legislators receive when they create new ones.

Stakeholders are not in agreement over the short- and long-term effects of TMI's closing on the local economy. In its 41-page report on its post-shutdown decommissioning activities for TMI Unit 1, Exelon dedicates only two paragraphs to socioeconomics. The report notes that "impacts are neither detectable nor destabilizing and that mitigation measures are not warranted" as a result of the decreased workforce.[10] Exelon employed roughly 675 people at TMI. That number, however, does not include ancillary contractors nor the additional 1500 workers contracted for outages every 18–24 months.

Regardless, the argument over the number of jobs attached to TMI's closure distracts from the necessary conversation about disrupted livelihoods. The rhetoric of "good-paying jobs" fails to recognize the complexity, stability, or availability of work by reducing the idea of a job to the paycheck earned.[11] Decisions that prioritize short-term economic gains have the potential to leave behind an entire TMI community.[12] The changing energy sector offers many promises of new good-paying jobs, but job retention is and will remain an important factor in managing a just energy transition.[13]

Environmental costs

The environmental costs of nuclear closures are predicted to significantly affect Pennsylvania's carbon-free energy efforts. The state was home to nine nuclear reactor units on five power plant sites before TMI's Unit 1 closure. Nuclear power alone accounted for 93% of Pennsylvania's zero-carbon energy, which emitted no sulfur oxides, nitrous oxides, or particulate matter. "We believe that the loss of today's nuclear fleet would be a terrible blow to the progress already made in reducing Pennsylvania's contribution to climate change and would hamstring all of our combined efforts moving forward," testified Davitt Woodwell, then president of the Pennsylvania Environmental Council, before the Nuclear Energy Caucus on 19 June 2018.

According to a March 2019 analysis by Andrew Place, then a Pennsylvania Public Utility commissioner, if the 2019 rate increase in AEPS Tier I energy resources remained constant, it would take Pennsylvania 12.6 years to replace the carbon-free electricity that TMI Unit 1 produced. Despite the long replacement time, Place was vocally opposed to HB 11. The Pennsylvania Department of Environmental Protection projects that carbon dioxide emissions from the electricity sector will increase partially because of nuclear power plant closures and replacement by natural gas.

Nuclear power generation, however, does have negative environmental consequences because of its extractive practices, which include uranium mining and enrichment and utilization of uranium-235, and because of the ongoing national problem of storing and disposing of radioactive waste. Such activities have historically caused inequitable harm to vulnerable communities.[14] Additionally, regulatory reliance on quantitative risk analysis for predicting potential accident scenarios and other possible consequences of nuclear operations raise questions about reactors being safe enough.[15]

TMI Unit 1, shown in figure 4 before the 2019 closure, is currently being defueled and placed in a safe storage condition. In its post-shutdown report, Exelon states that the potential environmental impacts of TMI's Unit 1 decommissioning, including on water quality of the Susquehanna River, air quality, and aquatic ecology, are expected to be small. On-site independent spent-fuel storage installations, however, do hold high-level radioactive waste, given the federal government's failure to provide an option for permanent disposal, so their environmental legacy remains a concern to state officials. The Pennsylvania Department of Environmental Protection will be closely monitoring the site throughout the decommissioning process.

Nuclear at a crossroads

The closure of TMI Unit 1 in 2019 was accelerated by fracking and expanded natural-gas production in Pennsylvania over the past decade; the lack of state or regional subsidies to nuclear power plants for generating "clean," or at least carbon-free, energy under the AEPS; and the absence of a mechanism to reward nuclear power for its 24-7 baseload reliability and resiliency. Additional financial support might have made all the difference, as Exelon suggested in 2017. But for some grassroots organizations, the situation appeared as an unnecessary bailout for a highly profitable energy corporation playing power politics. Despite efforts to galvanize support for HB 11 by some legislators and labor unions, many stakeholders had no strong opinion either way on TMI Unit 1's closure.

The narrow calculus of energy prices on the regional market may benefit ratepayers in the short term, but it also obscures disruptions to local residents. Speaking strictly in financial terms often fails to capture the environmental, labor, community, and political costs of shuttering a nuclear plant. In TMI's case, the cause for Unit 1's closure was primarily market driven, according to Exelon, but examining arguments for keeping it open has uncovered potential unintended consequences of the permanent shutdown. Federal interventions such as the recently established Department of Energy Civil Nuclear Credit Program may help alleviate nuclear power plants' financial difficulties by addressing inequities in state-level energy-market structures. Such policies will be imperative for the industry's long-term economic viability.

How the various and often hidden costs are weighed against one another is a crucial conversation for navigating a fair and just energy transition and for maintaining the current fleet of nuclear power plants. Doing so will require a regionally focused discussion of nuclear energy production and a broadened cost-benefit analysis from regional transmission organizations, state and federal legislators, and citizens. The analysis should include a conversation about what regional well-being is and how nuclear energy might sustain it.

The opinions stated in this article are the authors' alone and should not be attributed to any commercial, government, or academic entity. Hannah Pell began employment with EnergySolutions after this article was completed but before it was published.

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NOREEN GRICE

This tactile image of the Milky Way is one of 19 such figures in *Touch the Stars* depicting celestial bodies and astronomical phenomena.

The universe at your fingertips

Touch the Stars

Noreen Grice; ill. Irma Goldberg and Shirley Keller
National Braille Press, 2019 (5th ed.). $35.00

"Wow! That's way over my head," my mother's coworker said to me after I gleefully explained galaxies and black holes to her. I wasn't in college for astronomy (yet). I wasn't even in high school—that would come much later. I was 11 and had just finished an earlier edition of Noreen Grice's *Touch the Stars*, an introductory book about astronomy written in braille and large print specifically for the blind. I was rereading my favorite parts and trying to share the wonders of our universe with whoever would listen to me.

When I finally got to college and took an entry-level astronomy course, *Touch the Stars* was still helpful, although by that point I had practically memorized its contents. The book's tactile illustrations, which were created by Irma Goldberg and Shirley Keller, depicted many of the topics covered in class, such as lunar phases, eclipses, planetary motion, and scale. That meant fewer images needed to be verbally described to me.

Touch the Stars has been a constant companion throughout my career in astronomy, and it is now in its fifth edition. The updated text includes references to more recent space probes and rovers such as *New Horizons* and *Curiosity*. The diagrams depicting lunar phases and eclipses are still useful to me: As recently as the past academic quarter, one of them was an invaluable help when I tutored an astronomy student who had trouble understanding the phases of the Moon.

Indeed, one of the book's many strengths is the quantity and quality of its tactile graphics: They are superb and hold up over time. *Touch the Stars* and Grice's other books on astronomy, which include *Touch the Sun: A NASA Braille Book* (2005) and *Touch the Universe: A NASA Braille Book of Astronomy* (2002), are some of the few books with tactile graphics that are intended for the general public. Even university-level blind students who are struggling to obtain braille textbooks will find *Touch the Stars* a great place to start. It also includes descriptions of how to navigate the images, which is great for young readers discovering tactile diagrams or for readers new to braille.

The descriptions of the illustrations also offer something unique: They make distinctions between conventions used in the book and observations of the sky. The most obvious example of that occurs when Grice describes constellations. The book helpfully explains that there are lines in the book, but no lines in the sky. To a blind reader without another frame of reference, that tidbit is crucial for understanding how observations differ from theory.

Another example occurs when Grice discusses a picture of a meteor shower: The description states that meteors may streak across the sky at a rate of one per minute, rather than the several per minute depicted in the drawing. A pocket in the back contains print versions of the included graphics so that all teachers can easily work with blind students.

Touch the Stars does a good job of covering the breadth of topics typically mentioned in a basic astronomy course. It also throws in some extras that cater specifically to blind readers, such as a description of how the sky looks on clear and cloudy days and nights. The book concludes with a brief history of how humans came to know our place in the universe. A line that captivated my imagination as a child still makes me smile now: "Numbers in space get very big very quickly."

Rereading the book after my experiences with the more quantitative side of astrophysics was also enlightening. I was particularly struck by the foreword by Kent Cullers, who writes that the book "whets the appetite for real science." It certainly did for me, as did Cullers's personal story: He is a blind scientist who made a career in astronomy. His example convinced me that I too could work in the space sciences.

Although the book was written for readers as young as 10 years old, it can also be enjoyed by college students and adults. Younger readers will appreciate that when a scientist, spacecraft, or scientific word is mentioned for the first time, it is underlined and, in the latter case, defined. With its myriad of tactile graphics—there are 19 figures in all, some with multiple panels—*Touch the Stars* throws open the doors of the universe to blind people. Readers who are especially intrigued by specific topics will find ample jumping-off points for further exploration.

Grice's book got me "touching" the stars all those years ago and started my journey in astronomy. I have no doubt that the new edition will do the same for many other students.

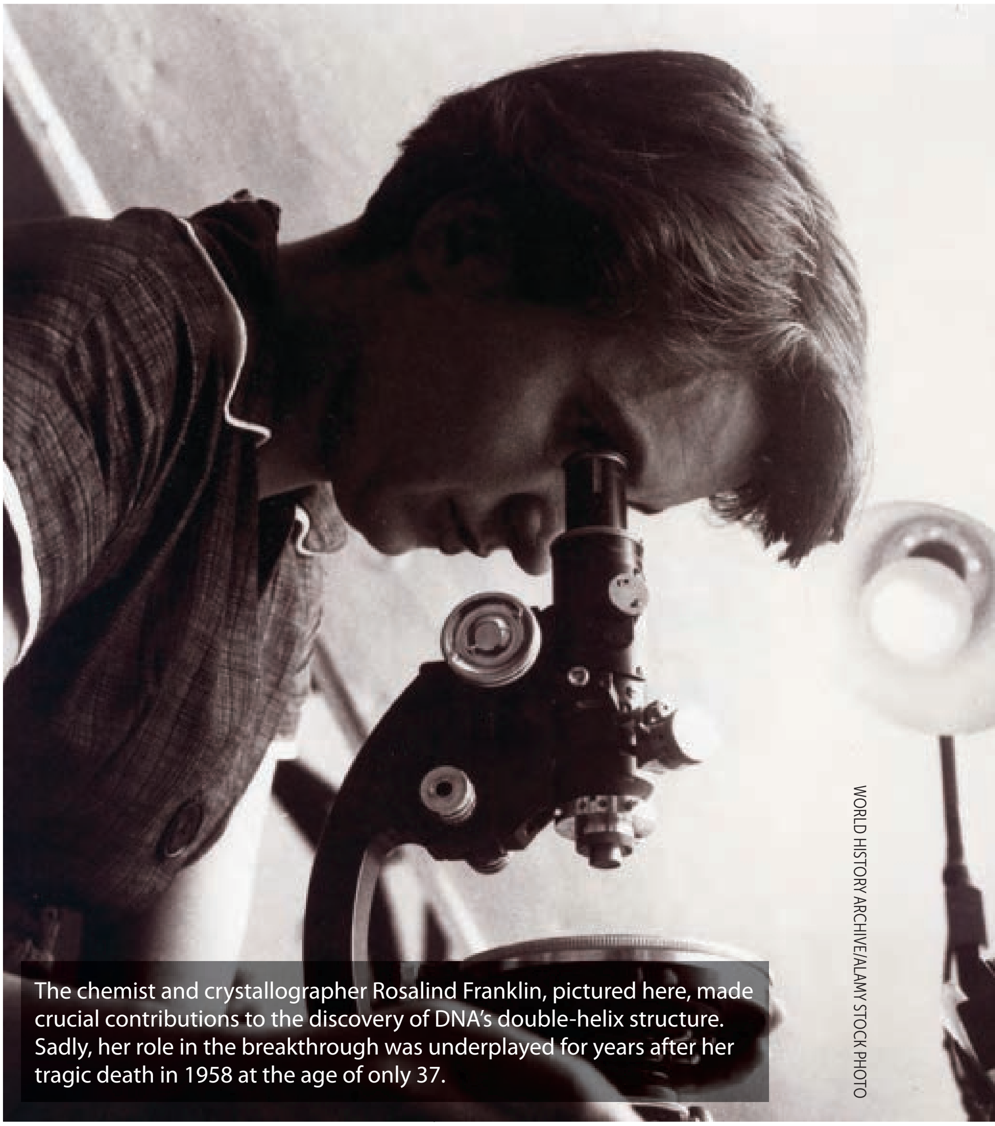
Chelsea Cook
University of Denver
Denver, Colorado

Constructing DNA, once again

James Watson and Francis Crick's discovery of the structure of DNA in 1953 is one of the most famous episodes in the history of biology. The story became notorious early on when Watson published his 1968 memoir *The Double Helix: A Personal Account of the Discovery of the Structure of DNA*. In that book, Watson famously insulted not only Crick but Rosalind Franklin, the scientist whose crucial x-ray image of DNA was shown to the two men without her permission. Tragically, Franklin died not long after that incident, which meant that she was ineligible for the Nobel Prize in Physiology or Medicine awarded to Watson, Crick, and Maurice Wilkins in 1962.

DNA is well known not only because drama surrounded the discovery of its structure but because its sequence of nucleotides encodes genetic information in all organisms. Moreover, its structure suggests its mechanism of replication, which ensures that its information content is passed along to future generations. But DNA is, in fact, a somewhat monotonous macromolecule: Regardless of the specific nucleotide sequence or organismal source, all DNA molecules are practically chemically identical.

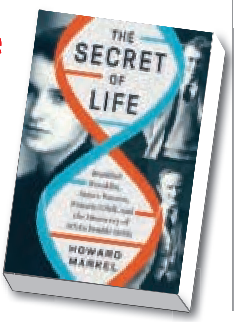
That property was exploited in the last part of the 20th century, when biologists devised a standard set of procedures to manipulate DNA and express foreign genes in bacteria and other organisms, which gave rise to the biotech industry. That industry fueled the mythologization of DNA as the alleged "secret of life" (a phrase that was first used to describe DNA in *The Double Helix*).



The chemist and crystallographer Rosalind Franklin, pictured here, made crucial contributions to the discovery of DNA's double-helix structure. Sadly, her role in the breakthrough was underplayed for years after her tragic death in 1958 at the age of only 37.

WORLD HISTORY ARCHIVE/ALAMY STOCK PHOTO

The Secret of Life
Rosalind Franklin, James Watson, Francis Crick, and the Discovery of DNA's Double Helix
Howard Markel
W. W. Norton, 2021. $30.00



The image of its double helix is frequently invoked to lend an air of cutting-edge science to consumer products, among other things: It was even used as the body of the seahorse in the modernized logo of the venerable Marine Biological Laboratory in Woods Hole, Massachusetts.

The Secret of Life is also the title of a new book by Howard Markel, a well-known historian of medicine. At more than 400 pages, the book is long but readable, and it retells the story of DNA from Crick's appearance as an aging graduate student at the Cavendish Laboratory at Cambridge University—where he met Watson—to the awarding of the 1962 Nobel Prize to Watson, Crick, and Wilkins. Considerable space is spent discussing the misogyny Franklin faced at Cambridge and King's College London, which were both prototypical old boys' clubs, and from the international scientific community.

One of Markel's goals is to make sure that Franklin's important contributions are acknowledged to be as significant as those of such players as Watson, Crick, Wilkins, and the physical chemist Linus Pauling. Markel also mentions John Randall, Franklin's boss, because of his role in the conflicts between the scientists looking for the structure of DNA. Although the details are still fuzzy, Randall apparently assigned Franklin to the DNA project without realizing that Wilkins, who was friendly with Crick, was still working on it. That created tension in the laboratory, which ultimately sidelined Franklin.

But do we need another book telling the DNA story? Watson's memoir is self-centered but still informative. Horace Freeland Judson's *The Eighth Day of Creation: Makers of the Revolution in Biology* (1979) provides a more detailed—although somewhat hagiographic—account based on extensive interviews with the main scientists involved. Robert Olby's slightly earlier *The Path to the Double Helix: The Discovery of DNA* (rev. ed., 1994) is a valuable scholarly work suitable for students interested in a scientific history of the discoveries. And most recently, Brenda Maddox's *Rosalind Franklin: The Dark Lady of DNA* (2002) earned well-deserved praise for righting the wrongs in Watson's depiction of Franklin and placing her firmly in the pantheon of scientists who were crucial to discovering DNA's structure.

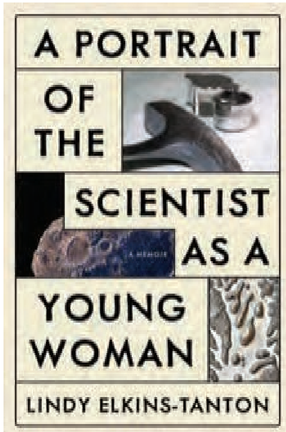
Nevertheless, as Markel realized when teaching his medical students before writing *The Secret of Life*, younger generations do not know or understand what happened almost 70 years ago now. Markel relied heavily on the earlier books on those subjects, but he also dipped into Judson's archives for more information and personally interviewed Watson and others. His book is thorough, but it does not provide any new insights, and it is somewhat disappointing that he does nothing to puncture the most egregious exaggerations of the DNA myth, such as claims that the human genome sequence is the "blueprint for life." Nevertheless, he provides a refreshed look at how it all started. It will be a compelling read for not only his medical students but many others.

Karl S. Matlin
University of Chicago
Chicago, Illinois

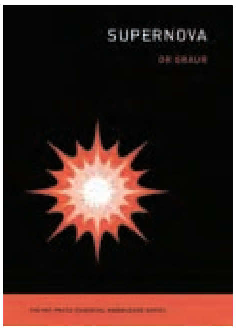
NEW BOOKS & MEDIA

A Portrait of the Scientist as a Young Woman

Lindy Elkins-Tanton
William Morrow, 2022. $29.99



In this deeply personal memoir, Lindy Elkins-Tanton recounts her tortuous path to becoming a scientist and principal investigator of a NASA deep-space mission. As a female student at MIT in the 1980s, she endured rampant sexism and battled depression and impostor syndrome. After attaining a master's in geochemistry, she put her academic career on hold for a decade as she married, had a son, and got divorced. Nevertheless, Elkins-Tanton would go on to not only attain a PhD and a professorship but also become one of the few women to lead a NASA mission. With *Psyche* poised to launch in August 2022, Elkins-Tanton's well-timed memoir alternates between the trials and tribulations of getting a NASA mission off the ground and her own storied experience as a woman in a traditionally male field. —CC



Supernova

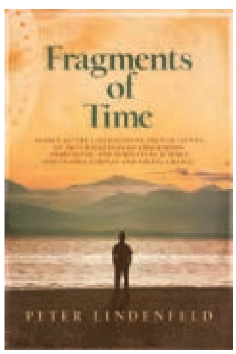
Or Graur
MIT Press, 2022. $16.95 (paper)

Supernovae—the explosions of stars—are some of the most luminous astronomical phenomena in the universe: According to contemporary Chinese, Islamic, and European records, the supernova of 1006 CE could be seen in broad daylight for several weeks. Supernovae also create and disperse many of the heavier elements that we use in our daily lives. In *Supernova*, a book in the MIT Press Essential Knowledge series, the astrophysicist Or Graur provides readers with a concise description of the current state of supernova science along with the field's history. As he puts it, "We owe our existence to supernovae." —RD

Fragments of Time

From a Secure Childhood in Prewar Vienna to the Challenges of Emigration, Adaptation, and Pursuits in Science and in Educational and Social Change

Peter Lindenfeld
Random Walk Books, 2021. $32.00



It's well known that Albert Einstein found refuge from Nazism in the US at the Institute for Advanced Study in Princeton, New Jersey, but Einstein's story was unique: Most Jews trying to flee Europe in the 1930s were not afforded the same luxurious welcome he received. Peter Lindenfeld's new memoir *Fragments of Time* is a powerful reminder of that fact. An eventual physicist, Lindenfeld was the child of a middle-class Viennese Jewish family that fled Austria after the Nazi Anschluss in March 1938. He and his mother eventually settled in Canada, but only after stops in Italy, Switzerland, and England. His father was not as lucky. Interned in the Buchenwald concentration camp for several months, he eventually escaped to England, but he was interned there as an "enemy alien" and sent to Australia. He only rejoined Peter in Canada in 1942. More a personal memoir than a scientific autobiography, *Fragments of Time* eloquently documents a period of 20th-century history that is rapidly receding from living memory. —RD

Last Exit: Space

Rudolph Herzog
Discovery+, 2022

In this new documentary, the director Rudolph Herzog confronts the techno-utopian fantasies of billionaires like Elon Musk and Jeff Bezos, who assert that humanity has an existential need to settle Mars, outer space, and exoplanets. Narrated by Rudolph's father, Werner, *Last Exit: Space* points out that space is an airless vacuum and that even Mars is a bleak, uninhabitable wasteland. The film isn't all critical: The Herzogs also profile the father–daughter team of Carsten Olsen and Anna Olsen, who are part of the Copenhagen Suborbitals, a hobbyist spaceflight program, and who idealistically hope to be the first amateur astronauts. But it's refreshing to see a healthy bucket of cold water thrown on the delusions of Musk, Bezos, and their ilk. As the space anthropologist Taylor Genovese remarks, life on a Martian colony would be akin to living in an "Amazon fulfillment center." —RD

Physics Girl

Dianna Cowern, host
YouTube, 2011–

It's no coincidence that Dianna Cowern's Physics Girl is one of the most-followed YouTube channels devoted to the field: Her enthusiasm for physics is infectious. One series of videos from summer 2021 follows Cowern as she road-trips across California in a car powered by a hydrogen fuel cell and explores the future of renewable energy. (The vehicle was provided by Toyota as part of a sponsorship.) During the trip, she looks at such topics as energy storage, solar-panel technology, and the changes that need to be made to the power grid to adapt it for the green-energy future. Another series reviews introductory physics and helps students prepare for AP Physics exams. Accessible and informative, the channel provides a highly engaging introduction to the discipline. —RD PT

NEW PRODUCTS

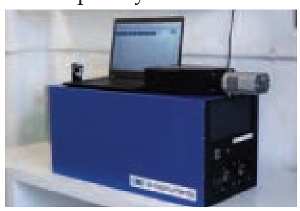
Focus on test, measurement, quantum metrology, and analytical equipment

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

System for deep-UV Raman spectroscopy

ODIN is a deep-UV resonant Raman instrument developed by IS-Instruments and Toptica for measuring biopharmaceutical products without degrading the sample. The system combines Toptica's newly developed TopWave 229 solid-state diode laser and a spatial heterodyne spectrometer into a single instrument with an all-reflective backscatter Raman collection probe. The inclusion of a dynamic sample positioning stage mitigates sample damage caused by extended laser exposure. According to the company, the instrument acquires spectra significantly more quickly than do other existing systems, and it is stable, reliable, and easy to use. Its compact size and low cost make deep-UV resonant Raman studies accessible to facilities with limited space and budgets. The company claims the technique could measure substances that other spectroscopic methods cannot. ***Toptica Photonics Inc****, 5847 County Rd 41, Farmington, NY 14425, www.toptica.com*



Self-contained Fizeau wavemeter

A compact wavelength-measurement device based on Fizeau interferometers, the FZW from MOGLabs provides reliably accurate measurements over a wide range of wavelengths (370–1120 nm) without recalibration. Its small, self-contained form factor makes the FZW easy to use for analysis: The measurement and calculation are performed on the device and the result displayed on the screen in less than 2 s, with no need for a host computer. Two-, four-, and eight-channel fiber switchers use MEMS technology for essentially infinite lifetime and rapid switching. Each channel has its own 16-bit digital-to-analog converter for laser frequency control. A built-in proportional-integral-derivative controller provides for laser-frequency stabilization. ***MOGLabs USA LLC****, 419 14th St, Huntingdon, PA 16652, www.moglabs.com*

Spectroradiometer for fieldwork

Spectral Evolution has launched a high-sensitivity spectroradiometer, which operates in the UV, visible, and near-IR ranges, specifically for remote-sensing applications. According to the company, the NaturaSpec spectroradiometer brings the high spectral resolution of laboratory instruments to field measurements. It lets users collect data *in situ* without sample preparation and offers the best signal-to-noise performance in field instruments currently on the market. To ensure robustness and provide excellent stability, solid-state photodiode-array detectors with no moving optical parts come standard on a rugged chassis. Thermoelectrically cooled photodiode array detectors deliver high sensitivity and spectral resolution in the IR range. The company's DARWin SP data-acquisition software optimizes spectral scans. Dark-current correction is automatically applied to every scan, and each detector is independently exposed to the signal at the optimum integration time. No tedious manual optimization is needed to ensure reliably repeatable data. ***Spectral Evolution****, 26 Parkridge Rd, Ste 104, Haverhill, MA 01835, https://spectralevolution.com*

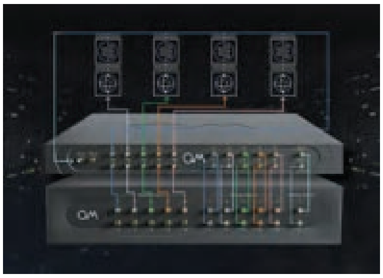
Digital bit-error performance analysis

Keysight has extended its M8000 series, a highly integrated bit-error-ratio (BER) test solution for physical layer characterization, validation, and compliance testing. The series is suitable for users seeking insight into the performance margins of high-speed digital devices. The new M8050A tester provides application-specific integrated circuit technology to help optimize designs to instrument requirements. According to Keysight, it delivers previously unachieved signal integrity in validating next-generation chip deployments of up to 120 GBd for the 1.6 Tb/s (trillion bits per second) market. In combination with the M8050A, the company's Infiniium 80 GHz UXR oscilloscope can be used as an acquisition-based error analyzer to provide a comprehensive BER tester. It supports not only non-return-to-zero and pulse-amplitude modulation (PAM) 4 but also the PAM 6 or PAM 8 formats likely required in the 1.6 Tb/s environment. ***Keysight Technologies Inc****, 1400 Fountaingrove Pkwy, Santa Rosa, CA 95403-1738, www.keysight.com*

Impedance measurements

Rohde & Schwarz (R&S) has introduced a new family of high-performance LCR meters, which measure the inductance, capacitance, and resistance of an electronic component. The R&S LCX LCR meters extend the frequency range of impedance measurements provided by the company's test equipment to cover AC components operating from 4 Hz to 10 MHz. The meters serve all established impedance measurements plus specialized measurements for selected component types. They provide the high accuracy required in R&D and the high speed needed in production testing and quality assurance. The R&S LCX family launches with two models: The R&S LCX100 covers a frequency range from 4 Hz to 300 kHz, and the R&S LCX200 a basic frequency range from 4 Hz to 500 kHz with options to cover frequencies up to 10 MHz. On both models, up to four measurements can be selected and plotted versus time, with minimum and maximum values included in the display for at-a-glance pass-fail analysis. ***Rohde & Schwarz GmbH & Co KG***, *Muehldorfstrasse 15, 81671 Munich, Germany, www.rohde-schwarz.com*

Frequency module for quantum computing



Quantum Machines has announced its Octave all-in-one RF up-conversion and down-conversion module. Integrated with the company's OPX Quantum Orchestration Platform, Octave enables R&D users to execute the highly complex algorithms needed to address advanced challenges in quantum computing. To benefit from the high level of quantum orchestration, many researchers must spend considerable time on RF engineering, setting up and calibrating components such as oscillators and intermediate-frequency mixers. As the system size scales, that can lead to systems that are bulky and difficult to calibrate. By continuous automatic self-calibration and in a fraction of a second, Octave removes the need for complex engineering. The compact, rack-mountable module with built-in local oscillator sources ensures that the system can keep pace with user needs as the numbers of qubits continue to scale. ***Quantum Machines***, *Yigal Alon St 126, Tel Aviv-Yafo, Israel, www.quantum-machines.co*

High-speed spectrometer

According to Ocean Insight, its Ocean SR2 spectrometer provides high-speed spectral acquisition and delivers a high signal-to-noise ratio (SNR) of 380:1. Its applications include laser characterization, plasma monitoring, and absorbance measurements that benefit from its high SNR. The Ocean SR2's combination of speed—integration times to 10 µs—and SNR provides application versatility. Preconfigured models are available with entrance slits in widths of 5 µm to 200 µm (full width at half maximum), which provide users with a range of optical-resolution and signal-throughput options. The Ocean SR2 spectrometer is compact, highly configurable, and versatile, and offers excellent thermal stability. The included OceanDirect cross-platform software-developers' kit with an application programming interface lets users optimize spectrometer performance and access critical data for analysis. ***Ocean Insight Inc***, *8060 Bryan Dairy Rd, Largo, FL 33777, www.oceaninsight.com*

Roundness metrology software

Digital Surf and Taylor Hobson have released an updated version of Metrology 4.0 software with the manufacturer's new Talyrond 500 PRO instrument for roundness metrology. The surface-analysis features of Digital Surf's Mountains platform have been integrated into the updated software, which allows both measurement and analysis to be performed on Taylor Hobson's roundness instrument series. Because users can better control the measurement process and directly create and export analysis documents, a more fluid and optimized workflow is achieved. Specific features include desktop publishing and high-quality 3D visualizations of cylinders and flatness scans. Thanks to the multi-instrument compatibility of the Metrology 4.0 software, various measurement types, such as roundness, flatness, cylindricity, surface finish, and contour, can be represented on the same document. ***Digital Surf***, *16 rue Lavoisier, 25000 Besançon, France, www.digitalsurf.com* PT

Gene Dresselhaus

A man ahead of his time, Gene Dresselhaus excelled as a theoretical physicist, student mentor, husband, and father; he was the embodiment of the consummate human being for the 21st century.

Gene was born on 9 November 1929 in the Panama Canal Zone, a former US territory. He grew up in California and studied physics at the University of California, Berkeley, where he earned both his bachelor's degree in 1951 and his PhD in 1955. His PhD adviser was Charles Kittel, and his thesis was titled "Electronic energy bands in semiconductors with cubic crystal structure." Gene was a postdoctoral fellow at the University of Chicago in 1955–56. There he met his beloved wife, Mildred. They got married in 1958 and moved to Cornell University, where Gene started his junior faculty position and Millie did a postdoc.

In 1960 Gene gave up his professorship to search for a single solution to the "two-body" problem, and the couple moved to work together at the MIT Lincoln Laboratory. In 1967 Millie joined the MIT faculty, and in 1976 Gene accepted a research appointment at the Francis Bitter National Magnet Laboratory, also at MIT. They both worked at MIT until their last days (Millie died in 2017).

Gene is best known for his seminal contribution on spin–orbit coupling in crystals, known later as the Dresselhaus effect. He based his analysis on the effective mass theory for explaining the cyclotron resonance in semiconductors. His work on the spin–orbit interactions that occur in the absence of an inversion center made Gene a go-to authority in semiconductor physics. His single-authored paper titled "Spin–orbit coupling effects in zinc blende structures," published in *Physical Review* in 1955, has been cited more than 4000 times, and it paved the way for the determination of the electronic structure of semiconductors.

That was just the shining starting point of Gene's brilliant scientific career; his nonstop research activities continued for nearly 60 years. His scholarly output included 559 peer-reviewed journal papers—with more than 60 000 cumulative citations, according to Scopus—and eight books, among them *Science of Fullerenes and Carbon Nanotubes* (1996), *Physical Properties of Carbon Nanotubes* (1998), *Raman Spectroscopy in Graphene Related Systems* (2011), and *Group Theory: Application to the Physics of Condensed Matter* (2008).

Gene and Emmanuel Rashba were jointly awarded the American Physical Society's 2022 Oliver E. Buckley Condensed Matter Physics Prize for their "pioneering research on spin–orbit coupling in crystals, particularly the foundational discovery of chiral spin–orbit interactions, which continue to enable new developments in spin transport and topological materials." The prize is considered the most prestigious award in the field, and in 2008 Millie received the same prize for her work on the electronic properties of materials.

For most of their lives, Gene and Millie worked close to each other on campus. Gene contributed, in some sense unofficially but in all senses unequivocally, to the research group of his wife. Gene didn't travel abroad much and would support the group while Millie was traveling tirelessly around the globe. At meetings of the group, known as mgm, everyone would have lunch together and engage in lively discussions. Graduate students and researchers came to the mgm group from all over the world, and it was inspiring watching Gene always treating young people from many countries as equals and engaging them with his unique humor. Gene understood exactly what we said in our poor English and helped us flesh out the most important points of our research data, and he was always available to give us advice and answer any questions, whether work or nonwork related.


Gene Dresselhaus

Everyone who shared their time will lovingly remember seeing Millie and Gene leaving from the end room on the third floor of MIT Building 13 to the elevator at 5:00pm after every working day. Gene would have to urge Millie to keep moving through the corridor as many students and collaborators tried to talk to her about their work. Another of our vivid memories is working with Gene on weekend mornings, then joining him to have a bagel for lunch and hike to the suburbs to stay in good health.

It is our impression that the great progress of research in the mgm group, despite the various cultures and values, was because of Gene´s ability to attract students with his kindness and humor and Millie´s oddly powerful ability to promote research. Gene left us on 29 September 2021, at age 91, and we are grateful to him for his guidance in our research and impact on our lives.

Ado Jorio
Federal University of Minas Gerais
Belo Horizonte, Brazil

Riichiro Saito
Tohoku University
Sendai, Japan

Jing Kong
Massachusetts Institute of Technology
Cambridge

George Secor Stranahan

Born in Toledo, Ohio, on 5 November 1931, George Secor Stranahan died in Denver, Colorado, on 20 May 2021 of a stroke and complications following heart surgery. George was a person of many talents and interests—he was a physicist, educator, photographer, entrepreneur, and philanthropist—who had a major impact on theoretical physics through his role in the founding and development of the Aspen Center for Physics (ACP).

George had grown up with a strong interest in science. He majored in physics as an undergraduate at Caltech and received his degree in 1953. After service in the US Army during the Korean War, he enrolled at the Carnegie Institute of Technology (now Carnegie Mellon University) to pursue a PhD. He spent his summers in the late 1950s in Aspen. It was a splendid setting, with many outdoor activities for his free time. But in 1959, while working on his dissertation research, George realized, as he put it, "I cannot do physics alone. I have to have someone to talk to."

That led, through several steps, to a collaboration in 1961 among George, Michael Cohen at the University of Pennsylvania, and Robert Craig, executive director of the well-established Aspen Institute for Humanistic Studies (AIHS)—with much support from Michel Baranger at Carnegie Tech—to establish a summer research institute in Aspen under the auspices of the AIHS. George, one of the heirs to the Champion Spark Plug Company, raised funds locally, underwrote the construction of a first building, and covered initial operating expenses not covered by a grant from the Office of Naval Research and corporate and foundation contributions. As George had expected, the Aspen location made it easy to attract outstanding physicists to the ACP's informal program beginning with its first summer in 1962, with important collaborations forming in the early years on topics in high-energy particle physics, formal field theory, current algebras, and the physics of neutron stars.

George made sure the visiting physicists experienced the attractions of the area, suggesting weekend hikes in the mountains, organizing family outings and picnics in remote locations, and cowriting (with me) a guide to the local mountains. He continued to lead and support the ACP through its incorporation as an independent nonprofit in 1968. He was its first president and chair of the board of trustees.

That same year, at the request of Robert Wilson, director of the National Accelerator Laboratory (now Fermilab), George underwrote the construction of a second "temporary" building—it was used until 1995—to accommodate people working on the lab's design study for its experimental areas. Wilson had visited the previous summer and been impressed with the ACP's atmosphere that promoted lively interactions and collaborations without the many distractions at home institutions. The ACP took over the new building in 1970 and was able to expand its activities over the years, from 42 participants the first summer to about 1000 a year in its current summer and winter programs.

George phased out his active involvement with the ACP after 1972 but continued to represent it in external interactions for many years. The center's influence on the progress of theoretical physics has been recognized by the American Physical Society through its designation of the ACP as a Historic Site. George left a lasting mark on physics through his work with the ACP.

George completed his PhD in radiative neutron–proton capture in 1961 with Richard Cutkosky, had a postdoctoral appointment at Purdue University, and then joined the faculty at Michigan State University in 1965, where he received tenure. His other interests called, however, and unsatisfied with university life, he resigned in 1972 and moved permanently to the Aspen area to pursue those interests. He was a rancher for almost two decades, raising prize-winning Limousin cattle while engaging in numerous other activities.

Acting on his long-standing interest in improving lower-level education, George was instrumental in the founding of the Aspen Community School in 1970 and later the Aspen Science Center. The latter sponsors science programs for children in conjunction with the ACP and promotes lifelong learning about science.

George was an accomplished photographer for many decades. "As I look at my photos now," he said in 2009, "I think


George Secor Stranahan
BERNICE DURAND

that perhaps they are the serious work of my life." Two books of his black-and-white photographs (and musings) were published; one, *Phlogs: Journey to the Heart of the Human Predicament* (2009), received a Colorado Book Award.

George was a natural entrepreneur. He started the noted Woody Creek Tavern, often associated with his friend the gonzo journalist Hunter Thompson, and later started the Flying Dog Brewery and Stranahan's Colorado Whiskey. (The nationally prominent craft brewery and his Flying Dog Ranch were named after a painting he saw in Rawalpindi, Pakistan, after an aborted trek to K2, the world's second-highest mountain.) George's philanthropic and charitable activities, including the founding of several community foundations, are too numerous to mention. His impact was truly large in many areas.

Loyal Durand
Aspen, Colorado PT

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David Mermin has collected his 1988–2014 PHYSICS TODAY essays, with further remarks, in *Why Quark Rhymes with Pork, and Other Scientific Diversions* (2016). Much biographical information is cited in its index.

There is no quantum measurement problem

N. David Mermin

The idea that the collapse of a quantum state is a physical process stems from a misunderstanding of probability and the role it plays in quantum mechanics.

There are three types of quantum physicists: (1) those who think quantum mechanics is defaced by a so-called measurement problem; (2) those who think, as I do, that there is no measurement problem; and (3) those who think the issue is not worth serious thought. You can find the diverse views of 17 physicists and philosophers from the first two groups in chapter 7 of Maximilian Schlosshauer's *Elegance and Enigma.*

Most people in all three groups would agree on the following: Quantum mechanics describes a physical system entirely in terms of states. A state is a compendium of probabilities of all possible answers to all possible questions one can ask of the system. Quantum mechanics is inherently statistical. There is no deeper underlying theory that gives a fuller description.

The state assigned to a system can change in time in two ways. If no question is asked of the system, then its state evolves in time deterministically: continuously and according to fixed rules. If a question is asked of the system—called making a measurement—then when the question is answered, the state changes discontinuously into a state that depends both on the state just before the question was asked and on the particular answer the system gives to that question. The second process is called the collapse of the state. Collapse is generally abrupt, discontinuous, and stochastic.

A physical system together with another physical system that carries out a particular measurement—an apparatus—can be treated by quantum mechanics as a single composite system. If the composite system is not questioned, then quantum mechanics gives a deterministic time evolution to the state assigned to it. If the entire composite system is questioned, however, the state assigned to the composite system gives probabilities that correlate the possible answers given by the state assigned to the original system with states assigned to the apparatus that indicate those possible answers. The associated probabilities are just those that quantum mechanics would give for the original system alone. So as far as probabilities are concerned, it makes no difference whether one applies quantum mechanics to the original system alone or to the composite original system + apparatus.

Many physicists in group 2 would add the following: There are no consequences of a quantum state assignment other than all the probabilities it gives rise to. While many (perhaps most) physicists view probabilities as objective features of the world, most probabilists and statisticians do not. As the celebrated probabilist Bruno de Finetti put it, "The abandonment of superstitious beliefs about the existence of Phlogiston, the Cosmic Ether, Absolute Space and Time, . . . , or Fairies and Witches, was an essential step along the road to scientific thinking. Probability, too, if regarded as something endowed with some kind of objective existence, is no less a misleading misconception, an illusory attempt to exteriorize or materialize our actual probabilistic beliefs."

Physicists who materialize their own probabilistic beliefs must also materialize quantum states, which are nothing more than catalogs of such beliefs. But a physicist who regards probabilities as personal judgments must necessarily view the quantum states he or she assigns as catalogs of his or her own personal judgments. That the quantum state of a system expresses only the belief of the particular physicist who assigns it to the system was emphasized by the theorists Carlton Caves, Christopher Fuchs, and Rüdiger Schack at the turn of the 21st century as being crucial to the interpretation of quantum mechanics.

The quantum measurement problem

The measurement problem stems from the two ways of viewing a measurement: the system alone or the system + apparatus. If the system alone is measured, its state collapses. But the state of the composite system + apparatus does not collapse until the apparatus is examined. Which description is correct? Which is the real state?

The answer from group 2 is that there is no real state of a physical system. What one chooses to regard as the physical system and what state one chooses to assign to it depend on the judgment of the particular physicist who questions the system and who uses quantum mechanics to calculate the probabilities of the answers.

The interplay between continuous and stochastic time evolution is also a feature of ordinary classical probability. When a statistician assigns probabilities to the answers to questions about a system, those probabilities vary in time by rules giving the smooth time evolution of the isolated unquestioned system. But those probabilities also depend on any further information the statistician acquires about the system from any other source. That updating of probabilities is the abrupt and discontinuous part of the classical process. Nobody has ever worried about a classical measurement problem.

ISOLATED EXCERPTS from Niels Bohr can support many diverse views. But a quarter century after publishing my concluding quotation, he wrote that "physics is to be regarded not so much as the study of something *a priori* given, but rather as the development of methods for ordering and surveying human experience." It's the same opinion, and it has the same ambiguity: Is "human experience" individual or collective? (Photograph by A. B. Lagrelius and Westphal, courtesy of the AIP Emilio Segrè Visual Archives, W. F. Meggers Gallery of Nobel Laureates Collection.)

If the entire content of a quantum state is the catalog of probabilities it gives rise to, then each physicist using quantum mechanics is acting as a statistician. The acquisition of further information by that physicist—whether it be through reading the display of an apparatus, or through communication with other physicists, or just through rethinking what that physicist already knows—can lead to an abrupt change in those probabilities and thus to an updating of the quantum state that the physicist uses to represent them. There is no quantum measurement problem.

Physicists in group 1 deal with their measurement problem in a variety of ways: In their otherwise superb quantum mechanics text Lev Landau and Evgeny Lifshitz insist that quantum mechanics is not to be viewed as a conceptual tool used by observers. This leads them to declare that a measurement is an interaction between objects of the quantum and classical types. How to distinguish between the two (which they never explain) is their (unstated) measurement problem.

Others eliminate the physicist from the story by introducing a particular kind of physical noise that interacts significantly only with subsystems that contain a macroscopic number of degrees of freedom. This special noise is designed to provide a physical mechanism for an objective collapse of an objective state. They solve their measurement problem by introducing a new physical process.

Still others remove the personal judgment of each physicist by eliminating collapse entirely. They take quantum states to describe an inconceivably vast multitude of continuously bifurcating universes—the many-worlds interpretation—that contain every possible outcome of every possible measurement.

Such solutions all take quantum states to be objective properties of the physical system they describe and not as catalogs of personal judgments about those physical systems made by each individual user of quantum mechanics.

Keep the scientist in the science

Why does our understanding of scientific laws have to be impersonal? Science is a human activity. Its laws are formulated in human language. As empiricists, most scientists believe that their understanding of the world is based on their own personal experience. Why should I insist that *my* interpretation of science, which *I* use to make sense of the world that *I* experience, should never make any mention of *me*? The existence of a quantum measurement problem, either unsolved or with many incompatible solutions, is powerful evidence that the experience of the scientist does indeed play as important a role in understanding quantum theory as the experience of the statistician plays in understanding ordinary probability theory.

Niels Bohr never mentioned a quantum measurement problem. I conclude with a statement of his that concisely expresses the view that there is no such problem, *provided* both occurrences of "our" are read not as all of us collectively but as each of us individually. I believe that this unacknowledged ambiguity of the first person plural lies behind much of the misunderstanding that still afflicts the interpretation of quantum mechanics.

"In our description of nature the purpose is not to disclose the real essence of the phenomena but only to track down, so far as it is possible, relations between the manifold aspects of our experience."

Additional resources

▶ M. Schlosshauer, ed., *Elegance and Enigma: The Quantum Interviews*, Springer (2011), chap. 7.

▶ B. de Finetti, *Theory of Probability: A Critical Introductory Treatment*, A. Machi, A. Smith, trans., Interscience (1990), p. x.

▶ C. A. Fuchs, R. Schack, "Quantum-Bayesian coherence," *Rev. Mod. Phys.* **85**, 1693 (2013).

▶ N. Bohr, *Atomic Theory and the Description of Nature*, Cambridge U. Press (1934), p. 18.

▶ N. D. Mermin, "Making better sense of quantum mechanics," *Rep. Prog. Phys.* **82**, 012002 (2019).

▶ N. Bohr, *Essays 1958–1962 on Atomic Physics and Human Knowledge*, Ox Bow Press (1987), p. 10. PT

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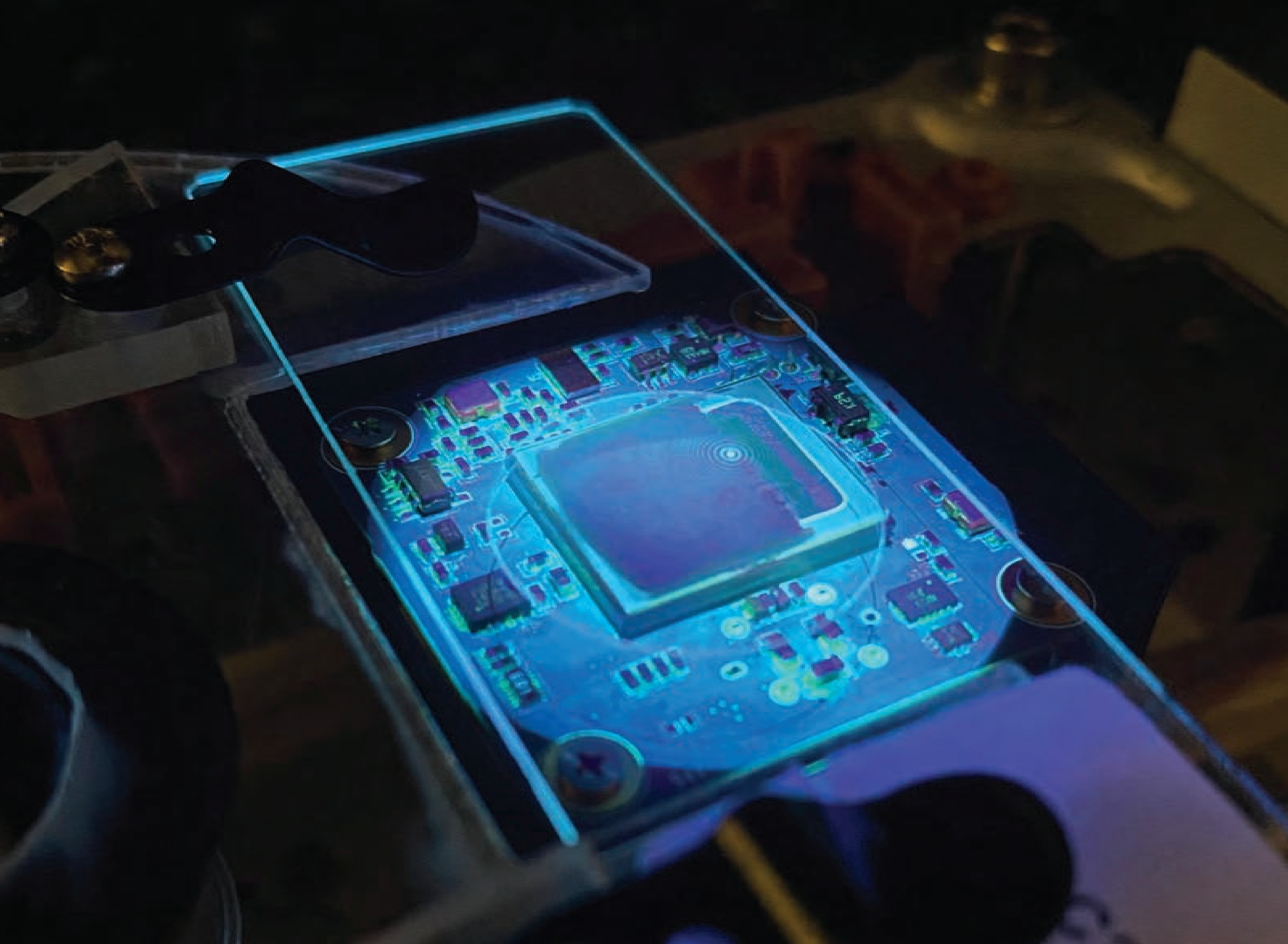

Blu-ray microscope with blood-cell lens

A traditional light microscope can have a large field of view with poor resolution or a small field of view with good resolution but not both. To address that limitation, Guoan Zheng at the University of Connecticut and his colleagues developed a high-resolution computational biolens. They smeared a monolayer of blood cells on top of an image sensor and fixed the cells in place with alcohol. The blood-cell layer redirects light diffracted at a large angle by an object of interest to smaller angles that reach the image sensor. Previously inaccessible high-resolution details can then be acquired using the sensor's pixel array underneath the blood-cell layer. The biolens's field of view is limited only by the size of the silicon chip for the image sensor, which can be as large as 36 mm by 24 mm.

The microscope prototype shown here was built using a modified Blu-ray player, which makes it inexpensive, compact, and portable. Biological samples were affixed atop the transparent rotating disk in the photo, and the blood-coated sensor was mounted on the translation stage of the player. As the disk rotated, the Blu-ray player's 405 nm laser illuminated the samples. The resulting coherent diffraction patterns from the biological samples were recorded by the blood-coated sensor. At the heart of the image-reconstruction process is a lensless coherent-diffraction-imaging algorithm termed rotational ptychography. (For more on ptychography, see the article by Manuel Guizar-Sicairos and Pierre Thibault, Physics Today, September 2021, page 42.) A model of the spinning disk and light diffraction recovers the high-resolution sample image with both intensity and phase information. In a proof of concept, the researchers monitored live bacterial cultures across an entire 35 mm petri dish and resolved individual cells. (S. Jiang et al., *ACS Sens.* **7**, 1058, 2022; photo courtesy of Guoan Zheng.) —AL