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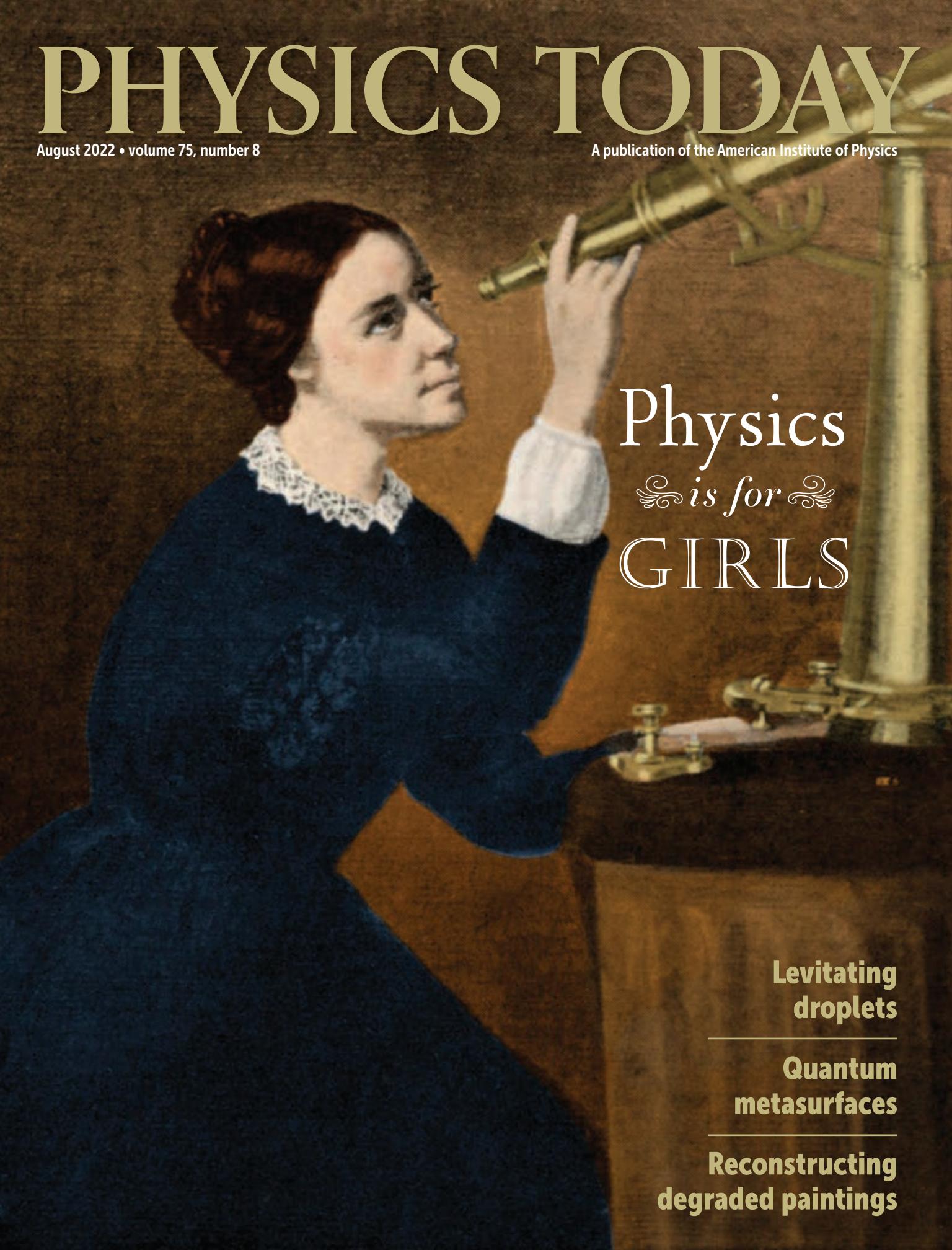
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# PHYSICS TODAY

August 2022 • volume 75, number 8

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Physics  
*is for*  
GIRLS

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Levitating  
droplets

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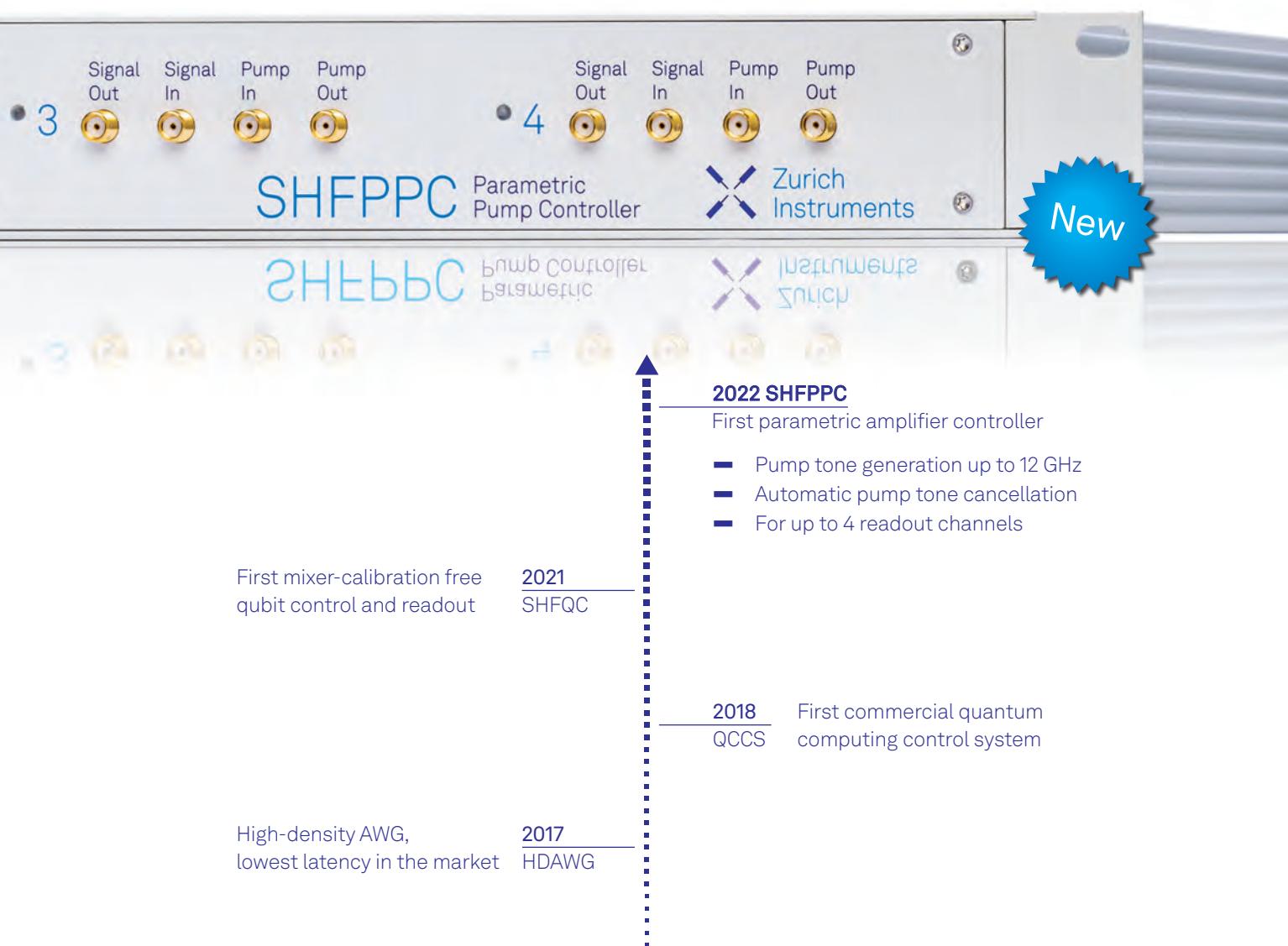
Quantum  
metasurfaces

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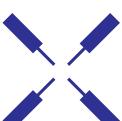
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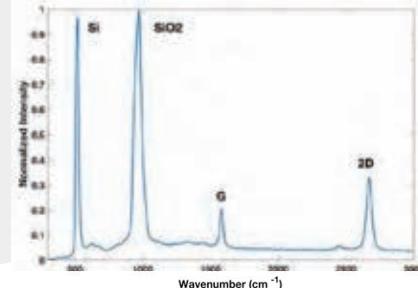
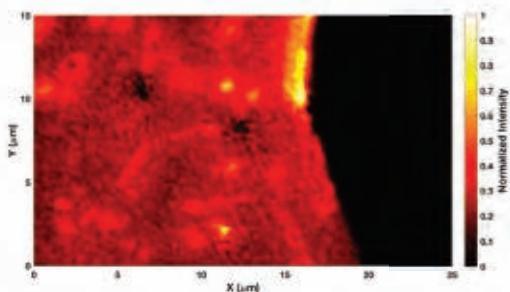
15x15 $\mu$ m $\times$ 2 $\mu$ m @ 4K

### Temperature Range

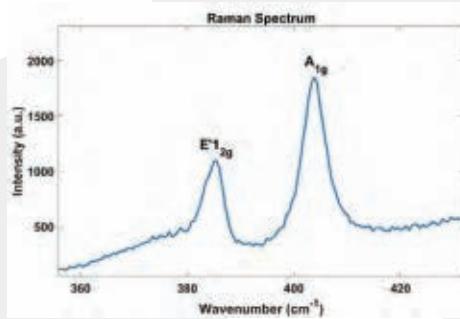
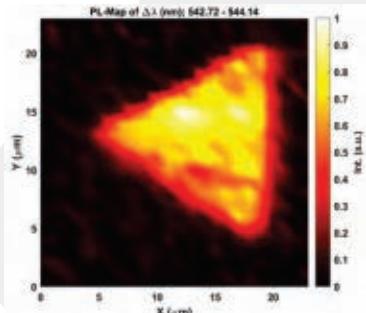
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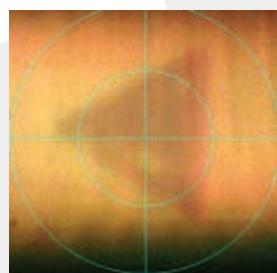
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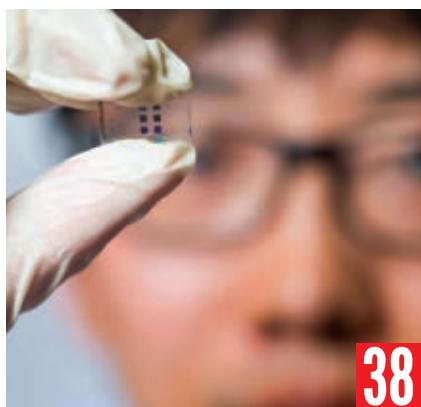
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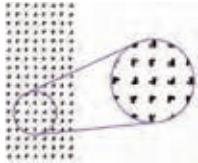
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NATURE 606, 501 (2022)

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Subwavelength planar structures can generate, reshape, and entangle photons in a compact and stable device.

### 46 Einstein would be doubly amazed

Roman Schnabel

Quantum-correlated light embodies all the weirdness of quantum physics. Now it is being used to aid in the observation of another exotic phenomenon: gravitational waves.



**ON THE COVER:** Modern-day educators struggle with the stereotype that physics is an inherently masculine subject. But a look to the past shows that not only was science education widely offered to young women in the 19th-century US—producing such figures as Maria Mitchell, shown here—but natural philosophy, the predecessor subject of physics, was perceived as being more for girls than for boys. To learn more, turn to the article by Joanna Behrman on **page 30**. (Color enhancement of Maria Mitchell portrait, painted by Herminia Dassel, 1851, from Science History Images/Alamy Stock Photo.)

**PHYSICS TODAY** (ISSN 0031-9228, coden PHTOAD) volume 75, number 8. Published monthly by the American Institute of Physics, 1305 Walt Whitman Rd, Suite 110, Melville, NY 11747-4300. Periodicals postage paid at Huntington Station, NY, and at additional mailing offices. POSTMASTER: Send address changes to **PHYSICS TODAY**, American Institute of Physics, 1305 Walt Whitman Rd, Suite 110, Melville, NY 11747-4300. Views expressed in **PHYSICS TODAY** and on its website are those of the authors and not necessarily those of AIP or any of its member societies.



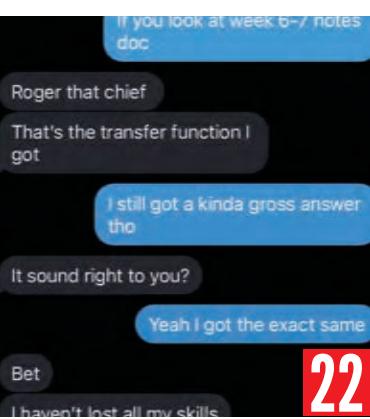
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## Commentary

# The future (budget) of the academic library

Academic librarians are stewards of resources invested for the collective campus good. Responsible stewardship includes serving the institution's mission, meeting the needs of researchers and learners, and anticipating what needs will emerge next.

For more than a decade, I've been exploring the power of futures thinking for driving library strategic planning and decision making.<sup>1</sup> Futures thinking is a framework for considering multiple scenarios for what the future might hold and evaluating those scenarios for likelihood and potential consequences. By considering which futures are possible, librarians can then develop strategies and policies that move toward desirable futures while also, hopefully, avoiding undesirable ones. Futures thinking also offers the opportunity for other library stakeholders—faculty, students, and administrators—to see their roles in ensuring the health of their libraries.

So, what of the current state of academic libraries? Put bluntly, times are hard.

For decades, academic librarians have dealt with the realities of collections budgets that have not grown to match the expanding volume of journals, books, media, databases, and other resources that faculty and students need for research and learning. Many budgets have not even kept pace with inflation.

Pandemic disruptions only intensified the financial pressures that academic libraries already faced. An Ithaka S+R survey of US academic library deans and directors found that by September 2020, 75% of those libraries that did have a budget for 2020–21 had experienced a budget cut compared with what would have otherwise been expected before the pandemic.<sup>2</sup> A notable proportion took cuts greater than 10%. Even more challenging, 20% of academic libraries did not yet have a budget for the 2020–21 fiscal year by September, and many of those libraries had been considering substantial cuts.

The survey also documented that the cuts impacted all aspects of library bud-



**LISA JANICKE HINCHLIFFE**, the author of this commentary, uses futures thinking as a strategy for making decisions and plans for institutional libraries as their budgets continue to tighten. She is a professor and coordinator for research and teaching professional development at the University of Illinois at Urbana–Champaign library.

gets. Specifically, "62 percent made cuts to collections, 59 percent allocated cuts to staffing, and 53 percent cut funds from operations." The collections budget cuts further exacerbate the challenges libraries face as scholarly output continues to grow while library budgets shrink.

One of my favorite futures thinking exercises is the Futures Wheel, which is a visual method for exploring implications of a given change by brainstorming consequences of the change and then consequences of those consequences, consequences of those consequences, and so on. The goal is to see the full impact of a particular change from a variety of perspectives and to unearth potential unintended consequences, particularly those that might be negative, so that they can be managed or mitigated.

Regardless of whether they have

done the Futures Wheel activity specifically, academic librarians are well versed in assessing and managing the implications of contemporary budget cuts and historically declining buying power.

As a result of library collections budget cuts, researchers might spend more time seeking out access to articles and books that they need—for example, through interlibrary loan—which would take time away from other work and increase the time needed to complete a project. Students might need to pay for course materials that are no longer available through the library, which would add to the cost of their college education. And libraries might cancel scholarly society journal subscriptions, which would diminish support for scholarships, travel grants, and other programs funded by publishing revenues.

Given those potential consequences—and recognizing that a significant reversal of budgetary trends is as implausible as it would be desirable—academic librarians have been pursuing both short-term and long-term methods for maximizing the impact of the budgets that they do have while also seeking to alter the financial dynamics of the scholarly communications system as a whole.

Strategies for making the most of collections budgets have focused on negotiating lower prices, canceling lesser-used subscriptions, and providing delivery-on-demand services, particularly for journal articles. Research libraries have been canceling “big deal” packages with the largest publishers and replacing them with à la carte packages that reflect specific campus needs.<sup>3</sup> In some cases, they have just been canceling subscription packages altogether. Unsub, an online subscription analysis tool, has been notably useful in those efforts.<sup>4</sup> Libraries were assisted during the pandemic by the publishers that held prices steady rather than increasing fees or even offered pricing relief. Many of those programs, however, were temporary and have ceased. In sum, libraries are spending smarter and buying less.

Negotiating for discounts and similar efforts are unlikely to fully address declining purchasing power or the reality of expanding scholarly output. Librarians have therefore also been attempting market interventions with the aim of shifting scholarly publishing business models. Transformative agreements, which seek to shift library spending from paying for subscriptions to paying for open-access publishing, are particularly noteworthy for the increased value received by institutions for their library spending.<sup>5</sup> But they have yet to lower the overall costs to libraries as some have envisioned.

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The University of California’s multi-payer model, in which its libraries give financial support to all authors while requesting that those with grant funding cover part of the cost of article publication, is a unique approach to addressing that issue, but it is still in its earliest years of implementation, so it is difficult to evaluate whether it can be scaled to other institutions.

Hidden in the discussion of those realignment strategies is a challenging reality: The strategies rely on robust backroom operations and the expansion of other library services. With cuts to staffing and operations as a result of the pandemic, libraries may not be able to mitigate as they once did the negative consequences of cuts to the collections budgets.

That is why I want to return now to the observation at the start of this commentary—that futures thinking offers the opportunity for faculty, students, and administrators to consider their roles relative to the future of their libraries. To be clear, I am not saying that everyone needs to understand the inner workings of library management. I am saying, however, that faculty, students, and administrators need to understand the impact of the library on their work—and also what a library makes possible collectively.

Academic libraries are inherently a lever for equity. They ensure that regardless of one’s background, personal financial resources, social network, or other circumstances, if one is a member of the campus community, one has equal access to information resources. It may be easy for individuals to fall into thinking that they don’t need the library and that they have personal options. But the question to consider is whether the campus community needs the library.

The current realities of academic library budgets reflect the challenges of the past decades. Good stewardship of declining resources is still a story of declining resources. Librarians need to ensure that they are creating value for their institutions and communicating their impact. But librarians alone cannot ensure that the vision of a library as a collective good is a campus reality. The message that investment in the library is investment in the community is delivered best by the researchers and learners that libraries serve.

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## LETTERS

# Engineering better science education

Thanks to Stephen Pompea and Pedro Russo for their comprehensive overview of science education activities (PHYSICS TODAY, September 2021, page 26). The authors mention in passing that the evaluation of innovative science education projects was included in their studies of educational transformation. It would be interesting to learn what was found in their evaluations and in others that may have been performed. NSF alone spends some \$1 billion on STEM (science, technology, engineering, and mathematics) education, so it is important to assess what effects those activities have had on science appreciation and competence.

I constructed a small observatory in my town and operated it with NSF and NASA support for over 20 years. The opportunity to increase the awareness of astronomy in my community was enjoyable.<sup>1</sup> But the experience raised some concerns about the current emphasis in science education. For one, I was surprised to find that while there are many astronomy projects on the Web focused on specific topics like building a model solar system or a rocket, the one resource that elementary or middle school teachers might most need—a comprehensive

introduction to astronomy at that level—seems to have been overlooked. The only such general introduction that my colleagues and I were able to find at that time was an excellent textbook by Jay Pasachoff<sup>2</sup> that wasn't available anymore, although a revised edition has since appeared. An experienced teacher working with me commented that the currently popular emphasis of Web-based resources for teachers and students on relatively narrow topics makes it difficult to present a subject like astronomy cohesively.

Another concern is the impact of too many curriculum changes on teachers. Our daughter teaches third grade, and one wonders how many enthusiasts of frequently revamping STEM curricula understand how much work goes into handling 25 rambunctious kids and their sometimes-difficult parents. Attrition of experienced teachers is a serious problem, and finding out that they need to master yet another way to teach math or science could be the last straw for some.

It would be interesting to hear from the authors whether such concerns have been covered in past evaluations or how they might be addressed in the future.

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Peter Foukal

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Nahant, Massachusetts



It doesn't take a rocket engineer to recognize the widely used and unfortunately misleading technoscience cliché in the subtitle of the worthy September 2021 article "Improving science education: It's not rocket science—it's harder!" (page 26).

In the NASA History Series book *Remembering the Space Age*, Monique Laney, a historian at Auburn University, declares the term "rocket scientist" a "misnomer used by the media and in popular culture."<sup>1</sup> She points to the condemnation of the term by former National Air and Space Museum space history chair Michael Neufeld, who associates it with "a deep-rooted failure in the English-speaking media and popular culture to grapple with the distinction between science and engineering." Neufeld acknowledges that "the boundaries are fuzzy,"

but he asserts that "the correct term is 'rocket engineer.'"<sup>2</sup>

Most who mastermind and shepherd spaceflight to serve science—and maybe commerce—are engineers.

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Steven T. Corneliusen

Poquoson, Virginia

► **Pompea and Russo reply:** We agree with Steven Corneliusen that the term "rocket science" is a poor overall descriptor of the scope of aerospace engineering. However, the term resonates with the public in describing endeavors that it views as difficult and complex or where failure would be highly visible (for example, the efforts to bring back *Apollo 13*).

When the astronaut, scientist, and educator George "Pinky" Nelson observes that education is harder than "rocket science," he accurately describes the complexities and difficulties in advancing STEM (science, technology, engineering, and mathematics) education. Just getting a rocket off the launchpad is much easier than getting the payload into the specific orbit desired. STEM education undertakings also benefit greatly from well-designed, intentional efforts from teams that use a systems-based approach.<sup>1</sup>

We also agree that effective classroom science education, especially at the elementary school level, is difficult for the reasons outlined by Peter Foukal. Science teachers are challenged by curriculum changes, poor textbooks, a paucity of computers and other equipment, and inadequate training in pedagogical content knowledge for the subjects they teach. From our experience, teaching is one of the most challenging professions; its difficulty is significantly underappreciated by other professionals. It is no wonder that there is currently a critical shortage of science teachers in the US (see PHYSICS TODAY, March 2022, page 25).

Most concerning to us is that public education in the US has been under attack for decades, a topic well explored by Diane Ravitch, a former US assistant secretary of education. Public funding for education is increasingly being diverted

to private and religious schools, which weakens the public school system. STEM professionals and their organizations need to take a more active role as stewards of local public STEM education in order to preserve the rapidly deteriorating educational ecosystem.<sup>2</sup>

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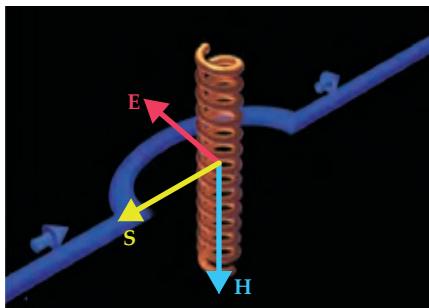
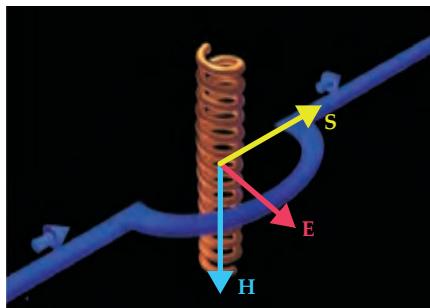
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## Lesson from a lost radioactive source

appreciated the item "Replacing high-risk radioactive materials remains a challenge" in the September 2021 issue of PHYSICS TODAY (page 23). In 1972 my career at the University of Rochester started with periodic source replacements in the Tandem Van de Graaff accelerator, which used iridium-192. My colleagues and I also used the same nuclide in radiation-therapy breast implants. I had to assist in the operating room to ensure no iridium seeds were lost. Over the years we dealt with blood irradiators and several cobalt and cesium therapy machines and with many smaller sealed sources.

The only "lost" source that I can recall is a cesium-137 capsule used for a three-day cervical implant. It was removed from the patient on a weekend, and procedures were not followed. An inventory on Monday morning revealed that one source was missing. We found it under a conveyor belt that workers used to sort laundry by hand. The source was not damaged, and none of the workers received a significant radiation dose. The incident does, however, support the challenge referenced in the article—a challenge that is easily met by following procedure.

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## Revisiting the electric potential

In the Quick Study by Eve Vavagiakis, Thomas Bachlechner, and Matthew Kleban (PHYSICS TODAY, August 2021, page 62), the authors' claim about the ontology of the electromagnetic vector fields seems too simple. As indicated in the figure above (adapted from the authors'), an electron taking either of the paths around the solenoid has an electric field  $E$  extending into the solenoid, where there is a nonzero magnetic field  $H$ . For a short time, the electron creates a Poynting vector  $S$  carrying momentum. That momentum has to be taken away from the initial momenta and thus affects the phase difference between the paths. That quantum mechanical phenomenon, called the magnetic Aharonov-Bohm effect, depends on only the magnetic flux. The obtained phase change does not depend on the distance to the solenoid. Its size is easy to calculate for an infinite solenoid.

Usually, a properly renormalized electron can be thought of in quantum mechanics without considering the constantly emitted and absorbed photons building up the electric field. But for an electron passing around a solenoid, there is an exception, as noted by Lev Vaidman.<sup>1</sup>

The electrostatic version nicely described by J. J. Sakurai and Jim Napolitano is more straightforward.<sup>2</sup> At some point, the electrostatic potential has to be switched on, which, independent of the geometric details, has to involve an electric field. That electric field crosses the particle path and takes away or adds momentum, resulting in the observed phase difference between both paths.

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► **Vavagiakis, Bachlechner, and Kleban reply:** Fritz Bopp correctly points out that creating a potential difference necessitates a nonzero electric field. He goes on to assert that the field must cross the particles' paths, differentially accelerating them. If that were the case, the difference in phase could indeed be explained by the interaction of the particles with the electric field. As we describe in our Quick Study, however, the field could be switched on for a while and then off again while the particles are deep inside two long, tubular Faraday cages. Those cages shield the particles from contact with the nonzero field, yet while the field is on, there is a potential difference between the interiors of the two cages. That potential difference is therefore responsible for the difference in phase.

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## Correction

July 2022, page 5—The last sentence of the “On the cover” description should read “the world's largest cryogenic particle detector.”

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# A star's demise is connected to a neutrino outburst

The most conclusive evidence to date demonstrates that high-energy neutrinos could be formed by tidal forces that rip apart a star near a supermassive black hole.

**O**n 1 October 2019, the IceCube Neutrino Observatory in Antarctica detected an exceptionally energetic 0.2 PeV neutrino. The Zwicky Transient Facility in California followed up seven hours later with wide-field observations of the sky at optical wavelengths. The facility observed optical emission in the 90% uncertainty region of the incoming neutrino.

After studying the large energy flux of the optical emission, its location within the reported uncertainty region of the sky where the high-energy neutrino came from, and some modeling results, researchers concluded that the two observations could be connected.<sup>1</sup> The optical emission was caused by a bright transient phenomenon known as a tidal disruption event (TDE) that had first been observed one year before the neutrino.

TDEs occur when stars get close enough to supermassive black holes to experience spaghettification—the stretching and compressing of an object into a long, thin strand that is caused by the black hole's extreme tidal forces. (See the article by Suvi Gezari, PHYSICS TODAY, May 2014, page 37.)

Two theory papers proposed that neutrinos with energies above 100 TeV, like the 2019 sighting, could be produced in relativistic jets of plasma, which are composed of stellar debris that's flung outward after such an event.<sup>2</sup> Active galactic nuclei (AGNs) and other possible emitters of high-energy neutrinos have been debated in the literature before IceCube detected the first extragalactic ones in 2013 (see the article by Peter Mészáros, PHYSICS TODAY, October 2018, page 36). But with only the one reported TDE-neutrino association from 2019, re-



**FIGURE 1. A TIDAL DISRUPTION EVENT** occurred when a star much larger than the Sun traveled too close to the supermassive black hole in the center of a galaxy 4.4 billion light-years away from Earth. In this illustration, radiation from the tidal disruption at the center vaporized the dust in its immediate vicinity. The more distant, red-colored dust half a light-year away heated up and began to glow at IR wavelengths. That dust echo was detected months after the event's initial optical emission. The blue emissions depict jets of plasma launched by the event. (Courtesy of the Science Communication Lab for DESY.)

searchers haven't been able to conclusively establish TDEs as high-energy neutrino sources.

Now the Zwicky Transient Facility observed another TDE that was located within the uncertainty region of a neutrino detected by IceCube. With their colleagues, Simeon Reusch and Marek Kowalski (German Electron Synchrotron and Humboldt University of Berlin) estimated that the probability of a second such pairing happening by chance is 0.034%, lending more credence to TDEs as sources of high-energy neutrinos.<sup>3</sup>

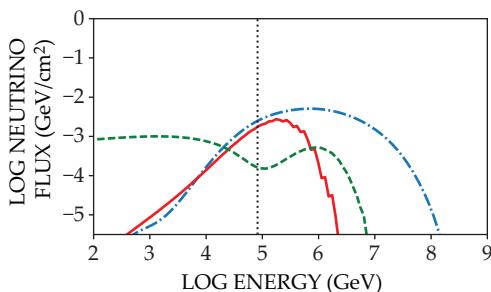
## Star light, star bright

The newly observed TDE is located in an AGN—the luminous, compact center of a galaxy. The galaxy in question is 4.4 billion light-years from Earth and has at its center a black hole with a mass of 31.5 million Suns. After a star got close

enough to be ripped apart, its remains likely swirled around the black hole, accreted, and began shining brightly across many wavelengths.

That transient flare was first discovered at the Zwicky Transient Facility in May 2019 and reached peak luminosity in August 2019. The associated neutrino was detected by IceCube nine months later, by which time the flare's flux had decreased by about 30%. Such flares often last several months, although this one was still detectable as of June 2022.

A TDE isn't the only possible source of the flare. It could have come directly from the AGN. Because AGNs are far more numerous than TDEs, their emission is more common. And the first data of the flare suggested that it could have been a superluminous supernova—a stellar explosion with a luminosity that's at least 10 times as bright as a typical



**FIGURE 2. HIGH-ENERGY NEUTRINOS** could be produced from various mechanisms associated with a tidal disruption event—the demise of a star by a supermassive black hole's tidal forces. The energy of one such neutrino (vertical dotted line), detected by the IceCube Neutrino Observatory in 2020, is consistent with all the modeled possibilities. It may have been generated from relativistic jets of plasma expelled from the event (blue dotted-dashed line), the collisional plasma inside the coronal region of an accretion disk composed of stellar debris (red solid line), or a subrelativistic wind of ejected material (green dashed line). (Adapted from ref. 3.)

supernova. To better establish whether a TDE was, in fact, the source of the optical emission, Reusch, Kowalski, and colleagues looked at measurements of the flare that spanned nearly the entire electromagnetic spectrum.

Some of the most useful evidence came from the eROSITA telescope, which is part of the Russian-German *Spektr-RG* satellite. The instrument scanned the sky location of the putative TDE four times. On the third scan in March 2021, after the peak luminosity of the flare had declined, it detected low-energy, or soft, x-ray emission, which would be quite uncommon for a superluminous supernova.

## Sluggish IR

A second critical piece of evidence in support of the TDE came from mid-IR observations collected by the NEOWISE space telescope—NASA's reactivated *Wide-Field Infrared Survey Explorer* whose current mission is to identify and characterize near-Earth objects (see PHYSICS TODAY, March 2015, page 19). The mid-IR observations showed a peak IR luminosity that curiously lagged the peak of the optical emission by a year.

"The time delay led us to the dust-echo interpretation," says Reusch. Figure 1 shows an artistic illustration of the AGN surrounded by a preexisting dust cloud; it heated up and started to glow as light traveled through it. The dust in the immediate vicinity of the disrupted star was destroyed by the TDE's radiation, which left only the far-flung dust surrounding the TDE.

In the dust-echo interpretation, some of the IR light emitted from the TDE was absorbed and reemitted by the surrounding dust. Light traveling directly along the line of sight to the TDE arrived at Earth first. IR light from the heated dust

that was initially emitted perpendicular to the direct line of sight or from the far side of the system must travel farther and thus arrived months later than the optical emission.

Reusch, Kowalski, and their colleagues first modeled the combined IR, optical, and UV light coming from the TDE using a single blackbody as the radiation source. But the results were inconsistent with the spectral shape of the observations. The best fit, they found, came from a model composed of two blackbodies at different temperatures: one for the TDE emission and the other for the IR dust-echo emission.

## From jets, the disk, or wind?

To better understand how the unusually long-lasting TDE may have produced high-energy neutrinos, the research team simulated three possible mechanisms. Besides relativistic jets, a TDE could also generate a disk of gaseous material accreted from the remains of a star. With sufficiently high accretion, collisional plasma in the coronal region of the disk may accelerate particles and produce neutrinos. Such an accretion disk could also launch a subrelativistic wind of ejected material that's energetic enough for generating neutrinos.

Figure 2 shows the predicted neutrino flux for each of the possible mechanisms as a function of energy. Any of the three mechanisms could reasonably generate a neutrino with the energy (vertical dotted line) observed by IceCube.

Other details of the TDE-neutrino association remain murky. For example, in their statistical analysis, IceCube researchers couldn't rule out the possibility that the neutrino may have formed from atmospheric processes on Earth. They concluded that the neutrino had a

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59% probability of having an astrophysical origin.<sup>3</sup>

## Multimessenger astrophysics

Detecting more TDEs and better establishing their relationship to high-energy neutrinos should be possible as early as next year. The Vera C. Rubin Observatory, previously named the Large Synoptic Survey Telescope, is currently being built in Chile. Once it sees first light, its wide-field Simonyi Survey Telescope will have the capability of photographing the entire sky every few nights.

If the TDE–neutrino association is true, TDEs would have to be extremely efficient particle accelerators. The energies of high-energy neutrinos are many orders of magnitude higher than can be reached in even the most impressive

terrestrial particle accelerators, and they reach Earth largely unperturbed.

High-energy neutrinos, therefore, are a natural part of a multimessenger astrophysical laboratory. They can't be controlled or replicated as in a traditional lab experiment, but they can be used to study high-energy processes and test fundamental ideas about particle physics.

For example, some of the densest and most energetic conditions in the universe are found in supernovae. Because neutrinos are very light and only interact by the weak nuclear force, they can pass through the dense core of a supernova and probe the conditions there.

Neutrinos are also theoretically expected to be produced during neutron star mergers. None were seen after the

2017 binary neutron star merger in which gravitational waves and a gamma-ray burst were observed (see “The era of multimessenger astronomy begins,” PHYSICS TODAY online, 16 October 2017). Nevertheless, the hunt for them continues. And should any be detected, they may offer bits of information about the density of a neutron star merger and how energy is dissipated from it.

Alex Lopatka

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# A triatomic molecule is laser cooled and trapped

Molecules that stretch, bend, and rotate offer many new avenues for ultracold physics experiments. But they're also harder to control.

In March 2020, as the world was grappling with the implications of the COVID-19 pandemic, John Doyle and colleagues at Harvard University were faced with the bleak prospect of shutting down their experiments on ultracold atoms and molecules, perhaps indefinitely. So they turned their physics expertise to a rather different but more timely set of problems: Could N95 masks, in perilously short supply at the time, be decontaminated and reused?<sup>1</sup> And how could the risks of airborne disease transmission be most effectively mitigated in a laboratory or office setting?<sup>2</sup>

Through their work, they helped Harvard develop a plan to safely and quickly reopen its research labs—including their own, shown in figure 1. “By June 2020 we were working at 70% capacity,” says Doyle, “and a couple months after that we were back to essentially 100%. Although we didn’t have any visitors during the shutdown, we enjoyed the opportunity for quiet and concentration.”

That opportunity has paid off. In one of a steady stream of papers published since the start of the pandemic, they’ve now demonstrated the laser cooling and magneto-optical trapping of calcium monohydroxide ( $\text{CaOH}$ ), the first three-

atom molecule to be so cooled and trapped.<sup>3</sup> The extension of ultracold techniques to larger molecules promises to make possible new experiments in quantum information, tests of fundamental physics, and more.

## Will the cycle be unbroken?

Laser cooling and trapping of atoms is a decades-old technology that garnered the 1997 Nobel Prize (see PHYSICS TODAY, December 1997, page 17). In its simplest form, it works by optical cycling: An atom repeatedly absorbs and emits photons as it hops between its ground and excited electronic states. Each absorbed photon imparts some momentum, which counters the atom’s thermal kinetic energy, thereby slowing and cooling it.

The success of that method hinges on getting the atom to reliably return to its ground state. If there’s some other low-lying state that it can relax into instead, researchers need to add another laser to repump the atom from that state; if the atom ever ends up in a so-called dark state that isn’t repumped, the cooling cycle ends and the atom is lost from the experiment. The easiest atoms to laser cool are therefore those with the simplest energy-level structures, mostly

alkali metals such as potassium and rubidium and alkaline earth metals such as calcium and strontium.

Extending ultracold methods from atoms to molecules is useful for a wide range of experiments. Some of those experiments are obvious, such as studying chemical reactions in the quantum regime (see the article by Debbie Jin and Jun Ye, PHYSICS TODAY, May 2011, page 27); others are less so, such as searching for hypothetical supersymmetric particles that might endow the electron with a permanent electric dipole moment (see the article by Dave DeMille, PHYSICS TODAY, December 2015, page 34).

But all the challenges of laser cooling atoms are compounded in molecules, which possess not only electronic quantum states but also quantized rotations and bond vibrations. The veritable continuum of low-lying states would, in the general case, require many dozens of repumping lasers to keep under control.

Because of the difficulty of cooling molecules directly, most ultracold-molecule researchers build their molecules from atoms that are already cooled. Although that approach works well, it yields exotic, weakly bound molecules such as KRb (see PHYSICS TODAY, February 2020, page 12) and  $\text{Sr}_2$  (see PHYSICS TODAY, October 2019, page 18) that are essentially unknown outside of ultracold research.



**FIGURE 1.** A THICKET of optical elements directs the laser beams that cool and trap the triatomic molecule calcium monohydroxide. Laser cooling and magneto-optical trapping of atoms is standard practice, and a few groups have succeeded in cooling and trapping diatomic molecules. But never before has a three-atom molecule received the same treatment. (Photo by Loïc Anderegg.)

But some special molecules can be cooled directly without too much trouble. The trick is to find a molecule whose ground and excited electronic states have nearly the same equilibrium shape. (For diatomic molecules, the “shape” is merely the length.) The molecule can be cycled between those states without stretching it, and most molecules reliably relax to the vibrational ground state. Occasionally they might end up with one or a few quanta of vibrational energy, but a small number of repumping lasers can coax them back to the vibrationless state.

Two molecules that fit the bill are strontium monofluoride and calcium monofluoride. In each case, the alkaline earth metal atom—Sr or Ca—has an extra electron that doesn’t participate in the metal-fluorine bond. Exciting that electron doesn’t change the bond length much at all. Both molecules can be laser cooled with just a handful of additional repumping lasers. (See PHYSICS TODAY, January 2010, page 9.)

Importantly, there are multiple tiers of what’s meant by “laser cooling.” Because of their extra electrons, SrF and CaF aren’t stable enough to be carried around in bottles; they have to be synthesized from their constituent atoms in a molecular beam. It’s relatively straightforward to apply lasers perpendicular to the molecular beam to cool the molecules’ transverse motion while they hurt-

le along at some 100 m/s—and for some applications, that form of cooling is enough.

For experiments that require lower temperatures or optical lattices, however, researchers need to catch the molecules in a trap, which requires first slowing the molecular beam to a virtual stop. To do so with just lasers, they need to get the molecules to cycle more than 10 000 photons without ever landing in a dark state. That challenging feat, even for diatomic molecules, has been achieved by only a handful of groups in the world so far.

### The bends

Going from two atoms to three introduces another important degree of freedom: Not only can triatomic molecules stretch and rotate, but they can also bend. The bending mode gives rise to some potentially interesting new effects. For example, in strontium monohydroxide, it so happens that three quanta of bending have almost exactly the same energy as two quanta of the Sr–O stretch. That accidental degeneracy makes the SrOH spectrum potentially sensitive to some postulated types of dark matter.

For another example, exciting the bending mode breaks an otherwise linear molecule’s linear symmetry. A bending molecule therefore has quantized rotational motion not just from tumbling

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end over end but also from turning like a spindle about the molecule's length. For complicated quantum mechanical reasons, molecules that possess angular momentum about their internuclear axes are extremely easy to align with an applied field. That capability comes in handy in searches for the electron electric dipole moment, use of the molecules as qubits, and more.

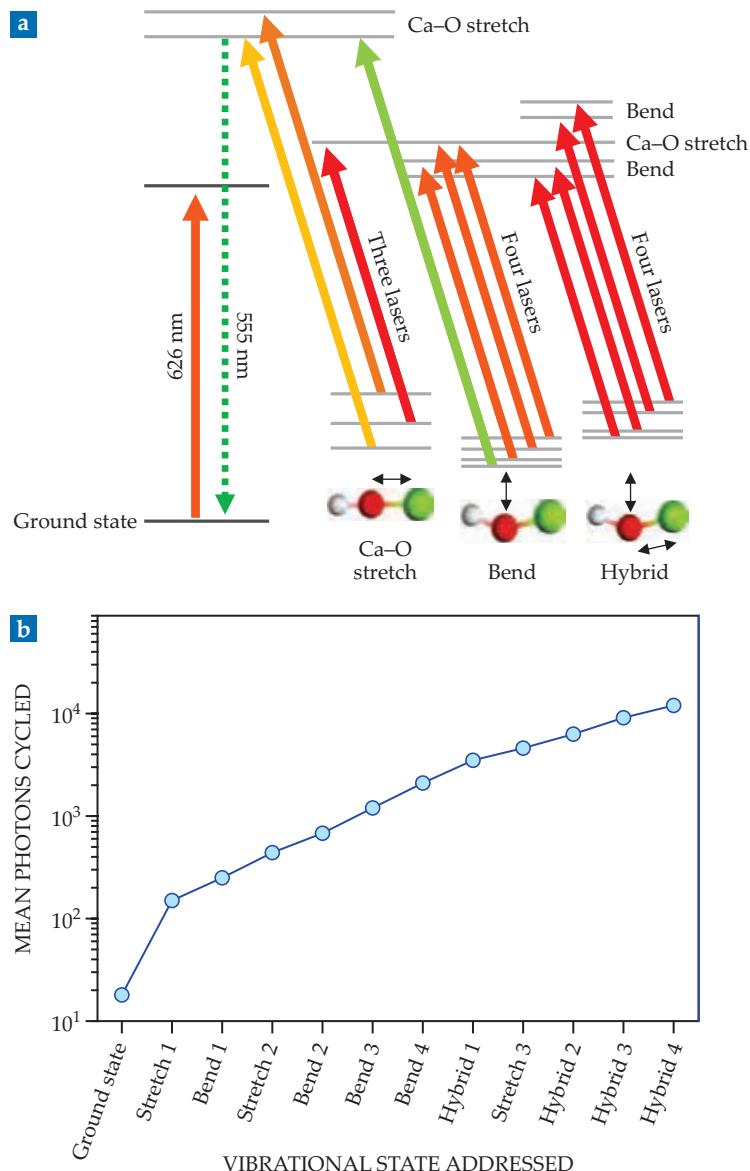
But the bending mode introduces the same challenge to laser cooling as a diatomic molecule's stretching mode does: It creates more vibrational states into which the molecule might relax and break the optical-pumping cycle. Fortunately, the same advantage of SrF and CaF also applies to CaOH (which Doyle and colleagues chose over SrOH simply because its transitions lie at more convenient laser frequencies): The Ca atom's extra electron doesn't participate in bonding, so most molecules relax into the vibrational ground state. But a few relax into states excited in the Ca–O stretch, the bend, or both.

Doyle and colleagues transversely cooled CaOH in a molecular beam just before the start of the pandemic. It took six lasers, one to drive the main transition and five to repump vibrationally excited states.<sup>4</sup> That scheme cycled an average of about 1000 photons per molecule. To reach the 10 000-photon threshold required to slow the beam to a stop, the researchers had to add six more laser frequencies, for a total of 12, as depicted in figure 2a.

Fortunately, the molecules don't all fall into a dark state after the same number of cycles. The mean number of photons cycled, plotted in figure 2b, is the number of photons scattered per molecule before the number of molecules is reduced by a factor of  $e \approx 2.718$ . So even though the 12 lasers cycle an average of just 12 000 photons per molecule, only slightly more than the 10 000 needed to stop the beam, they still leave more than  $\frac{1}{e}$  of the molecules available to be caught in the magneto-optical trap.

### Bigger and bigger

Bending and Ca–O stretching aren't the only vibrational modes available to CaOH. There's also stretching of the OH bond, which the Harvard researchers' laser scheme doesn't address at all. But that's because it didn't need to: Optically cycling CaOH molecules almost never



**FIGURE 2. TWELVE LASERS** combine to laser cool calcium monohydroxide. (a) The 626 nm laser cycles the molecule between the ground and electronically excited states, and 11 more lasers repump molecules that relax into vibrationally excited states. (b) The blue circles show the cumulative number of photons cycled as each new repumping laser is added. A six-laser scheme (from "ground state" through "bend 3") cycles just 1000 photons per molecule. But using all 12 lasers increases that number to 12 000—enough to slow and trap the molecular beam. (Adapted from ref. 3.)

end up with any quanta of O–H stretching motion. It's intuitively easy to understand why. The cycling excitation is centered on the Ca atom, which is physically separated from the OH bond. The two parts of the molecule simply have little to do with each other.

That line of reasoning would seem to imply that laser-coolable molecules can be made arbitrarily large: Just attach a Ca (or Sr) atom to an O atom to just about anything. As with CaOH, one could

optically excite the unpaired electron, repump a few stretching and bending vibrational states, and leave the rest of the molecule alone.

The reality is almost certainly not so simple. Larger molecules have greater mass, so they'd have to cycle more photons to be slowed to a stop. And the sheer density of states of large molecules can introduce complicating effects, such as the coupling of disparate vibrational modes of similar energy.

Nevertheless, preliminary research suggests that the outlook for laser cooling larger molecules is good. Theory groups led by Anna Krylov, Svetlana Kotochigova, and Anastassia Alexandrova have analyzed the vibrational structures of many candidate molecules, and they predict that coolable molecules can incorporate some rather large organic structures, including benzene rings.<sup>5</sup> On the experimental side, Doyle and colleagues have already done transverse in-beam cooling of calcium monomethoxide ( $\text{CaOCH}_3$ ), although they still have a long way to go before they can catch that molecule in a trap.<sup>6</sup>

Cooling larger molecules would introduce even more richness to cold-molecule experiments. For example, if researchers could cool a molecule that breaks mirror symmetry, they could investigate whether the laws of physics treat such asymmetric molecules differently from their mirror-image counterparts. More broadly, by bringing all the well-known power of chemistry to bear on the ultracold regime, researchers could design ultracold molecules with shapes and properties to suit any purpose. "We don't know whether our techniques are as broadly applicable as that," says Doyle. "That's a frontier scientific question."

We're very interested in seeing what's possible."

**Johanna Miller**

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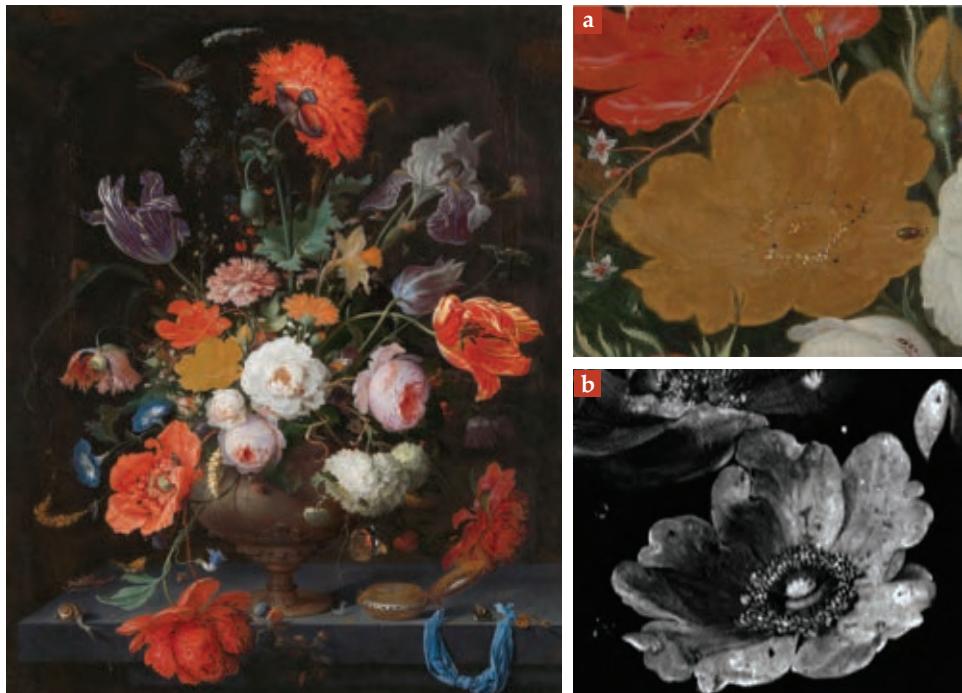
# X-ray imaging shows how a 17th-century painting lost its color

When an arsenic sulfide pigment chemically degraded, it stripped the painting's yellow rose of visible details.

As beautiful as they are to look at, art masterpieces are not eternal. For example, pigments and binders in oil paintings inexorably degrade. Light, humidity, and temperature fluctuations are the usual culprits, but exposure to certain cleaning solvents during conservation and the mixing of incompatible pigments by the artist can also render paint unstable over time.

The task of conservation scientists is to understand the chemical reactions that cause the degradation in order to answer three questions: How was the painting made, how did it originally appear, and how did it change—either naturally or by intervention? Those questions are not entirely backward-looking. By reconstructing how a painting deteriorates, conservators may be able to forestall further damage and better preserve it.

Paintings conservator and doctoral student Nouchka De Keyser (Rijksmuseum, University of Amsterdam, and University of Antwerp), her advisers Katrien Keune and Koen Janssens, and their colleagues have scientifically addressed all three questions in their analysis of a yellow rose in Abraham Mignon's mid-17th-century painting *Still Life with Flowers and a Watch*,<sup>1</sup> shown in figure 1. Mignon painted his yellow roses with the mineral orpiment ( $\text{As}_2\text{S}_3$ ), used by artists

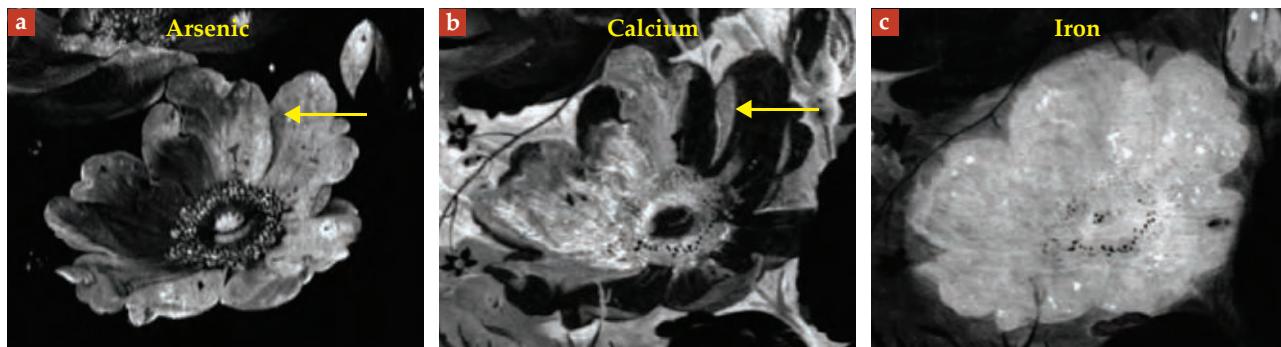


**FIGURE 1. STILL LIFE WITH FLOWERS AND A WATCH** (left), by Abraham Mignon, oil on canvas (c. 1660–79), Rijksmuseum. (a) In its current form, the central yellow rose appears flat and lifeless. (b) The map of arsenic distribution reveals the element's presence throughout the rose and Mignon's original painted details. X-ray powder diffraction identifies the arsenic in the form of transparent lead arsenates rather than the original yellow-orange mineral orpiment (arsenic sulfide). (Adapted from ref. 1.)

since antiquity to give a bright and vibrant appearance. But orpiment can be problematic. Over time, the mineral can severely discolor, changing the look of painted orange draperies, lemons, yellow flowers, and golden metal in old masterworks.

Many artists, possibly including Mi-

gnon, were aware of those and the mineral's other problems—it dries poorly, is incompatible with other pigments, and is extremely toxic. Yet it remained widely used until the 18th century. And orpiment was not the only troublesome pigment. In Vincent van Gogh's 1888 painting *The Bedroom*, for instance, the fading



**FIGURE 2. X-RAY FLUORESCENCE** maps. (a) The distribution of arsenic in the paint reveals detailed features on the petals and stamens and how the rose would have looked when illuminated from the upper left. (b) The distribution of calcium correlates with the shadows cast by upper flower petals on a neighboring petal (marked by the yellow arrows). (c) In the iron distribution map, only the rough shape of the flower is visible. From comparisons with powder-diffraction maps of the area, the iron signal stems from a more uniformly applied ochre underpainting beneath the flower. (Adapted from ref. 1.)

of red pigments turned its purple walls blue and its pink floor brown. De Keyser and her colleagues wanted to understand what happened in the case of Mignon's yellow rose. "The most interesting part of my job," she says, "is to play detective, look for evidence of specific chemical reactions, and retrace their steps to figure out what an artist really had in mind."

### Chemical analyses

Most of the flowers in Mignon's painting remain brilliant. But the rose stands out as flat, monochrome, and peppered with microcracks. De Keyser and her colleagues first analyzed the rose using x-ray fluorescence imaging. When an x ray shines on the surface, it can knock out a core electron from an atom in the paint. That electron emission, in turn, prompts an outer valence electron to drop from a higher to a lower orbital and fluoresce. The light's wavelength is characteristic of chemical elements in the paint layers that absorbed the x rays. And when the x-ray beam and photon detector are raster scanned over the painting, the resulting image reveals the spatial distribution of those elements.

The researchers mapped the locations of arsenic, calcium, iron, sulfur, lead, and copper in the area containing the rose. Surprisingly, the analysis revealed painterly features—light and shadows defining the petals and stamens—that are optically invisible in the rose's now-degraded image (figure 1a). But because the elements still reside there, albeit in different molecular form, the arsenic map of their microscale distribution (figure 1b) uncovers the rose in most of its former glory. To compare

specific element distributions, see figure 2.

X-ray fluorescence cannot, however, resolve specific chemical compounds, into which orpiment transformed over the centuries. So the group turned to x-ray diffraction. Because pigments were originally ground into powders to make the paint mixture, the randomly oriented grains in Mignon's canvas allowed the researchers to avoid alignment difficulties associated with single-crystal diffraction. Indeed, obtaining molecular specificity from powder diffraction is becoming an increasingly key technique to study old paintings.<sup>2</sup>

To resolve molecular structures at the painting's surface, the group used an instrument developed in Janssens's lab at the University of Antwerp. In reflection mode, x rays strike the paint surface at a shallow 10° angle. De Keyser and her colleagues raster scanned the instrument across the area of the rose in 1.5-millimeter steps with 10-second exposure times per pixel. Altogether, the scan took 13 hours.

Those powder-diffraction maps primarily identified two lead arsenates—schultenite ( $PbHAsO_4$ ) and mimetite [ $Pb_5(AsO_4)_3Cl$ ]. The reactions leading to them start with the photooxidation of orpiment into arsenolite ( $As_2O_3$ ), a semi-soluble molecule that can diffuse throughout the multilayered paint system. When the oxide comes across lead ions, subsequent reactions prompt the precipitation of schultenite and mimetite. Each of them has a distinct spatial distribution in the painting.

### The transparent and the visible

Schultenite and mimetite lack the bright yellow appearance of orpiment; rather,

they're colorless and pale-yellow crystals, respectively. And when blended with calcite ( $CaCO_3$ ), gypsum ( $CaSO_4 \cdot 2H_2O$ ), and quartz ( $SiO_2$ )—other minerals that are identified by powder diffraction and whose refractive indexes match that of oil—the yellow paint used to create the rose becomes virtually transparent. Crystals of orpiment still exist in the painting, but only along the border of the rose. The pigment's early prevalence is now gone, chemically transformed into largely transparent crystals.

The fluorescence map bears out the result. Iron is pervasive over the surface of the rose, and the diffraction map identifies it in the form of goethite, a key ingredient in yellow ochre. Like other 17th-century still-life painters, Mignon is thought to have adopted a multistep method. He first blocked out the position of the flowers with a monochrome, ochre-based underpainting and then built up the details by applying glazes for shadows and orpiment for sunlit parts.

In that approach, he marked the location of the rose using the inexpensive ochre. Indeed, because the original orpiment has faded into transparency, the ochre underpaint is now the only optically visible remnant. The modern rose looks dull, flat, and monochrome—the opposite of what Mignon would have intended.

**R. Mark Wilson**

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## Clean hydrogen edges toward competitiveness

States and regions around the US are readying their bids to host centers for hydrogen production, distribution, and end uses.

The Biden administration's vision for wider adoption of hydrogen accelerated in June with the announcement of a \$504 million loan to finance construction of an innovative carbon-emission-free hydrogen production and storage facility in Utah. Also in June, the Department of Energy detailed plans for spending \$8 billion in public funding to create up to 10 regional hydrogen "hubs," which were called for in last year's bipartisan Infrastructure Investment and Jobs Act.

The loan to the Advanced Clean Energy Storage (ACES) project in Delta, Utah, will finance construction of what project officials say will be the world's largest green-hydrogen production and storage installation when completed in 2025. Green hydrogen is produced with no carbon dioxide emissions by water electrolysis powered with renewable sources. The Utah project's storage capacity of 5500 tons will be equivalent to that of all the nation's grid-scale battery-storage capacity projected for 2030, says Jigar Shah, director of DOE's Loan Programs Office.

The hydrogen will be stored at 69 bar or greater in caverns to be carved out in underground salt formations. It will be burned in combination with natural gas during periods of peak electricity demand in a new natural-gas-fired plant to be built by the electric utility Intermountain Power Agency. That power plant will generate electricity from turbines driven both by combustion of gases and with steam produced from the exhaust heat. To be fueled with a 30:70 mix of hydrogen and natural gas initially, the plant will be converted to all-hydrogen operation by 2045.

"Hydrogen has enormous potential for energy storage, as a transportation fuel, a source for 24/7 clean dispatchable power, and as a means for decarbonizing heavy industry," Energy secretary Jennifer



ACES DELTA

**GREEN HYDROGEN** will be produced and stored in salt caverns at the Advanced Clean Energy Storage site in Delta, Utah. The Department of Energy in June finalized a \$504 million loan to the project, which will generate hydrogen from water using surplus renewable energy. The hydrogen will be stored in underground salt caverns and burned in combination with natural gas in an adjacent power plant to be built by 2025. In this rendering, the salt caverns are shown at the end of the injection pipes. The large gray-and-white-shaded areas depict salt formations.

Granholm told reporters on 8 June. "This loan will help reduce market risk and scale the hydrogen economy."

Michael Ducker, the chief operating officer of ACES Delta and a senior vice president at Mitsubishi Power, one of the project partners, says the Utah plant's 220 MW of electrolyzers will nearly double the world's total installed capacity of 250 MW. Electrolyzers will be supplied by Norway's HydrogenPro.

Today the world's largest green-hydrogen production facility, located in Fukushima, Japan, produces 2.4 tons a day from 10 MW of electrolyzers that are powered by on-site solar panels. It opened in 2020. In June, BP and partners announced plans to build a green-hydrogen facility in remote Western Australia. Known as the Asian Renewable Energy Hub, the project will be powered with 26 GW of wind and solar energy—enough to produce one-third of all electricity gener-

ated in Australia in 2020. When completed in 2027, it will have an annual capacity of 1.6 million tons of hydrogen or 9 million tons of green ammonia. Much of its output is intended to be shipped to markets in Asia.

Electrolysis must be powered with renewable energy to earn a green label. If powered with electricity from fossil-fuel-intensive power grids, electrolysis can be more than twice as carbon intensive as gray hydrogen—produced from natural gas without CO<sub>2</sub> capture and storage. That process is currently the source of nearly all the hydrogen produced globally.

In concert with the growth of renewable energy in the western US, especially in California, the amount of surplus solar and wind energy that can't be used during peak generation periods is growing. That is particularly the case during the late winter and early spring, when power



FUKUSHIMA HYDROGEN ENERGY RESEARCH FIELD

**THE WORLD'S LARGEST** green-hydrogen plant, the Fukushima Hydrogen Energy Research Field, opened in 2020 and produces 2.4 tons per day. It is powered by on-site solar panels.

demand is low relative to other times of the year (see the figure on page 24). The surplus renewable electricity will be transmitted to Utah via Intermountain Power's dedicated transmission lines.

The DOE loan is the first made to a renewable-energy project since 2011. The agency has loan and loan-guarantee authorizations totaling \$40 billion, but Shah says clean-hydrogen-related projects are eligible for only \$11 billion of that. DOE has already received loan applications that exceed that amount, he adds.

Mitsubishi and its partner, Magnum Development, are hoping to attract carbon-intensive industries to the Utah location. The water to be electrolyzed and that needed for power-plant operations will total about one-third of the water used by the existing coal power plant, Ducker says.

## Hubs ahead

Meanwhile, states, cities, and regional entities across the US are lining up for a share of the \$8 billion that DOE will dole out for a yet-to-be determined number of hydrogen hubs. The hubs were conceived by lawmakers as centers of clean hydrogen production, storage, distribution, and consumption.

On 6 June DOE published a notice of intent to issue a funding opportunity announcement, in which the department said it plans to award \$6–7 billion of that \$8 billion to 6–10 hubs. The Infrastructure Investment and Jobs Act requires that DOE award at least four hubs within one year of receiving proposals.

Each grant will range from \$400–500 million to \$1–1.25 billion, according

to the announcement. The remaining \$1–2 billion will be reserved for subsequent solicitations for future hubs, new technologies, or other purposes. Bidders are required to provide matching funds. The entire process, from planning to completion of hub construction, is expected to take 8–12 years. The hubs must be able to produce a minimum of 50–100 tons of clean hydrogen per day; DOE will give greater preference, and provide more funding, to bidders who show they can produce greater amounts. Bidders must have a plan for continuing financial viability once the federal funding runs out.

Congress set multiple requirements for choosing hubs. At least one must demonstrate so-called blue hydrogen, in which the CO<sub>2</sub> emissions in the production of hydrogen from methane are captured and permanently stored in geological formations. Nuclear energy and renewables are to power at least one hub each. Lawmakers further stipulated that at least one center demonstrate clean hydrogen use for electricity production, one for heavy industrial operations, one for residential and commercial heating, and another for transportation.

Congress also required DOE to ensure that the hubs be geographically dispersed and use energy resources that are abundant to their regions. The law instructs DOE to give priority to hub proposals that are expected to create opportunities for job training and long-term employment for the greatest number of residents in the area. The agency says it will require proposers to show "substantial engagement with key local and regional stakeholders to ensure these

projects generate local, regional, and national benefits while mitigating significant environmental or community impacts." Additionally, 40% of the overall hub benefits should flow to disadvantaged communities, without exacerbating their already disproportionate exposure to pollution.

Although DOE hasn't committed to a date, some bidders say they expect the agency will formally open the competition for hubs in September or October. Bidders are then to submit concept papers within two months. The agency will notify bidders within a month regarding whether it encourages or discourages the bidders' plans. Full proposals will be due four months later, and the agency may take "several months" to review them before making awards.

## Loads of interest

The Gulf Coast is a likely location for at least one hub. Most of the nation's existing hydrogen-pipeline network is located in Texas and Louisiana. Houston alone is home to one-third of US hydrogen production, according to the nonprofit Center for Houston's Future. Brett Perlman, the center's CEO, says the center has organized a wide-ranging coalition of companies, universities, and nongovernmental organizations to "help catalyze the Houston region, and Texas, into a clean energy hub." With an abundance of natural gas and wind-energy resources, Houston, and Texas generally, could qualify as both a blue- and green-hydrogen production hub.

Other regional partnerships have formed in anticipation of the hub

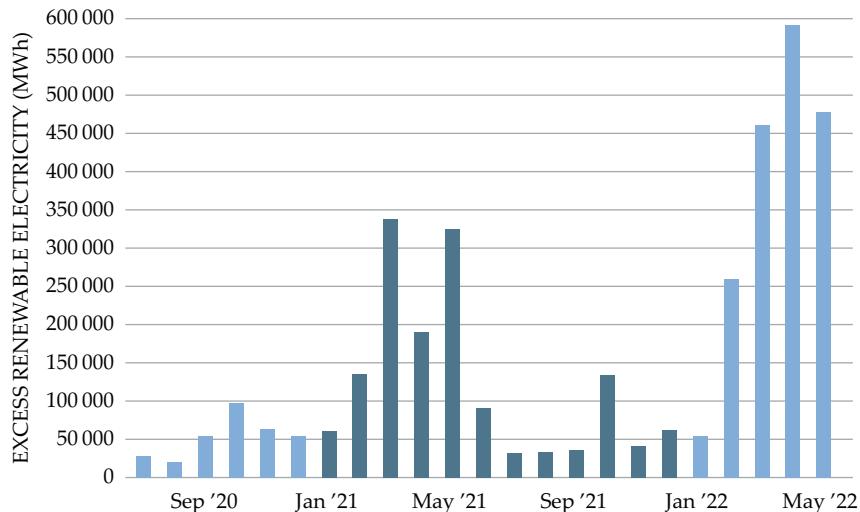
competition. In March, New York Governor Kathy Hochul announced a collaboration with Massachusetts, Connecticut, and New Jersey that also includes dozens of corporations and universities. The governors of Louisiana, Arkansas, and Oklahoma have agreed to collaborate on a regional hub, and Colorado, Utah, New Mexico, and Wyoming have joined forces. Other states that are preparing solo bids or have pending legislation to do so include Arizona, California, Illinois, Kentucky, Nebraska, Pennsylvania, and West Virginia.

The Delta site may become the anchor for one hub, Shah says. There is room at the location for at least 70 more caverns of the same size as those to be excavated for the ACES Delta project, says Ducker. That amount of hydrogen-storage capacity "provides opportunities to help balance [electricity] load across the entire West," he says.

Some states have multiple proposals. The University of Toledo is convening an Ohio-focused hub proposal. Frank Calzonetti, the university's vice president for research, says the hub will power electrolysis with both nuclear and solar energy. The collaboration is to include the Davis-Besse nuclear plant near Toledo, which is already operating a 2 MW electrolyzer in a hydrogen demonstration that DOE is supporting with a \$9.2 million grant. (See PHYSICS TODAY, August 2020, page 20.)

The infrastructure act requires that hubs arrange purchase agreements with consumers of hydrogen. Northern Ohio is home to a lot of heavy industry, including the largest flat-rolled steel plant in the nation and glass manufacturing. Industry partners that have signed on to the Toledo collaboration include General Electric Aviation, which in February announced a collaboration with Airbus to develop hydrogen-fueled aircraft engines. Others include the glassmaker Owens-Illinois, solar-panel manufacturer First Solar, and sustainable-aviation-fuel producer LanzaTech.

With an abundance of natural-gas resources in the region, the Columbus-based Ohio Clean Hydrogen Hub Alliance will focus on blue hydrogen. That process is in place at a handful of plants around the world. Most of those consume the hydrogen for their own industrial needs, such as fertilizer and synthetic-fuel production. In the US, a



**SURPLUSES** of renewable electricity generation have grown as more wind and solar power is added to California's grid. The excess energy, which can't be stored, can be used to produce hydrogen to fuel electricity generation during times of peak demand. (Data from the California Independent System Operator.)

DOE-funded blue-hydrogen facility in Texas operated by the industrial-gas producer Air Products has been in operation since 2013. Its output is used in petroleum refining, while the CO<sub>2</sub> is piped to the state's oil fields for enhanced oil recovery. Air Products said in October 2021 that it will build a \$4.5 billion blue-hydrogen plant in Louisiana, with completion expected in 2026.

HyDeal Los Angeles, organized in Southern California by the Green Hydrogen Coalition, is projecting a green-hydrogen cost below \$2/kg. Achieving that target will require pipelines to transport the hydrogen to salt-dome storage, the coalition says. The nonprofit has identified demand for 1–3 million tons of the light gas in heavy-duty transport, industry, and power generation in the Los Angeles basin. The largest prospective consumer for HyDeal LA is the Los Angeles Department of Water and Power, which operates four natural-gas-fired power plants in the area, with a combined capacity of 1600 MW. Los Angeles also has significant cement and oil refining activities, and it is home to more hydrogen fueling stations than anywhere else in the US.

### A European model

HyDeal LA is patterned after Europe's HyDeal Ambition, a coalition of producers and consumers who have committed to making and using 3.6 million tons of green hydrogen annually at €1.50/kg by

2030, equivalent to the price of delivered natural gas in Europe. The coalition was formed after the European Commission announced in July 2020 a goal for 10 million tons of green hydrogen a year by 2030. HyDeal Ambition's first component, HyDeal España, will pipe green hydrogen produced at renewable-energy facilities in northern Spain to an industrial complex in the region beginning in 2025. That project aims for an electrolyzer capacity of 7.4 GW by 2030. Partners in the venture include the steelmaker ArcelorMittal, which last year announced it will spend \$1 billion to halve CO<sub>2</sub> emissions from its Spanish operations within five years through the use of green hydrogen.

Jonathan Lewis, director of transportation decarbonization at the nonprofit Clean Air Task Force and an adviser to HyDeal LA, says that project is estimated to cost \$25 billion. Although he notes that DOE has received some "pushback" from prospective hub proposers on the 50% cost-share requirement, he applauds the hub program. "The most compelling part of the policy is that it lifts both the demand side and supply side. Neither side has to make a leap of faith," he says. "As producers are building out capacity, they know there is also investment being made on the demand side."

State-government funding is likely to be needed for the cost sharing. Calzonetti says he is hoping to attract support from other states and institutions. He says that

DOE may try to foster interstate collaborations, perhaps by marrying the Toledo-led collaboration with Illinois, the state with the most commercial nuclear plants. Illinois's own proposal includes the University of Illinois at Urbana-Champaign and Argonne National Laboratory.

Although there is "tremendous demand" for hydrogen in industrial appli-

cations, he says, much will depend on the price. DOE's Hydrogen Shot program, launched a year ago, established a target cost for green hydrogen of \$1/kg in 10 years. That's an 80% reduction from its current cost of around \$5/kg, the agency says.

Ultimately, a hydrogen economy will require spokes as well as hubs. "We

shouldn't be looking at this as a competition between regions," Houston's Perlman told a panel discussion organized by the nonprofit Energy Futures Initiative. "Creating a real network is where the real power is going to come from, working together across the US to create a national market for hydrogen."

David Kramer

## College instructors adapt their teaching to prevent cheating

WEBS EDGE

Pressures, isolation, and the temptation of easy online answers are changing why and how students cheat.

**H**ave your students used unfamiliar variables in test solutions? Have they followed bizarre chains of logic? Have multiple students submitted identical wrong answers on homework or tests? If so, chances are they turned for answers to Chegg or some other online education company.

Chegg offers libraries of searchable solutions and the option to post new problems with requests for solutions. Other companies, such as Quizlet, Bartleby, and Course Hero, provide similar services. Quizlet profits through advertising; the others charge monthly fees ranging from \$9.95 to \$39.99.

The companies bill themselves as tutorial services for many subjects, including physics. "Everything we do is designed to put students first and let them achieve greater success with less stress and less cost," Chegg president and CEO Dan Rosensweig says in a promotional video. But students can—and do—use the services to cheat.

Cheating isn't new, but university instructors say its incidence has grown significantly with the easy access afforded by the internet and with changes in social and study habits brought on by the COVID-19 pandemic. Teaching "in the time of Chegg" is challenging, says a physics and astronomy professor at a medium-sized university in the Southeast who requested anonymity because of departmental politics surrounding the issue of how to handle students' cheat-



**ANGELA SPECK**, chair of physics and astronomy at the University of Texas at San Antonio, teaches astronomy in a flipped classroom, in which students watch prerecorded lectures on their own time and solve problems together in class. When students work on problems in class, they have less incentive and opportunity to cheat, and instructors get a sense of students' grasp of concepts.

ing. "Students think I want to see the right answer. That's not true. I want to see that they have learned the material."

College instructors across the US and beyond are grappling with how to deter cheating and reassessing how they assess their students. "The educational system will break down if cheating is widespread," says the anonymous professor. "I regard it as a public health problem rather than a crime."

### Detecting foul play

Before the pandemic lockdowns, Mark Messier, a neutrino physicist at Indiana

University Bloomington, was grading exams for the introductory mechanics course he was teaching. It was obvious that some students had cheated, he says. "I saw idiosyncratic features repeated in the solutions that multiple students turned in." A quick Google search turned up five of the six problems from the take-home exam on Chegg. "I could see they were scanned versions of my exam problems," he says.

Samantha Kelly graduated this past spring from the University of California, Berkeley, with a double major in math and physics. After she finished an online

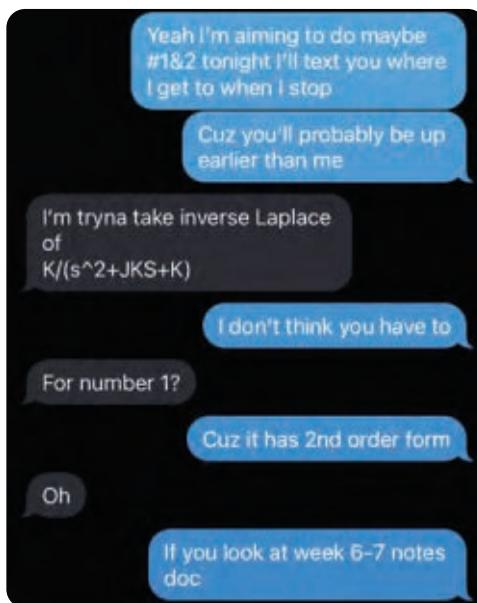
midterm exam for a junior-level quantum mechanics class in summer 2020, she “poked around online and found it had been uploaded to Chegg” while the exam was still in progress. She has also seen group chats online where students discussed how they would work together on an upcoming exam.

The distributions of grades on exams have started to reflect cheating—whether by Chegg, group chats, or other means,” Kelly says. “Instead of a nice Gaussian distribution, you see a normal curve but with a smaller peak, plus a significant peak at the 95 to 100 mark.”

Chegg—whose name comes from combining the words “chicken” and “egg”—has been around since 2005. But the use of it and other virtual aids spiked with the wholesale switch to online classes early in the pandemic. For example, Berkeley’s Center for Student Conduct received some 202 reports of academic misconduct in fall 2019; that jumped to 858 in fall 2020 and then dropped to 217 in fall 2021, when instruction was again in person. “The threshold for copying and cheating [in online settings] is severely lowered,” says Austin Hedeman, an instructor and academic coordinator for the university’s physics department. “Temptation and pressure are both high.”

Another consequence of going online and living under lockdown is that students largely lost access to easy interactions and group study situations. Instructors say students have become more hesitant to come in for help. “Working together fosters teamwork,” notes Dominik Elsässer, a senior scientist at the Technical University of Dortmund in Germany whose research and teaching focus is in astroparticle physics and radio astronomy. “That got lost in the pandemic, and companies like Chegg jumped in.”

Juan Gutiérrez, chair of mathematics at the University of Texas (UT) at San Antonio, says that for online exams, he has “witnessed answers being posted on Chegg within five minutes of a test going live.” Companies like Chegg, he says, disproportionately attract students who enter college with less preparation—often from less affluent school districts, which tend to produce more Hispanic and African American students. “Every city has sections that are under-resourced, and often students from those areas have a



**DURING A TAKE-HOME TEST** in an upper-level physics class, students broke the rules to consult with each other. (Courtesy of a regretful cheater.)

harder time and feel more pressure to turn to companies like Chegg.”

When Hedeman discovers his own work on Chegg, he requests that the company take it down. “If they don’t, they become liable for copyright violation,” he says. “This is one of our most effective tools.” Berkeley has made scores of such requests, he says, and the problems are usually removed within a few hours. “It’s quick, but not quick enough to prevent cheating on an exam.”

Even with the return to in-person classes, many instructors continue to offer a choice of taking exams in person or virtually. “Students pick the environment most suited to their success,” says Jonathan Perry, a physics instructor at UT Austin. Some students may feel more comfortable at home listening to music, while others find that the higher-stress in-class environment enhances their performance. And, adds Perry, “COVID is still a thing.” This past spring, about a quarter of his students chose to take their finals asynchronously from home.

Michael Marder, a UT Austin physics professor, says he has more questions than answers about how to prevent and deal with cheating. Still, he says, “a lot of the flexibility and trust of students was overdue. I’m talking about the ability to continue to participate if you have a personal crisis that knocks you out for a

week.” The tools to handle such situations are a positive outcome of the pandemic, he adds, although it can be difficult to distinguish between “students who need the extra support and those who are taking advantage of the system.”

### Service or disservice?

Ramón Barthelemy is an assistant professor of physics at the University of Utah. “Chegg was around when I was an undergraduate,” he says. “Students also traded solution manuals to textbooks.” Given his experience, he sees such resources as neutral. “What matters is how you use them.”

Barthelemy emphasizes that cheating will catch up to students eventually. “I tell them they will be the future builders of bridges, makers of new chemical compounds, designers of biomedical devices. . . . I try to infuse in them good ethics, and I try to assume good intent. That’s what makes me want to be a teacher.” Still, he says, he does his best to “Chegg-proof” quizzes.

Tracy Hodge, an associate professor of physics at Berea College, a small liberal arts school in Kentucky, points to the availability of more reliable resources for physics help—often offered by academic institutions. “The biggest problem is the ethics these [for-profit] services teach students,” she says. “They teach that the goal is to get the right answer and get points rather than to master the material. They teach that it’s okay to cheat. Chegg gives students a shortcut that doesn’t help them. The company is out to make money.”

For its part, Chegg is “committed to academic integrity, which we believe is fundamental to the learning process and core to our mission of providing students with the support they need to navigate their own academic journeys and succeed,” according to a spokesperson. For example, in its Honor Shield program, the company blocks a test’s questions from appearing in search results for a set period if an instructor has uploaded the test at least 48 hours in advance. But Chegg’s program doesn’t solve the cheating problem, say instructors. “What about the other similar sites?” says Messier. “There is no way to keep up with this arms race.”

Chegg also invites instructors to provide content. In a November 2021 letter

to one physics instructor, the company offered \$375 per practice exam, \$75 per practice quiz, \$120 for lecture notes, and so on. "The goal is to provide reliable study materials to college students authored by dedicated educators like you, while compensating you for your previous hard work," the letter says.

## Slippery slope

The first intervention for cheating is often a conversation along the lines of "If you cheated, you will be found out. If you come forward on your own, the consequences will be less radical than if you don't." The penalty may be harsher for cheating on exams than on homework and for students who post problems requesting they be solved than for those who copy from archived solutions.

Depending on the instructor and school, misconduct cases may be handled by the individual instructor or be sent to a campus office. On a first offense, students who admit to having cheated may be asked to write a statement about why they cheated and why they shouldn't do it again. Some, but not all, instructors assign a "0" on the homework or test a student cheated on. Subsequent offenses may lead to increasingly severe consequences, including academic probation and dismissal.

Even students who have signed pledges of academic honesty are often perplexed that their actions are construed as cheating. Karen Daniels, a condensed-matter physicist at North Carolina State University, says her students "don't see using Chegg as cheating."

UC Berkeley graduate Kelly says that the attitude among her peers about getting exam help from classmates during an exam seems to be "the professors know everyone does this," and toward online services, it's "I just use it as a backup to check my answers."

## Learning and assessing

The uptick in cheating has triggered deep discussions among faculty about how to encourage learning, says Gutiérrez. "We have to plan our assessments knowing we have this pollution [of Google-able and on-demand solutions]. The technology is not going to go away, so we have to adapt and to create problems that cannot be solved like that. It makes instructors' lives much more difficult."

Some instructors link each exam copy

**Find solutions to your homework** **Search**

**Question** **please help me!**

**Problem 9** **Ball Rolling Down a Ramp**  
A solid metal ball of mass  $m = 3.00 \text{ kg}$  is released from rest at height  $h = 1.00 \text{ m}$  and rolls down a ramp, skipping along a horizontal track. The coefficient of friction is  $\mu = 0.225 \text{ m}$ , and the ball has radius  $r = 0.05 \text{ m}$ . What is (a) the ball's velocity at the top of the ramp? (b) the ball's height when it reaches the bottom of the ramp? (c) the ball's velocity when it reaches the bottom of the ramp? (d) Why is the height in (c) less than the height at which the ball was released? (3.0 J)  
Explain in one sentence.

**Concept Selection:**

**Show transcribed data**

**Expert Answer** **Anonymous answered this** **1,385 answers**

**Continue to post**

**Free Same Day Delivery, No Min. Order, Free Same-Day Delivery with No Order Minimum.**

**THIS TEST PROBLEM** is one of several that an instructor discovered had been posted to Chegg during a remote physics exam in May 2021. Solutions are sometimes supplied in time for students to copy them—which, the instructor says, they sometimes do wholesale and sometimes more cleverly, making cheating harder to detect. (Courtesy of the problem's author, who requested anonymity.)

to a particular student. Perry, for example, individualizes tests by customizing the values of variables. Hedeman embeds a unique watermark in each exam, which allows him to identify who uploaded any problem he finds on Chegg. Some instructors create new problem sets each semester so they won't already be in the companies' archives.

Another approach is to devote in-class time to solving problems tutorial style. "I can give tougher problems, and I can get a sense of how well they understand them," says Barthelemy. For smaller classes, Daniels asks students to explain their work in detail. "It's a ton of work for them," she says, "and even if they get an answer from a friend or from Chegg, they are still responsible for explaining the steps. That mitigates the problem." Other instructors pose essay questions or give oral exams.

Those approaches can work for assignments that are individually graded. But in introductory classes at large institutions, classes can have hundreds of students, and tests are typically multiple choice. For those classes, Perry has taken to shortening test times and increasing the number of possible answers.

Many instructors have lowered the

weight they give homework. "It should count, but not be so valuable that they care enough about getting 100% to cheat," says Hodge. She now weights homework about 15% of the grade, down from 35%. Dealing with cheating has changed her philosophy about homework. "I don't believe it's about a grade anymore. I see it as developmental for students. If they are cheating on homework, they will do poorly on the exams. They are mostly hurting themselves."

Similarly, Messier has adjusted his attitude toward both homework and tests. He devotes more class time to working on problem-solving skills, and he administers two-hour tests rather than take-home ones. Whereas before he viewed exams as teaching tools and an opportunity for students to be creative, "now they are purely for assessment," he says. "The complexity and real-world applicability of problems is diminished."

"What annoys me most is that the cheating puts teachers and students into an antagonistic relationship," says Hedeman. "I don't want to have to view students with suspicion. I work hard to maintain a cooperative and collaborative environment."

Toni Feder 

## 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

**N**etworking 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 pro-



**Samantha Pedek**

fessionals at the height of their careers were all under one roof for three days.

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-



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

## 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](http://www.spsnational.org/programs/internships)

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 re-

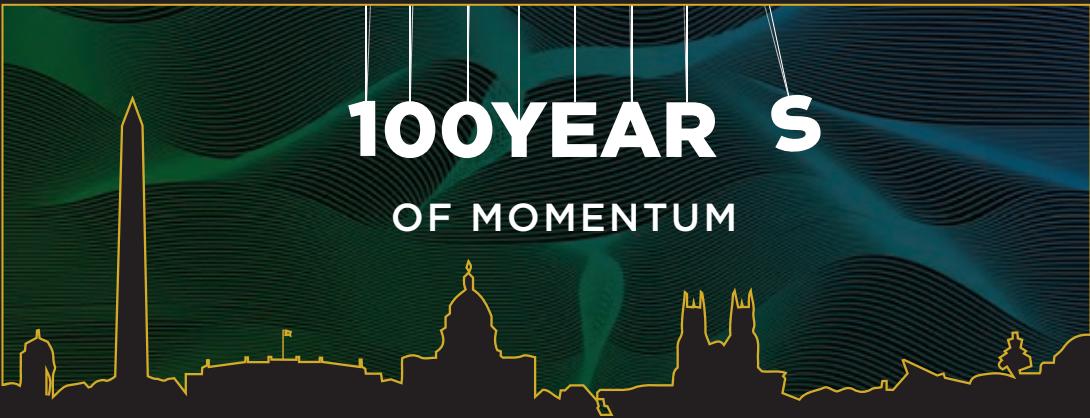


2019 Physics Congress attendees visit one of the many graduate school booths in the exhibit hall to learn about the program and check out physics demonstrations. Photo courtesy of SPS National.

search?" 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



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# Physics . . .



A mother cuts an orange in half to demonstrate the concept of hemispheres to her children. (From M. A. Swift, *First Lessons on Natural Philosophy, for Children. In Two Parts. Part First*, new ed., Brown & Gross, 1884, p. 11. Courtesy of the Niels Bohr Library and Archives.)

**Joanna Behrman** is a public historian at the Center for History of Physics of the American Institute of Physics in College Park, Maryland.



# is for girls?

Joanna Behrman

**Contrary to modern stereotypes, the laws of the natural world used to be considered a fundamental part of young women's education.**



*S*ometimes history can be quite unexpected. A look to the past can quickly overturn an idea we might think of as having always been true. For instance, although the physics community now struggles with the perception that physics is a discipline for boys, not girls, that stereotype is only about a hundred years old. Once upon a time, physics—or natural philosophy, as it was called until the second half of the 19th century—was a girls' subject.

The US has a long history of science education for women through female academies, seminaries, and colleges. Although science education in the 19th century was most readily accessible to the white middle and upper classes, it was available to Catholics and Protestants alike and even to some elite Black and Indigenous women.<sup>1</sup> The historians Kim Tolley, Margaret Nash, and Jessica Linker, among others, have shown that an important part of education for young girls and women was natural philosophy: the scientific study of physical things, including their composition, behavior, and context. In fact, as Tolley has shown, natural philosophy was considered a more important part of a girl's education than a boy's. More girls than boys took it in schools, and many influential popular science and educational texts were written by women. (See

the article by James Secord, PHYSICS TODAY, January 2018, page 46.)

By the early 20th century, however, the present-day notion of physics as a boys' subject had taken hold. So why were things different—and what changed?

## Science and God

In the early 19th century, female secondary schools, known somewhat interchangeably as academies and seminaries, enrolled students from their early teens to their early twenties. Around 1800 they generally advertised courses in English, arithmetic, and geography. But geography encompassed far more than the names of countries and their capitals. A course on the subject might include a discussion of minerals, air pressure, the solar system, and other aspects of the physical sciences.

# PHYSICS...IS FOR GIRLS?



**FIGURE 1. A FATHER** demonstrates an air pump to his family in the parlor. Other natural philosophical apparatus sit arrayed on shelves in the background. Parlors were often sites of scientific demonstrations, discussions, and early childhood education. (From R. G. Parker, *First Lessons in Natural Philosophy. Designed to Teach the Elements of the Science. Abridged from the Compendium of School Philosophy*, A. S. Barnes & Co, 1848, frontispiece. From the author's collection.)

By the 1820s and 1830s, science curricula were expanding even further. Hartford Female Seminary in Connecticut, at its opening in 1823, offered geography, natural philosophy, chemistry, arithmetic, algebra, and geometry.<sup>2</sup> As Nash discovered in a study of 91 academies, the number offering courses in algebra increased from just 19% in the 1820s to 67% in the 1830s. Moreover, by the 1830s, 72% of academies offered botany, 77% offered chemistry, and 68% offered astronomy.<sup>3</sup> Science was well integrated into female education at the primary and secondary levels.

No science was more widely studied in schools for girls, however, than natural philosophy. Nash's survey showed that in both the 1820s and 1830s, 84% of academies offered natural philosophy. In addition, Tolley surveyed schools in North Carolina, Virginia, and some northern states, and she found that natural philosophy was the most widely offered scientific subject in girls' schools—more commonly taught than astronomy, chemistry, botany, mineralogy, or natural history. And girls were learning it well: As Tolley's comparison of competitive

examinations at 19 Boston schools in 1845 revealed, not only were female students taking the natural philosophy examinations in greater numbers than male students, but they were also outscoring the boys.

Natural philosophy, at its heart, was the study of the laws of nature on Earth and in the universe. A course on the subject would have included lessons on mechanics, machines (as shown in figure 1), light, heat, rudimentary astronomy, and more. But the natural philosophy education of the early 1800s differed in many ways from the physics education of today. For instance, although instructors might perform scientific demonstrations—despite their smaller budgets, many women's academies invested in experimental equipment—students would not have participated in laboratory work themselves.<sup>4</sup> Laboratory education did not develop in the US until the late 19th century.<sup>5</sup> In addition, natural philosophy education at the primary and secondary school levels was largely conceptual. Although the diagrams in figure 2 might look familiar to a modern-day physics student, the numerical calculations would have been absent. The interweaving of mathematics into physics education developed over the 19th century and, as with laboratory education, took hold initially and most quickly at the collegiate level.

But perhaps the biggest difference is in the role of religion: Natural philosophy presented the physical world as evidence of the wonder and extent of God's creation. The link between natural philosophy and religion was part of a larger movement of natural theology, which gained popularity in the UK in the early 1700s and whose proponents argued that the mechanisms or design of nature attested to the presence of a creator. Natural theology was popular in the American colonies and in the US throughout the 18th century; for example, the noted theologian Jonathan Edwards supplemented his biblical study and prayer with study of the natural world. And during the Second Great Awakening, from 1795 to 1837, which saw a revival of many Protestant denominations in the US and a general increased fervor for religion, adherents also encouraged the study of the natural world.<sup>2</sup> Linker has argued that natural philosophy was perceived to boost intellectual and moral fortitude and stand as a bulwark against irreligion and superstition.<sup>6</sup>

It was in part through the moral and religious dimension that natural philosophy came to be closely associated with girls' education. For instance, in 1834 John Ludlow, a clergyman and theologian, declared at the opening of a new female academy in Albany, "The analysis of science and revealed religion will ultimately terminate in the same point. That point, if point it may be called, is the invisible God. He is at the foundation of both. Hence, whether you study science or revelation, it is only perusing different pages in the same great Book, which the Creator has spread out before his intelligent creatures."<sup>7</sup>

## A useful education

A look at some of the educational material of the time shows how natural philosophy was taught and why it was such a prevalent subject in girls' schooling. Some commonly used

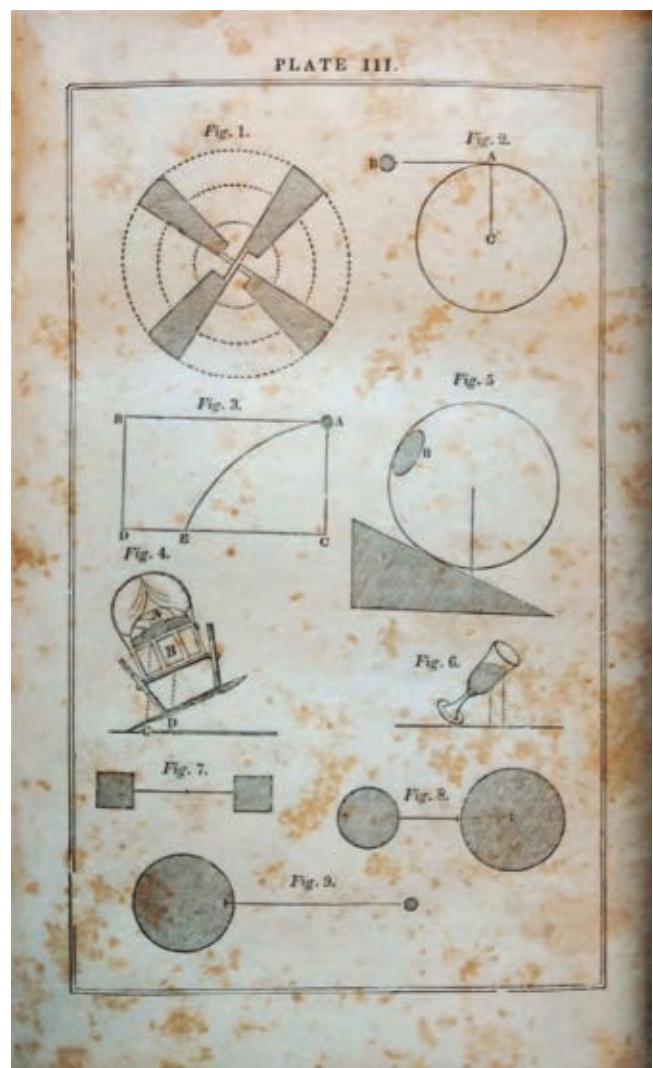
books include *Conversations on Natural Philosophy, in Which the Elements of That Science Are Familiarly Explained* by Jane Marcet (1826), Richard Parker's *First Lessons in Natural Philosophy, Designed to Teach the Elements of the Science* (1848) and *Juvenile Philosophy: or, Philosophy in Familiar Conversations; Designed to Teach Young Children to Think* (1851), and Mary Swift's *First Lessons on Natural Philosophy, for Children* (3rd edition, 1839). Swift, who served as the second principal of the Litchfield Female Seminary in Connecticut, wrote two primers on natural philosophy constructed as question-and-answer dialogs between children and their parents. Box 1 shows how Swift embedded moral and religious lessons into the scientific discussion: A discourse on prisms, the nature of light, and rainbows turns seamlessly to the biblical story of Noah.

Although Swift's and Parker's books were written for younger children, Swift would certainly have embedded the same moral valences into her lessons for secondary-school-age students. The structure of books for younger children could also mimic the styles of religious education by using a catechism format: a question-and-answer oral dialog in which the student memorized the answers. For older students, Marcet's books took the form of a conversation between the sophisticated and knowledgeable Mrs. B. and two young women named Emily and Caroline. Although Marcet intended her books for a general audience, they were frequently used as textbooks in secondary schools, and their conversational style was later imitated by such textbook authors as Mary Townsend and Elizabeth Cary Agassiz.<sup>2</sup>

Natural philosophy lessons were not only for female students—Swift's, Marcet's, and Parker's books were all directed at both boys and girls. But their social implications differed according to the student's gender, as figure 3 illustrates. At men's colleges, in which a classical curriculum was a marker of higher-class education, science was perceived as having a vocational or lower-class nature. At women's academies, in contrast, science education was more commonly the mark of an upper-class education.<sup>2</sup> Even the same material taught in the same institution would be put to different purposes by male and female students. For example, according to an instructor at the Litchfield Academy, which at that time was coeducational, astronomy was taught to male students for the practical skill of navigation. For female students, the same content was used to display "the wonders of God's universe."<sup>8</sup>

To truly understand the time period, however, we must reject the modern bias that assumes that the male students received a useful science education and the female students an ephemeral one. As Linker has argued, ideas of what made an education "useful" were not the same in the 18th and 19th centuries as they are today.<sup>6</sup> Lessons might be considered useful not just for their applications to practical or vocational labor—or to daily life, as shown in box 2—but also for reasons of culture or ideology. Textbook authors such as Marcet and Almira Hart Lincoln Phelps justified women and girls' education in chemistry, for instance, because it had both domestic and religious uses: cooking, cleaning, and appreciating God's creation. Such reasoning supported a scientific education that far exceeded the minimum necessary for domestic or religious needs alone.<sup>9</sup>

Even so-called ornamental subjects, such as sewing, dancing, and drawing, were often closely intertwined with academic subjects.<sup>10</sup> Consider the importance of illustration in



**FIGURE 2. ALTHOUGH INSTRUCTION** was largely qualitative, Jane Marcet's book on natural philosophy contained many diagrams recognizable to physics students and teachers today. The figures here come from the chapter on compound motion and determining an object's center of mass. (From J. H. Marcet, *Conversations on Natural Philosophy in Which the Elements of That Science Are Familiarly Explained*, Lippincott, Grambo & Co, 1852, plate 3. Courtesy of the Niels Bohr Library and Archives.)

botany, especially in the days before photography. In another example, geography was often taught through embroidery of maps. Geography was touted as encouraging the mental discipline of women and girls, and it was also a convenient way to instill nationalism by depicting the successful expansion of the young country.<sup>11</sup> Natural philosophy education was justified through all the knowledge it taught about the universe: the religious and ethical dimensions as well as the practical.

## Wives, mothers, teachers

Women had a special role in upholding and transmitting values because they were responsible for early childhood education. Before children even attended a primary school, they often received their first schooling at home from their mother

## Box 1. Rainbow connection

A father points out a rainbow to his assembled children. The rainbow, like many other natural phenomena, was used to make a direct connection to faith in the divine. The accompanying text reads in part:

*Do you ever see a rainbow when it rains, unless the Sun shines bright?*

I do not.

*Then what two things are necessary to make a rainbow?*

A bright sunshine and a shower.

*Why is the rainbow so beautiful?*

It has beautiful bright colors, a splendid arch, and when we see it we remember the promise which God made to Noah, that he would not drown the world again.

*Why does the RAINBOW make you think of that promise?*

Because God said that the bow in the cloud should be a sign that he would never drown the world again.

*Then when we see the rainbow, is it not as if God was speaking that promise to us?*

It is; and it should make us very happy, and grateful to our heavenly Father for such kindness to us, whenever we look at the rainbow in the cloud.



(Image from M. A. Swift, *First Lessons on Natural Philosophy, for Children. In Two Parts. Part First*, new ed., Brown & Gross, 1884, p. 43. Courtesy of the Niels Bohr Library and Archives.)

or a female relative. For many poor students, that might be all the education they got, especially prior to the haphazard development of “common”—what we would now call public—schools.<sup>12</sup>

After 1820 dramatic socioeconomic changes in the US reinforced the need for moral education. Westward expansion, increased suffrage, and migration to cities all called into question the strength of traditional systems of social order.<sup>13</sup> Education, through both the family and the rapidly expanding system of formal schools, helped inculcate social norms and prepare children for the increasingly likely prospect of moving away from the community of their birth. As more male heads of households worked away from home, mothers took on an even greater role as intellectual and moral educators. A growing preference for female schoolteachers reflected the idea of the mother as the greatest moral example and influence.

The historian Linda Kerber coined the term “Republican Motherhood” to explain the sentiments of the day. The ideal Republican Mother was a woman who integrated political and domestic values for the purpose of upholding the fledgling republic. She instilled values in her children, kept her husband on the straight and narrow path, and thereby had her role in directing the young country’s growth. In fact, the figure of the Republican Mother was used by reformers to justify the expansion of education for women in the decades after US independence. Enlightenment beliefs and the practical necessity of certain kinds of knowledge also contributed significantly to the growth of women’s educational opportunities in the 18th and 19th centuries.<sup>14</sup>

But the notion of Republican Motherhood applied specifi-

cally to white women, and it argued only for white women’s education. Not surprisingly then, white female seminaries, including those in the northern states, largely barred Black women from attending despite decades of activism by Black male and female advocates. One exception was the Young Ladies Domestic Seminary in Clinton, New York, a majority-white female seminary run by a white abolitionist and one of the first racially integrated female seminaries in the North. Black women who attended private seminaries usually went to coeducational institutions run by white abolitionists, such as the Oberlin Collegiate Institute (later Oberlin College) in Ohio.<sup>15</sup>

Only a few Black female seminaries existed; most African American-run schools were coeducational because of a belief in joined education or pragmatism about cost. One of the rare seminaries geared towards Black women and girls was Sarah Mapps Douglass’s school in Philadelphia, which placed a strong emphasis on science education. Douglass’s seminary was eventually absorbed into the Institute for Colored Youth in the 1850s, where Edward Bouchet, the first African American to earn a PhD in physics, would also go on to teach.<sup>16</sup>

Even though the ideal of Republican Motherhood doesn’t fit exactly with African American women and children, the historian Kabria Baumgartner has shown that character education for citizenship was also an important part of African American education in the early 19th century. In particular, many African American women advocated an ideology of Christian domesticity, in which women were considered uniquely qualified to provide a moral and educational authority from their domestic domain. Although white female education advocates such as Catherine Beecher supported the same ideology, among

African American women, Christian domesticity could be an empowering tool of community uplift.<sup>15</sup>

## Changing times

Women's role as the first teachers of children continued to justify the teaching of physics to girls well into the late 19th century. In an 1887 address to the American Association for the Advancement of Science, the physicist William Anthony said:

Not only boys but girls should receive [physical science] training in order that the great truths of nature may become the heritage of future generations and be taught to the child from his earliest infancy. . . . I have in mind now a little boy of five years whom I have met this summer, whose father has a mill and machinery in operation, and whose mother is one of those rare women, gifted with a natural insight into physical laws. Partly by being about the mill, but mainly by his mother's teaching, this boy has learned. . . .<sup>17</sup>

But change was afoot. At the dawn of the 20th century, more than half of secondary-school physics students were female, but by 1950 only 20–30% were. As part of a shifting landscape in industry and higher education, many schools stopped requiring physics classes for graduation, and physics began to be perceived increasingly as a masculinized subject.<sup>18</sup>

Many reasons underlie that shift, including changes in wider cultural norms and the professionalization of science—but some have direct roots in secondary schools and colleges. First, over the 19th century, more and more colleges opened their doors to women, and more women pursued postsecondary education. The hallmark of a prestigious college education was a curriculum in the classics, so colleges for women increasingly adopted classics requirements to boost their status, and secondary schools added classes in the classics to stay with the trend. Some schools even encouraged girls to drop science classes in favor of studying Latin or Greek. Thus, even as science classes came to be dominated by boys, the humanities



**FIGURE 3. A NATURAL PHILOSOPHY** education had different meanings for boys and girls. Rollo, the fictional main character in a series of popular educational books for children, is helped in his natural philosophy investigations by his knowledgeable mother and sister. But Rollo applies his learning, such as the use of wedges and other simple machines, in industrial applications as modeled by his father and male workmen. (From J. Abbott, *Rollo's Experiments*, Hogan & Thompson, 1841, p. 61. Courtesy of the Niels Bohr Library and Archives.)

were experiencing the opposite trend. The primacy of classical study in college education has since waned, but the effect of its earlier importance is still felt.<sup>2</sup>

Second, as state governments passed education mandates in the early 20th century, more working-class children attended secondary school than ever before. Many states and schools then restructured their curricula to be more relevant to the working-class students who would presumably never attend college or need to know anything esoterically intellectual. Female students were directed toward classes in typing and home economics—and away from subjects less immediately useful, like physics.

The process of tailoring education to the needs of students was also shaped by the larger and ever-prevalent discussion of

## Box 2. Sweet and salty

A girl sprinkles salt in the background as a boy slips on an icy walk. The accompanying question-and-answer dialog touched on the practical connections of natural philosophical knowledge to daily life:

*What would happen to us if there were no friction?*

We could not walk a step before we should begin to slip along very fast, and could not easily stop ourselves.

*How do people increase the friction when the walks are covered with ice?*

They throw sand, or ashes, or something rough, upon them.

(Image from M. A. Swift, *First Lessons on Natural Philosophy, for Children. In Two Parts. Part Second*, new ed., William J. Hamersley, 1867, p. 83. From the author's collection.)



## PHYSICS...IS FOR GIRLS?

gender differences. Educators and school administrators feared that female students might be masculinized by scientific study—which by then was fully divorced from religion and sentiment; physics was now physics, not natural philosophy. If girls were to get a scientific education, they thought, better that it be in the domestic science of home economics. Some female scientists even used domestic science as a career strategy. At the collegiate level and above, home economics was often a way for women to work in the sciences on appropriately feminine topics of study (see the article by Joanna Behrman, *Physics Today*, May 2018, page 50). At the secondary school level, however, home economics classes were largely aimed at preparing girls—particularly working-class and African American girls—for their presumed future careers as domestic laborers, wives, and mothers, not scientists.

How can the present be so different from the past? We're no strangers to rapid cultural change in other areas—fashions in clothing, for instance, change extremely quickly. But ideas about who is good at or interested in science feel much more permanent. Even deliberate efforts to make physics classrooms more inclusive struggle against the stereotype that girls don't really belong or want to be there. How instructive it is, then, to think about a time when gendered expectations in science education were the opposite of what they are today. It goes to show how impermanent culture really is, and how much it depends on the context of time and place.

And if culture can change over time, let us undertake the effort to change it for the better.

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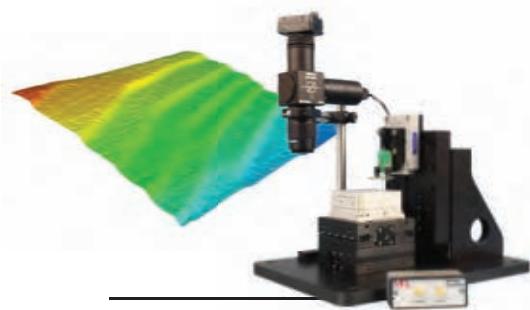
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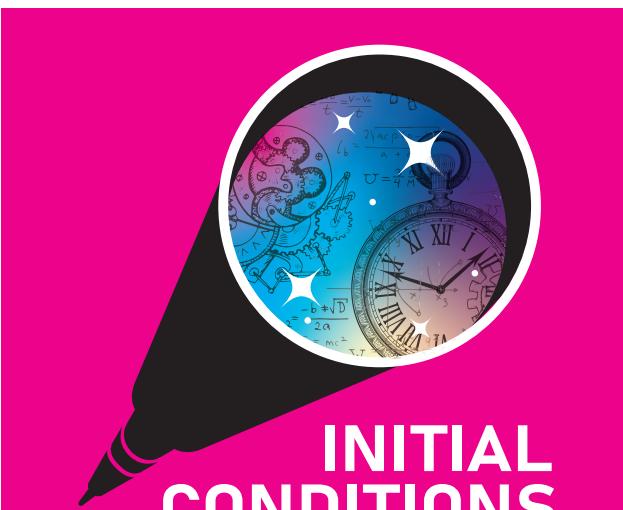
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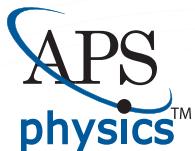
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# METASURFACES for quantum technologies

Kai Wang, Maria Chekhova, and Yuri Kivshar

Subwavelength planar structures can generate, reshape, and entangle photons in a compact and stable device.

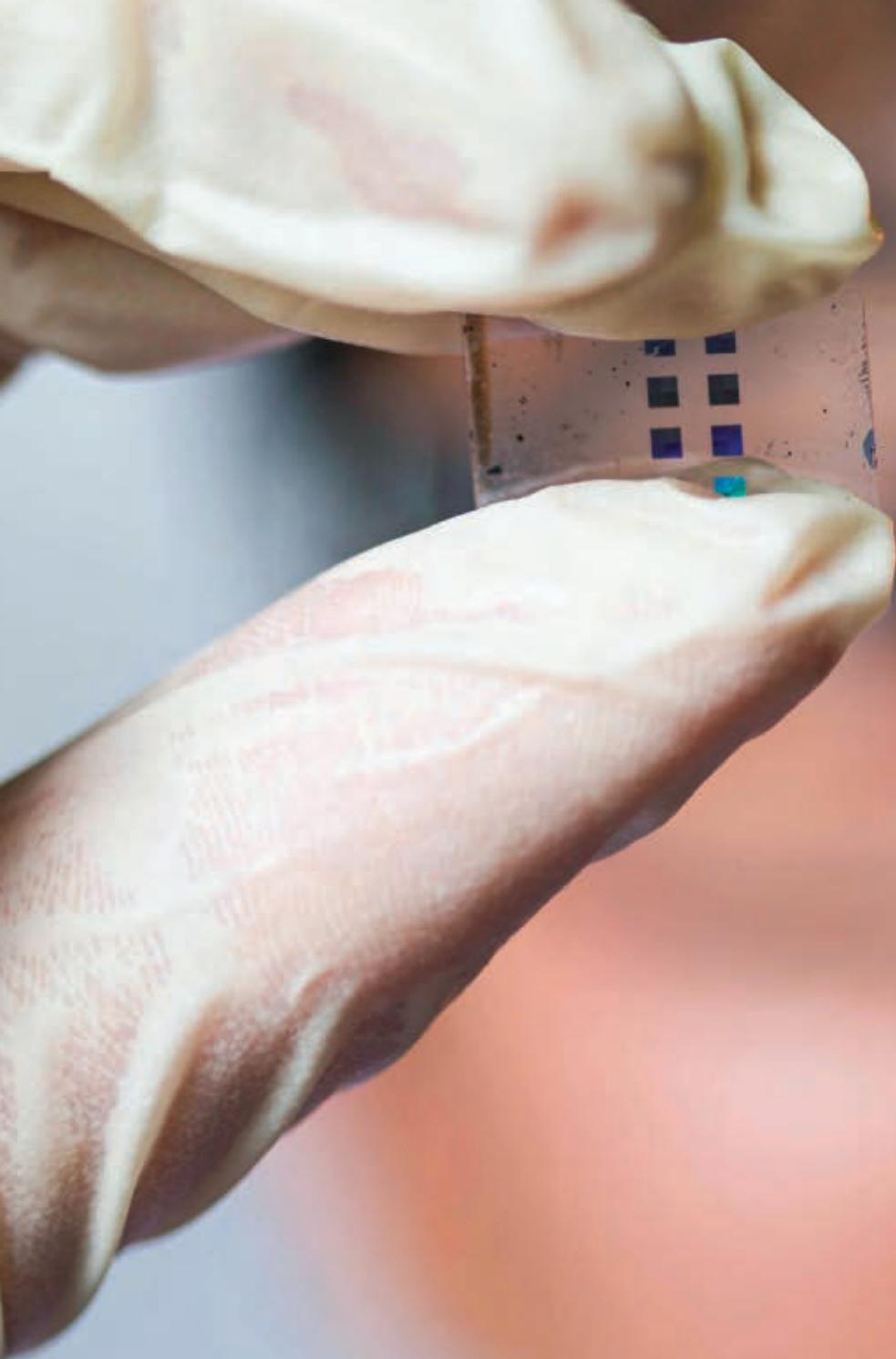
**I**n the past decade, optical metasurfaces have become increasingly popular tools for bending, focusing, and otherwise transforming light. They precisely control light-matter interactions with subwavelength structures. The planar surfaces comprise metallic or dielectric optical resonators that manipulate electromagnetic waves in specialized and novel ways.<sup>1,2</sup> The idea of pairing light scattering with planar optical structures isn't new: For more than 50 years, researchers have designed diffractive optical elements that serve as beam shapers, beamsplitters, and diffusers.<sup>3</sup> But metasurfaces are more efficient and adaptable than diffractive components and can provide flexible control of light-matter interactions.

Conventional optical components guide electromagnetic wavefronts as light propagates in a bulk medium along optical paths of different lengths. Metasurfaces, on the other hand, control the phase, amplitude, and polarization of light waves within a distance much less than the wavelength.<sup>2,4</sup> The resulting optical elements and devices are effectively two-dimensional, offer new functionalities, and outperform their traditional bulk counterparts.<sup>4-6</sup>

Metasurfaces consist of carefully ar-

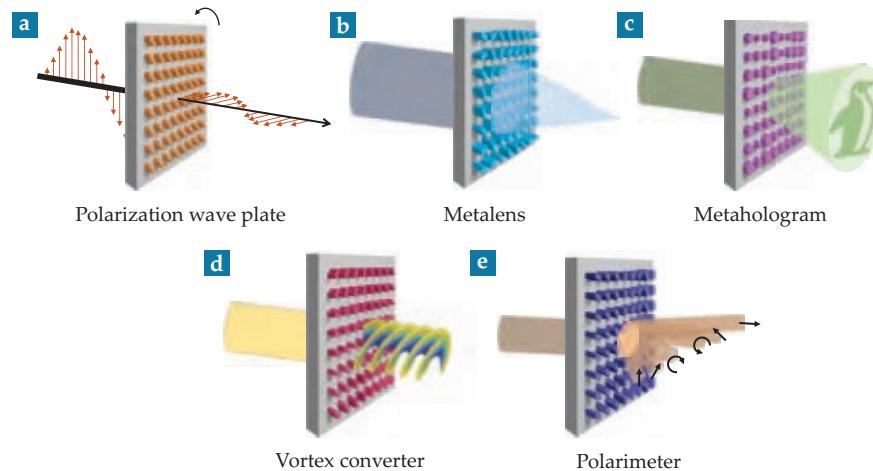
ranged subwavelength unit cells, often called meta-atoms. The optical response of a meta-atom depends on its height, width, material, and other properties. To achieve the desired functionality in an optical component, researchers fabricate an array of meta-atoms whose parameters vary across the device based on their specific contribution. Meta-atoms can operate as subwavelength resonators<sup>5,7</sup> (see box 1), or they can contribute to effective averaged parameters.<sup>4</sup>





Courtesy of Lannon Harley, the Australian National University.

# METASURFACES



**FIGURE 1. METASURFACES** use subwavelength structures to manipulate light's wavefront. They can (a) rotate light's polarization, (b) focus light, (c) generate three-dimensional images, (d) change light's orbital angular momentum, (e) separate light based on polarization, and more. The ultrathin devices can replace bulky traditional classical-optics components.

Optical metasurfaces have demonstrated many functionalities, such as those depicted in figure 1, and sometimes even several at once. Many of those applications constitute promising alternatives to conventional bulky optical elements and devices. The metasurfaces are ultrathin, lightweight, and ultra-compact and may overcome some limitations of their traditional counterparts. Metasurfaces may soon replace bulky traditional wave plates, vortex converters, lenses, and holograms operating at many frequencies. After successfully using them in classical-optics applications in the past decade, scientists have recently expanded the use of metasurfaces to the quantum realm.<sup>8</sup>

## From classical to quantum

In quantum information science and technology, photons are ideal information carriers. But encoding and transforming information in them requires new types of optical devices beyond classical ones. The flexibility, compactness, and high efficiency of metasurfaces are factors that make them promising quantum optics candidates.

The quantum states of light needed for quantum technologies include single photons and entangled photon pairs, among

others. All those states have properties that cannot be described by classical theories of light. Free-space quantum optics components are essential tools to control those states, because they can readily access multiple intrinsic degrees of freedom, such as polarization, orbital angular momentum (OAM), and frequency. So far, most free-space applications rely on bulk optical elements, including beam splitters, wave plates, and mirrors, many of which are designed to be dynamically reconfigurable to tune device behavior. Although those platforms have enabled the demonstration of quantum computation with linear optics,<sup>9</sup> they are challenging to align, bulky, prone to losing photons, and mechanically unstable, which introduces errors.

Metasurfaces can replace many of those bulky optical elements in quantum light applications in free space and at the interface between free space and photonic devices. As a conceptual illustration, figure 2 depicts how a metasurface could simultaneously transform photons from  $M$  input ports and send them to  $M$  transmission outputs. One could encode quantum information in multiple degrees of freedom: two degrees of freedom from the polarization,  $M_\omega$  degrees of freedom from the frequency,  $M_\text{O}$  from the OAM, and  $M$  from the different spatial paths. For an input  $N$ -photon quantum state,

## BOX 1. RESONANCES IN METASURFACES

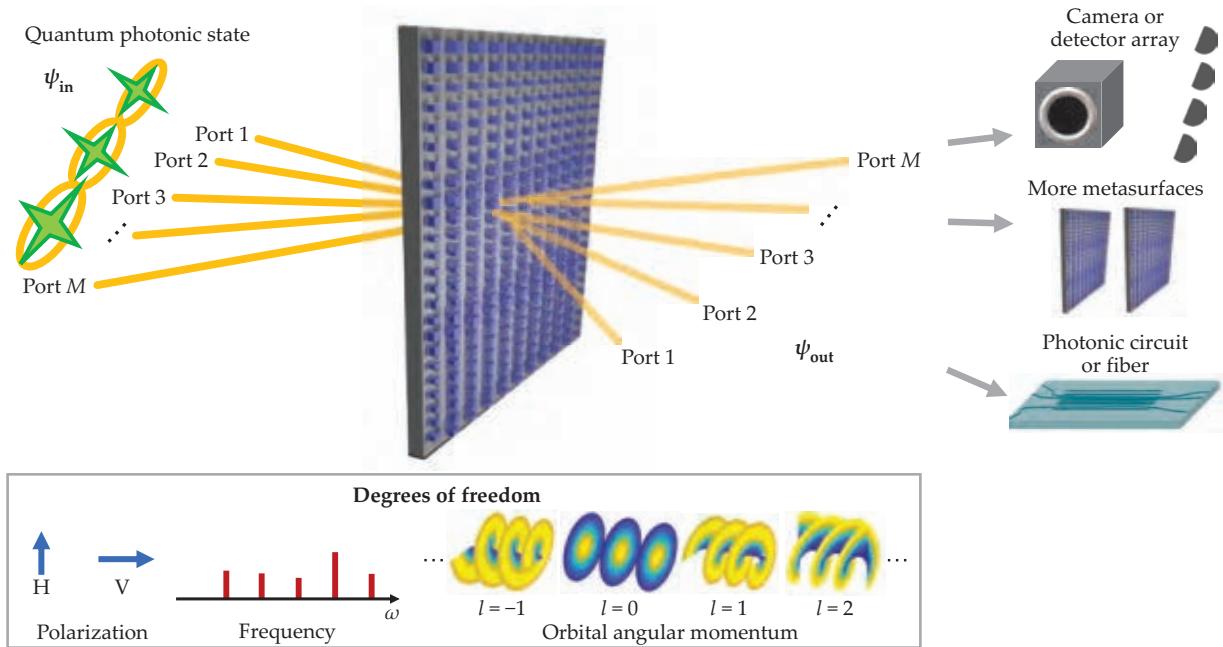
Resonances substantially enhance the electric and magnetic fields, which is an important requirement for many functionalities. Several physical mechanisms are responsible for the field enhancement and mode engineering in metasurfaces, including local resonances, such as surface plasmon resonances; Mie resonances of individual nanoparticles; and collective resonances, such as guided-mode resonances and bound states in the continuum (BICs). For quantum applications, Mie resonances and BICs are particularly important.

**Mie resonances** are associated traditionally with the exact solutions to

Maxwell's equations for the scattering of electromagnetic plane waves by spherical particles. In a broader context, they explain how high-index dielectric nanoparticles control light below the free-space diffraction limit, and recently, they have attracted attention because they can support optically induced electric and magnetic resonances of comparable strengths, which underpin the emerging field of Mietronics.<sup>7</sup>

**BICs** are light states that remain localized despite their energy residing in the continuous radiation spectrum of the surrounding propagating modes.

They have attracted considerable interest because they provide a mechanism for long-term trapping of electromagnetic energy in open resonators. A true BIC is a mathematical object with an infinite quality factor  $Q$ , which is defined as the ratio of the resonance frequency to its spectral width. In practice, a BIC can be realized as a quasi-BIC—produced by what's known as a supercavity mode—where both the  $Q$  factor and the resonance width are finite. High- $Q$  quasi-BIC modes enable light localization in conventional photonic structures, such as nanoantennas, coupled optical waveguides, and metasurfaces.



**FIGURE 2. IN QUANTUM OPTICS**, information can be encoded in light's polarization (horizontal H or vertical V), frequency  $\omega$ , orbital angular momentum (given by quantum number  $l$ ), and other properties. A metasurface can transform that information as it transmits photons from  $M$  input ports in state  $\psi_{in}$  to  $M$  output ports in state  $\psi_{out}$ . Those outputs can then lead to other optical elements, such as single-photon sensitive cameras, additional metasurfaces, and integrated photonic circuits or fiber interfaces, depending on the application.

the total number of degrees of freedom scales exponentially with  $N$  as  $(2 \times M_\omega \times M_O \times M)^N$ . The metasurface transforms an input state into a wide range of output states. Although the simplest metasurface designs offer static transformations, applying electric fields and many other emerging methods can dynamically tune the metasurface to make the transformations reconfigurable.

The metasurface's outputs can be used for quantum imaging, for example, which aims to improve imaging resolution, signal-to-noise ratio, and spectral range through clever applications of quantum entanglement. Cameras with single-photon sensitivity, such as single-photon avalanche photodiode image sensors, or arrays of single-photon detectors, such as superconducting nanowires, would then precisely measure the photons. Alternatively, the output could lead to other optical elements, such as additional metasurfaces or photonic circuits or fibers.

Many experimental efforts have demonstrated the use of metasurfaces for quantum state manipulation. One of the early explorations generated entanglement using the polarization and OAM of single photons.<sup>10</sup> In that 2018 work, Mordechai Segev and Erez Hasman of the Technion–Israel Institute of Technology and their colleagues directed a beam of linearly polarized single photons toward a metasurface that converted them to a superposition of states with OAM quantum number  $l = 1$  and left-handed circular polarization and with  $l = -1$  and right-handed circular polarization.

In another work, two of us (Wang and Kivshar) and our colleagues designed a metasurface that reconstructs the polarization states of  $N$  photons.<sup>11</sup> The design used one of  $M$  potential spatial input ports and sent the  $N$  photons that entered the port to the  $M$  possible output ports. Each output port projected the

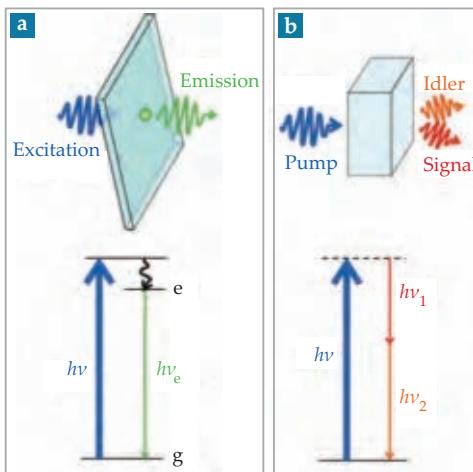
photon's polarization state to a judiciously designed polarization basis, and a detector was placed at each port. The detectors collectively measured the probability of  $N$  photons arriving at  $N$  ports simultaneously, known as  $N$ -photon nonlocal correlations. By repeatedly measuring the correlations between the measurements at the output ports, we reconstructed the density matrix of the  $N$ -photon polarization state—in our case, up to  $N = 2$ —which contains information about amplitude, phase, quantum entanglement, and coherence. The metasurface-based approach is scalable because the required number of output ports scales linearly with the photon number. What's more, fabrication imperfections can be accounted for with a one-time calibration measurement.

Metasurfaces are also particularly suitable for achieving nonunitary transformations—that is, state evolution that doesn't conserve energy. Such transformations can provide novel regimes for photon-state manipulation. For example, Xiang Zhang of the University of California, Berkeley, and his colleagues demonstrated that a nonunitary metasurface can tune the interference behavior between two photons.<sup>12</sup> The metasurface served as a beamsplitter with two spatial input ports and two spatial output ports, but it had an anisotropic phase response, a phenomenon that is responsible for the nontrivial losses behind the nonunitary response. By rotating the metasurface, Zhang and his team continuously tuned the photon interference between bosonic behavior, where the photons coalesced, and fermionic behavior, where they remained separate.

Andrey Sukhorukov's group at the Australian National University designed and realized a metasurface that performed nonunitary transformations to change the polarization states and degree of entanglement of two photons.<sup>13</sup> The nonunitary metasurface was made of silicon patterned with alternating

## BOX 2. OBTAINING SINGLE PHOTONS AND PHOTON PAIRS

Single photons and photon pairs are the simplest quantum light states available in the lab. Single photons (see panel a) are emitted by atoms or their solid-state analogues—quantum dots, organic molecules embedded in crystals, or color centers in diamond—as they spontaneously transition from an excited state (e) to a ground state (g). They typically get into that excited state through a stimulated transition: a pump photon of energy  $h\nu$  (blue arrow) followed by a relaxation to level e (black arrow). Then they spontaneously transition down (green arrow). Classical optics cannot explain such spontaneous transitions; their description requires a quantized field. A simple explanation is that the transitions are stimulated by the vacuum field. Although normally the vacuum field populates all radiation modes uniformly, it can



be enhanced for certain modes—here, at the frequency  $\nu_e$ —because of an optical cavity or a resonance. That enhanced vacuum field, in turn, enhances the spontaneous emission.

Photon pairs are most easily ob-

tained through nonlinear optical processes, the simplest one being spontaneous parametric down-conversion, shown in panel b. In SPDC, a pump photon splits into two daughter photons, called a signal and an idler. The process is similar to the spontaneous emission of single photons: A pump photon (blue arrow) excites the nonlinear material to a temporary virtual state, and then the spontaneous transition returns the system to the ground state. That transition, which is mediated by the material's second-order susceptibility, produces a pair of photons (red and orange arrows). Similar to a single-photon transition, an enhanced vacuum field caused by a resonance—in this case, at one or both of the frequencies  $\nu_1$  or  $\nu_2$ —increases the probability of a two-photon transition.

rectangular cuboids such that the diffractive loss depended on the input polarization state. Such a nonunitary metasurface can transform the polarization of a pair of photons in the same path from any arbitrary initial states to any desired final states.

### Generating quantum light

Replacing bulk linear optical elements with metasurfaces is not enough to implement quantum technologies on ultrathin platforms. Those platforms must also generate quantum states of light. The resonances in metasurfaces, explained in box 1, are essential for that task.

Resonances act not only on incident light; they can also enhance the efficiency of spontaneous light emission. The enhancement is best understood in terms of vacuum fluctuations—the tiny and transient electromagnetic fields that inevitably fill space even at zero temperature. In a meta-atom, resonances increase the vacuum fluctuations at certain frequencies and decrease them in the rest of the spectrum, similar to the Purcell effect in optical cavities. The resonances boost the spontaneous emission of single photons and photon pairs, as explained in box 2. Moreover, they shape the spectrum and direction of the emitted light.

That enhanced spontaneous emission is, for a few reasons, particularly useful in conjunction with quantum dots and other sources of single photons. First, most single-photon sources have insufficient photon-emission rates for many practical applications. Second, they typically emit photons in a broad range of directions, which makes the radiation hard to collect. Finally, in most cases, the sources emit a broad spectrum of light, in which individual photons remain distinguishable and thus not

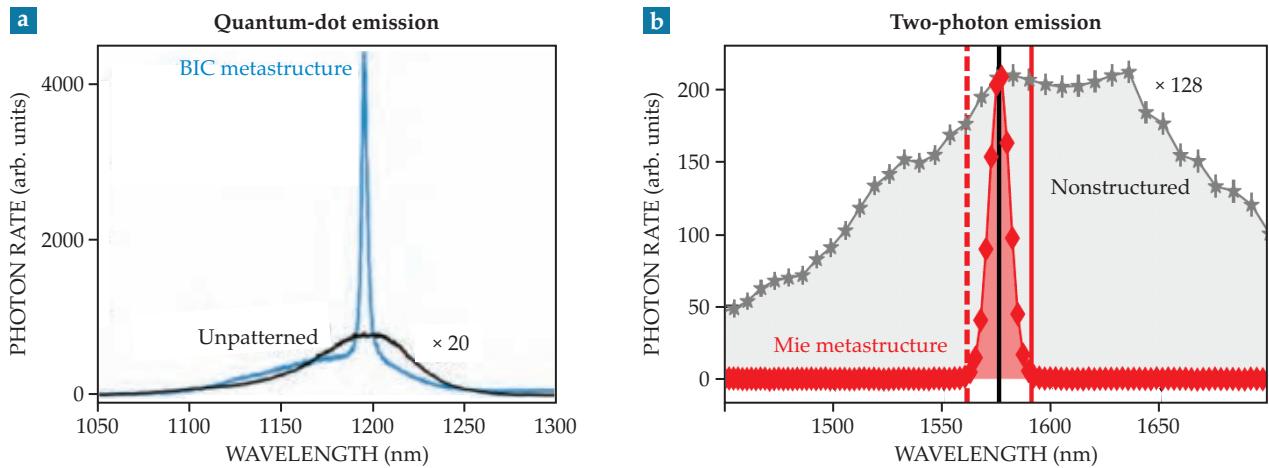
suitable for quantum technologies. All those problems can be solved by embedding single-photon emitters into resonant metasurfaces.

Figure 3a shows the effect of a gallium arsenide metasurface on embedded indium arsenide epitaxial quantum dots.<sup>14</sup> The metasurface consists of nanoresonators with broken symmetry: Instead of perfect cubes, each resonator has a corner removed. That broken symmetry leads to a quasi-bound state in the continuum (BIC) resonance, which is a trapped light state with a sharp frequency (see box 1). The BIC is at a wavelength close to 1200 nm with a quality factor  $Q$  of about 100—as a result, within a bandwidth of about 12 nm, the spectral density of vacuum fluctuations is amplified 100-fold. Accordingly, the emission of a quantum dot, otherwise broad and not too bright (the black curve in figure 3a), is enhanced about two orders of magnitude within a narrow spectral range (blue curve). The resonance also makes the quantum dot emit preferentially in the direction normal to the metasurface.

Today, only four years after that original study, more advanced designs yield quasi-BIC resonances with  $Q$  factors as high as  $10^4$ . Those resonances promise further enhancement of spontaneous emission and further shaping of the emission's spectrum and directivity. Metasurfaces can also shape the polarization by, for example, making a quantum dot emit differently polarized photons in different directions—an example of multifunctional operation.

### Photon pairs

Last year one of us (Chekhova), Frank Setzpfandt at the University of Jena, and our research groups used metasurfaces as sources of entangled photons through a mechanism called



**FIGURE 3. RESONANCES** in metasurfaces enhance and shape the emission of quantum light. (a) In a gallium arsenide metasurface, resonances known as quasi-bound states in the continuum (BICs) sharpen and enhance the emission from an embedded indium arsenide quantum dot (blue) compared with the quantum-dot emission in a nonstructured GaAs layer (black). (Adapted from ref. 14.) (b) In a lithium niobate metasurface, the emission of photon pairs by a process known as spontaneous parametric down-conversion is also dramatically enhanced within a narrow spectral range (red) compared with the emission from a nonstructured lithium niobate layer (gray). (Adapted from ref. 15.)

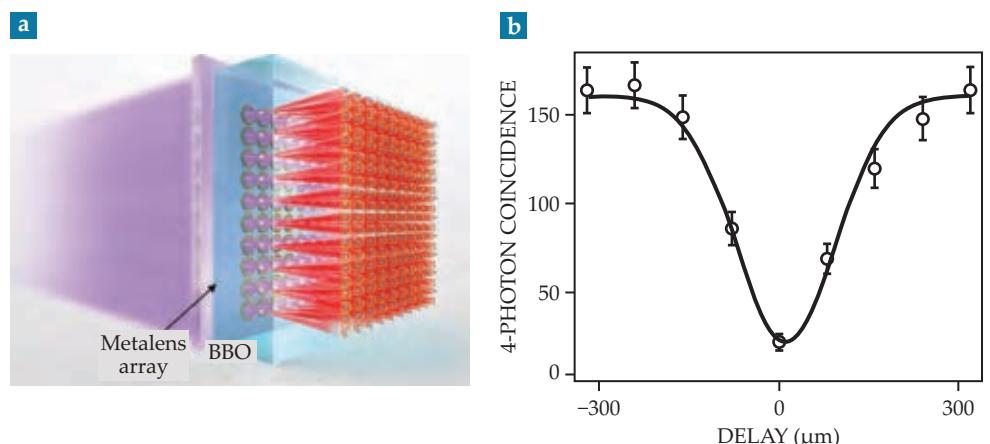
spontaneous parametric down-conversion (SPDC), in which a material is excited by one photon and then emits two photons to return to the ground state<sup>15</sup> (see box 2). In that experiment, we fabricated a lithium niobate crystal with trapezoid-shaped single meta-atoms that each had what's known as a Mie-type resonance (see box 1). As shown in figure 3b, that resonance at 1591 nm led to an increase in the pair generation rate (solid red line) by two orders of magnitude within a 15 nm band, compared with the emission from the unstructured layer of the same material.

As in any nonlinear effect, SPDC in bulk crystals requires phase matching. In terms of photons, phase matching is equivalent to momentum conservation: The momentum of the pump photon is fully passed to the two daughter photons, called the signal and the idler. Similarly, energy conservation dictates that the frequency of the pump photon is equal to the sum of the daughter-photon frequencies. In thin materials, such as metasurfaces, energy conservation is still valid, but momentum conservation in the direction normal to the surface is relaxed. That relaxation follows from the uncertainty relation; restricting the source of photon pairs in space allows any value of their total momentum.<sup>16</sup>

The result is that thin sources of SPDC can emit photons in any direction and at any wavelength. The gray profile in figure 3b, for a non-structured ultrathin layer of lithium niobate, illustrates just

how broad the SPDC spectrum can be. Structuring the lithium niobate such that it has a Mie resonance concentrates the vacuum fluctuations in a narrow band, so photon pairs are efficiently emitted only when the signal or idler photon is resonant. The strongest enhancement occurs when both signal and idler photons are at resonance: The red curve shows an enhancement of two orders of magnitude in the two-photon emission rate in a narrow band near the resonance.

The relaxed momentum conservation for SPDC in metasurfaces also introduces flexibility in the choice of pump photon frequency. If the pump photon frequency is not double that of the resonance, the total energy is split unequally between the two daughter photons. The signal photon takes the resonance wavelength, and the idler takes the wavelength needed to conserve energy. Chekhova, Igal Brener of Sandia National



**FIGURE 4. A METALENS ARRAY** creates a multipath quantum source. (a) The nonlinear crystal device produces photon pairs (red) from each circular lens embedded in the beta-barium borate (BBO) crystal. (b) A pair of neighboring lenses produces four indistinguishable photons, which interfere and therefore cause a dip in the number of detected photon quadrupoles. (Adapted from ref. 18.)

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Laboratories, and their research groups recently implemented such two-color SPDC in a BIC metasurface consisting of broken-symmetry GaAs resonators, similar to the metasurface that enhanced quantum-dot emission (shown in figure 3a). In that work,<sup>17</sup> the signal and idler wavelengths differed by about 50 nm. They can be separated even more by choosing other pump photon wavelengths.

A metasurface can offer multiple channels for SPDC photon-pair generation and higher-dimensional entanglement. For example, Din Ping Tsai of National Taiwan University and his colleagues implemented a multipath photon-pair source in a metasurface lens array integrated in a beta-barium borate crystal<sup>18</sup> (see figure 4a). The 10-by-10 metalens array forms a multichannel pump that, in turn, generates photon pairs in 100 channels. The researchers demonstrated four-photon and six-photon generation in which the photons from different lenses were highly indistinguishable. The dip in the measured four-photon coincidences at zero delay in photon arrival times (figure 4b), and similarly for six-photon coincidences, indicates that the photons have coalesced because of their indistinguishability. That metasurface-based quantum photon source can easily switch between various high-dimensional entangled quantum states.

Metasurfaces produce, route, and manipulate quantum states of light, which will be useful for free-space quantum communication, quantum information, quantum computation, and quantum imaging. Their key strength is the simultaneous control over many parameters of the quantum states. One promising application is integrating metasurfaces with single-

photon-sensitive cameras as a sort of quantum camera lens. The metasurface could then transform the light as needed for fast imaging-based measurements of quantum states. On their own, metasurfaces may provide a path to numerous applications, including unbreakable encryption and quantum information on a chip.

*We thank our many colleagues and students for their collaboration and discussions. We also acknowledge the support of the US Army International Office (grant no. FA520921P0034).*

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# Einstein would be doubly amazed

Roman Schnabel

Quantum-correlated light embodies all the weirdness of quantum physics. Now it is being used to aid in the observation of another exotic phenomenon: gravitational waves.

MARTIN JANČA/ALAMY STOCK PHOTO

**Roman Schnabel** is a professor of physics at the Institute of Laser Physics at the University of Hamburg in Germany.



# S

cientific history was made with the first observation of gravitational waves in 2015. The signal recorded by the Laser Interferometer Gravitational-Wave Observatory (LIGO) came from 1.3 billion light-years away and was generated by the merging of two black holes.<sup>1</sup> (For more on LIGO and gravitational-wave detection, see PHYSICS TODAY, April 2016, page 14, and the article by Barry Barish and Rainer Weiss, PHYSICS TODAY, October 1999, page 44.) The data were published the following year, 100 years after Albert Einstein's prediction of gravitational waves.<sup>2</sup>

Interestingly, during his later life, Einstein was no longer convinced that gravitational waves existed. In 1936 he prepared a manuscript that claimed he had mathematically proven their nonexistence. But after Howard Percy Robertson convinced him that the proof was flawed, Einstein completely rewrote it and subsequently said that he did not know whether there were gravitational waves (see the article by Daniel Kennefick, PHYSICS TODAY, September 2005, page 43). Since the existence of gravitational waves was only rigorously deduced from the general theory of relativity after Einstein's death, it can be assumed that his thoughts remained inconclusive on the question.

Einstein was also concerned with a particular consequence of quantum physics, namely quantum entanglement, or more generally quantum correlation. The effect was first mentioned as a thought experiment, now known as the EPR paradox, in a 1935 paper written by Einstein and his colleagues Boris Podolsky and Nathan Rosen.<sup>3</sup> The authors hypothesized that quantum correlations proved the incompleteness of quantum theory. Today, however, we know that Einstein and his colleagues were wrong, and it has since been proven that quantum theory is complete within its scope. Still, physicists struggle to make the physics of quantum-correlated systems understandable without adding assumptions that go beyond quantum theory.<sup>4</sup>

Without question, Einstein would be amazed that we are now using gravitational waves to understand the universe, that the first observations have already discovered a larger number of black holes in the universe than previously assumed, and that future observatories are expected to probe

the first fractions of a second of the Big Bang. But I suspect that he would be doubly amazed to know that the quantum correlations that he and his two colleagues described in 1935, which still elude a self-evident physical understanding, are now being used as a tool to improve observations of gravitational waves.

## The weirdness of quantum physics

In general, characterizing the spread of a quantum measurement's uncertainty requires a so-called ensemble measurement using many copies of the system of interest. All copies must be in the same quantum state, and the measurements need to be identical and precise enough to resolve the spread of the uncertainty. Although the settings for the measurements are identical, the individual outcomes nevertheless scatter around a mean value. The scatter range is the quantum uncertainty. In most cases, its size is completely characterized by the value of its standard deviation.

The scatter is truly random because quantum theory is complete; there are no hidden variables that could cause a particular value to occur. In quantum optics, for example, a system of interest is a Fourier-limited wave packet. The mathematics and physics of the Fourier transform enforce that the energy of such a wave packet, which is given by its quantum states, is homogeneously smeared over the entire wave packet. Measurements that resolve the energy distribution of the wave packet must therefore have results with a random distance from the mean. Such measurement results are used as quantum random numbers—they cannot be predicted, not even by a quantum computer, simply because they are truly random.

Quantum correlations refer to patterns within that randomness. A pattern of any kind could logically be viewed as counterevidence of randomness, and it is understandable that the existence of quantum correlations led scientists in the mid 20th century to question the true randomness in quantum physics. Einstein, Podolsky, and Rosen suspected the existence of so-called hidden variables, which are not part of quantum theory and would precisely specify the

# EINSTEIN WOULD BE DOUBLY AMAZED

results of quantum measurements. The existence of hidden variables would make quantum theory incomplete,<sup>3</sup> and quantum randomness would never be real, only apparent. Einstein spent the rest of his life searching for a complete theory, albeit unsuccessfully.

By the 1980s the experimental violation of so-called Bell inequalities finally made it clear that quantum theory is complete, that it has no hidden variables, and that wave-packet-resolving measurements must lead to truly random results.<sup>4</sup> The experiments also confirmed that quantum correlations within quantum uncertainties exist—a finding that seemingly contradicts the randomness of quantum measurements. That weirdness still has not been resolved. Famous quantum-correlated states include EPR entangled states, Schrödinger-cat states, and squeezed states.

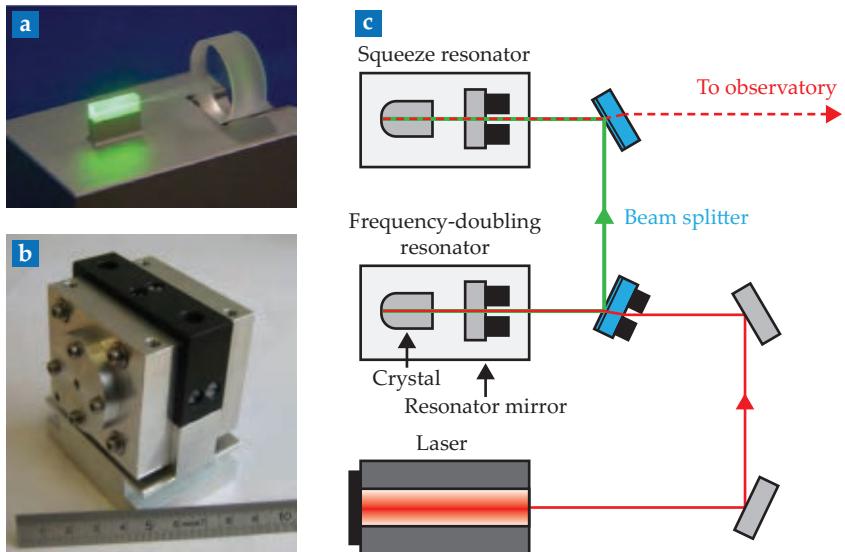
## Exploiting correlations with randomness

Squeezed light is produced by pumping a crystal inside a laser resonator (see figure 1), similar to how a conventional laser works. What's different is that the crystal is pumped with laser light, rather than light from a hot lamp, and that light must have exactly twice the frequency of the desired squeezed light. And the crystal needs to have a high second-order nonlinearity; that is, it needs to be suitable for frequency doubling of laser light.

Squeezed-light generation is based on degenerate optical parametric down-conversion, which is the reverse of the process used for frequency doubling of conventional laser light. A nonlinear crystal converts the pumping field, with optical frequency  $2f$ , into two indistinguishable fields with frequency  $f$ . The amplitude of any optical field must have a quantum uncertainty, and the same is true for the individual down-converted fields, which leads to an interesting situation: The amplitudes of the fields are uncertain, but they are nevertheless always identical. The result is the abovementioned quantum correlation—the correlation within a random measurement results from quantum uncertainty.

Squeezed light has its strongest quantum correlations when the laser producing it operates slightly below its oscillation threshold.<sup>5</sup> As a result, its beam is dim. To make a bright amplitude-squeezed laser beam, it must overlap with a conventional laser beam of the same wavelength with the optimal phase difference. Measurements on such a beam produce squeezed photon-counting noise like that in figures 2b and 2d.

LIGO and two other gravitational-wave observatories, GEO600 and Virgo, are now using squeezed states of light to reduce the noise in light's quantum uncertainty and thereby improve the observatories' sensitivities.<sup>5–9</sup> Figure 3 shows a schematic of the underlying optical layout. In addition to a conventional laser, the setup requires a laser that produces squeezed light whose optical field exhibits quantum correlations in time. When light from the two lasers is superimposed in an interferometer, the light fields in its arms become EPR



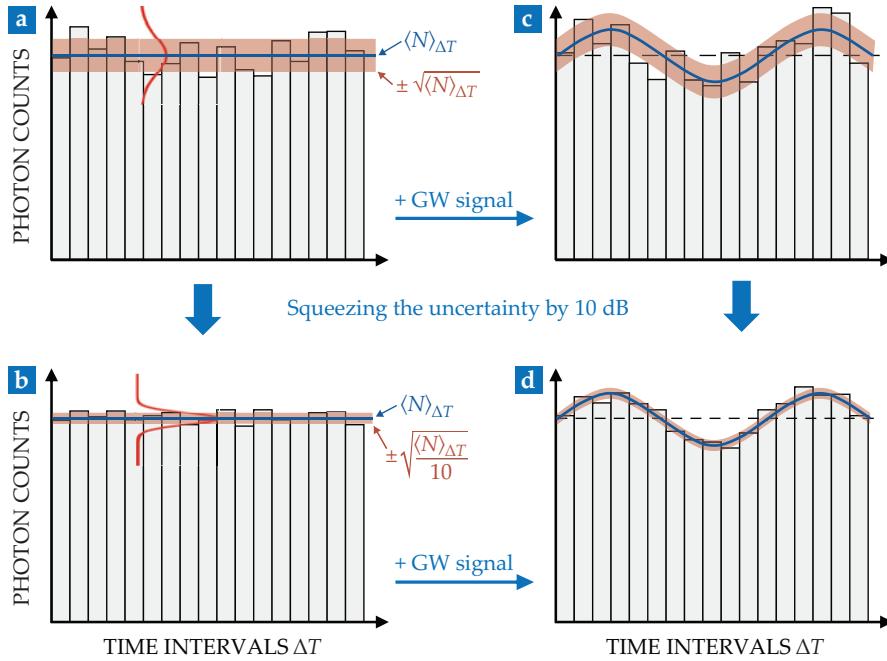
**FIGURE 1. GENERATING SQUEEZED LIGHT.** (a) The semimonolithic squeeze resonator shown here uses a periodically poled potassium titanyl phosphate crystal with a mirrored back and a separate resonator mirror to generate squeezed light. The crystal is pumped with green laser light with a wavelength of 532 nm. The squeezed light is created at the invisible wavelength of 1064 nm. (b) To produce a measurable squeezing effect, a squeeze resonator must be housed in a temperature-stabilized device like this one to maintain a specific temperature, typically 40 °C, at which both wavelengths have the same propagation speed over the entire crystal. (c) To generate squeezed light for gravitational-wave detectors, laser light (red) with the same frequency  $f$  as the light in the interferometer undergoes frequency doubling in a resonator. That light, with frequency  $2f$  and shown in green, goes through a beam splitter that's highly reflective at  $f$  and highly transmissive at  $2f$ . It is then used to pump the squeeze resonator. (Adapted from ref. 5.)

entangled. And, more importantly, the output field at the photodiode—which would contain any gravitational-wave signal—exhibits squeezed quantum noise. Figure 2 illustrates the improvement in photon-number statistics caused by using squeezed light. The reduction in standard deviation between figures 2a and 2b, which is caused by squeezing, improves the visibility of the gravitational-wave signal shown in figures 2c and 2d.

By itself, the best conventional laser produces a distribution of photon counts that is truly randomly distributed around a mean value  $\langle N \rangle$ . Consider, for example, a quasi-monochromatic laser beam whose residual spectral energy distribution is Gaussian with a half width  $\Delta f$ . The mathematics of the Fourier transformation enforces that the energy in the laser beam must be homogeneously smeared over a Gaussian wave packet with half width  $\Delta t = 1/(4\pi\Delta f)$ , where  $\Delta t$  corresponds to half the wave's coherence time.

Now imagine that photodiode measurements determine the beam's energy in a short time window  $\Delta T \ll 2\Delta t$ . It's well known that the energy values are integer multiples of the photon energy. But it is impossible for the detected photons to be in the short time window  $\Delta T$  before the measurement because the Fourier transform forces their energy to be homogeneously smeared over  $2\Delta t$ . Consequently, the photon events recorded must have occurred only during the measurement and in a truly random manner.

In the absence of any quantum correlations, the photon statistics would reflect mutually independent random parti-



**FIGURE 2. QUANTUM STATISTICS** of photon counts. (a) The photon numbers measured in short time intervals  $\Delta T \ll \Delta t$ , where  $\Delta t$  is the coherence time of the light, are uncorrelated; they correspond to random, mutually independent photon events. If the mean number of photons per time window is large,  $\langle N \rangle_{\Delta T} \gg 1$ , the quantum uncertainty in the photon number is described by a Gaussian distribution (red curve) with standard deviation  $\Delta N_{\Delta T} = \sqrt{\langle N \rangle_{\Delta T}}$ . (b) For a beam that has the same coherence time but is in an amplitude-squeezed state, the photon counts are random but correlated with each other, which produces a narrower distribution; here it's squeezed by a factor of  $\sqrt{10}$ . (c) Adding a sinusoidal gravitational-wave (GW) signal to the photon-count noise illustrates the difficulty presented by conventional quantum noise. (d) Using a squeezed light improves the signal-to-noise ratio for the same GW signal. (Adapted from ref. 10.)

cles, as shown in figure 2a, and the light measured during the interval  $\Delta T$  would be in a so-called coherent state. In that case, the properties of the Poisson distribution apply: If  $\langle N \rangle$  photons are found on average over  $\Delta T$ , the standard deviation is  $\sqrt{\langle N \rangle}$ .

With squeezed light, the spectral width  $\Delta f$  of the detected light is constant, so the photons still cannot be localized in the short time window  $\Delta T$ —the mathematics of the Fourier transform cannot be avoided! And the photons must occur randomly, as with a conventional laser. Curiously, though, the photon numbers for squeezed light measured over  $\Delta T$  vary less than  $\sqrt{\langle N \rangle}$ . The distribution's unexpectedly sharp peak is a manifestation of the quantum weirdness that is observed in all gravitational-wave observatories.<sup>10</sup> Since the Fourier-transform constraint still holds, the photon numbers measured in each time window must still result from a truly random process. At the same time, such processes must be correlated. Both of those facts must be reflected in the yet-to-be-found solution to the apparent weirdness.

### Observatory incorporation

Since April 2019, all gravitational-wave observatories worldwide have been using lasers that produce squeezed light as additional light sources. The squeezed light is spatially overlapped with the conventional, more powerful beams in the interferometer arms to produce squeezed-photon statistics—and therefore less noise—at the photodiode detector (see fig-

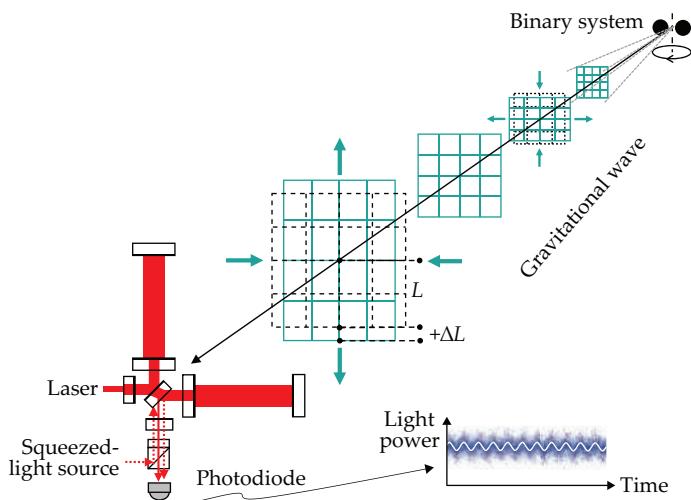
ure 3). LIGO and Virgo register on average more than one gravitational-wave event per week when they're taking data, and quantum-noise squeezing has improved the signal-to-noise ratio of those events.<sup>11,12</sup> It has also increased the average detection rate of binary-neutron-star mergers by up to 50% in LIGO and 20% in Virgo.<sup>8,9</sup> Discoveries aided by squeezed light also include black hole mergers and binary systems consisting of a black hole and a neutron star, all of which are recorded in a catalog of gravitational-wave events.<sup>11,12</sup>

The gravitational-wave detector GEO600 took on a pioneering role with its implementation of squeezed light<sup>7</sup> in 2010 (see PHYSICS TODAY, November 2011, page 11). Figure 4 shows a photo of the GEO600 squeezed-light laser, which was designed and built by my group at Leibniz University Hannover in Germany in 2009. It was the first such laser that was designed for indefinite use and started completely at the push of a button. The device has since been an integral part of GEO600's search for gravitational waves and is still in operation.<sup>13,14</sup> Many physicists had previously argued that quantum-correlated light would be too error prone for gravitational-wave observatories, given that their goal is to record data 24 hours a day and, if possible, 365 days a year.

But the GEO600 detector's squeezed-light source was so reliable that scientists at LIGO and Virgo decided to start using squeezed light as well.

Why wasn't squeezed light built into gravitational-wave observatories much earlier? One reason is that the technology had yet to be developed. Reference 6 provides a review of the challenges. The main reason, however, was that squeezed light was unnecessary as long as the light power in the interferometer's arms could be increased without major difficulties. At 10 times the light power, the gravitational-wave signal's power also increases tenfold, but the quantum noise only increases by  $\sqrt{10}$ , thereby providing greater sensitivity. From the beginning, gravitational-wave observatories were designed for high light powers. Building up the power in the arm resonators and incorporating minimally absorbing mirror materials and coatings significantly improved the observatories' sensitivities.

Squeezed light was not planned for Advanced LIGO, Advanced Virgo, or GEO600 at the start of construction. In the early 2000s, however, it became clear that the residual absorption of the light in the mirrors and beam splitters of all three observatories would make achieving the design sensitivities difficult, costly, and perhaps impossible on the targeted time scales. The major technological breakthroughs in the production of squeezed light for gravitational-wave detection<sup>6</sup> occurred in the groups of David McClelland and Ping Koy Lam at the Australian National University in Canberra and in my



**FIGURE 3. GRAVITATIONAL-WAVE DETECTION.** A gravitational wave with amplitude  $\Delta L/L$  dynamically expands and compresses spacetime perpendicular to its direction of propagation. Laser light propagating along an expanding spacetime axis is redshifted, whereas light moving along a shrinking spacetime axis is blueshifted. The effect is observed with Michelson interferometers that translate those frequency shifts into changes in the power output. All mirrors are suspended as pendulums and are decoupled to the greatest possible extent from environmental forces. The squeezed light reduces photon shot noise at the photodiode such that the sinusoidal signal in the noisy blue data becomes visible. (Adapted from ref. 10.)

group at Leibniz University Hannover between 2004 and 2009. Implementing squeezed-light production in GEO600 improved the detector's sensitivity without increasing the light output.

## Pushing performance

The use of quantum correlations in gravitational-wave observatories has been more than just a demonstration. Squeezed light has established itself as a technology that can improve performance at lower cost than potential alternatives. The cost of constructing a suitable laser that produces squeezed light can be estimated at a few hundred thousand euros. On the other hand, increasing the arm length of an observatory is a significantly more expensive proposition. The fact that GEO600, LIGO, and Virgo are still operating with optical powers in the arms below the design specifications reflects how valuable squeezed light is for improving photon statistics.

So far, the highest squeeze factor achieved in the signal output of a gravitational-wave observatory was at GEO600 with the laser shown in figure 4. The corresponding sensitivity improvement is equivalent to what would be achieved by a factor-of-four increase in light power in the arms.<sup>14</sup> Although lasers can deliver squeezed light with larger squeeze factors—well over 10 in the case of Virgo's laser—optical losses from decoherence limit the final value. If, for example, only 60% of the squeezed light is registered by the photodiode after passing through the interferometer, the squeeze factor drops<sup>8</sup> from 10 to approximately 2.2. Currently, an optical loss of 40% is typical, given absorption, scattering losses, imperfect beam superposition when the squeezed-light beam couples to the

conventional beam, and the imperfect quantum efficiency of the photodiode. But keep in mind that today's observatories were not designed to use squeezed light. Future observatories could achieve losses of less than 10%, in which case a squeeze factor of 10 could become realistic.

Loss caused by decoherence is a fundamental problem with the use of quantum-correlated states. If energy is lost to the environment, the strength of the quantum correlation decreases. Fortunately, squeezed states are still relatively insensitive to decoherence. And, to put the problem in perspective, reducing optical loss is indicated as the way to increase sensitivity at gravitational-wave observatories regardless of whether they use quantum correlations. Incorporating squeezed light just increases the benefit of reducing losses.

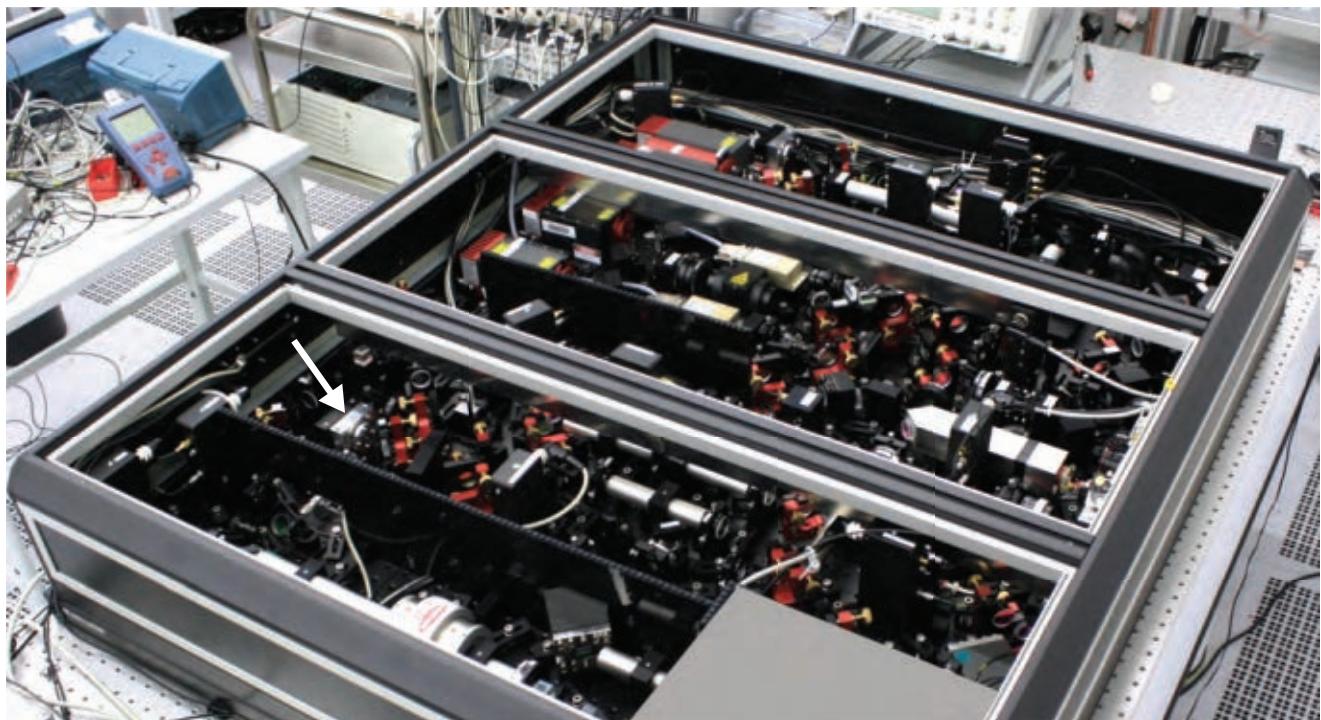
Optical loss is also the reason why no quantum-correlated states are being planned for the Laser Interferometer Space Antenna, or LISA, a future space-based gravitational-wave observatory. The huge arm lengths of 2.5 million kilometers will cause so much divergence of the laser radiation that only a small fraction of the photons will be registered. The gain from squeezed light would be minimal. Still, squeezed light has become an indispensable part of gravitational-wave astronomy. It will be an important factor in achieving the significantly increased measurement sensitivities targeted by the next generation of proposed ground-based gravitational-wave observatories, such as the Einstein Telescope and Cosmic Explorer.

## More uses for squeezing

Light with squeezed quantum uncertainty has a clear benefit when increasing light output is no longer straightforward. But it's also useful if mirror masses can no longer be easily increased. The four mirrors that form the arm resonators in the LIGO observatories each have a mass of 40 kg. They each consist of a piece of fused silica with low optical absorption and high mechanical quality, and they are shaped like cylinders and polished on all sides. Future gravitational-wave observatories should have mirror masses of 200 kg or more. The main reason for heavy mirror masses is that uncertainty in the laser light's properties results in uncertain radiation pressure on the mirrors—and, therefore, uncertain mirror momenta and random position changes. The result is what's called quantum radiation-pressure noise. A larger mirror mass reduces the disturbing effect.

It has been known only since the 1990s that the photon statistics on the photodiode (see figure 2) can be squeezed at the same time as the radiation-pressure uncertainty on the mirrors. It was previously thought that because of the Heisenberg uncertainty principle, reducing one type of quantum noise would lead to an increase in the other. Because of breakthroughs in understanding the nature of quantum correlations, we now know that simultaneously reducing both quantum-noise processes leads to a quantum correlation between the light field and the movement of the reflecting mirror. Those correlations were recently observed in one of the LIGO observatories using squeezed light.<sup>15,16</sup>

In the targeted Einstein Telescope, quantum correlations between mirror movement and reflected laser light should help the device achieve its desired sensitivity in the 2030s, thereby making the cosmic gravitational-wave background observable



**FIGURE 4. GEO600 SQUEEZED-LIGHT LASER.** The device's base-plate dimensions are 135 cm × 113 cm. In keeping with the laser wavelength of today's gravitational-wave observatories, this laser produces squeezed light at 1064 nm. The white arrow indicates the squeeze resonator. Also included are three commercial lasers, a frequency-doubling resonator, lenses and mirrors to couple the light into the resonator, and other components that enable long-term stable phase control of all laser beams in the device. This laser increased the GEO600 detector's signal-to-noise ratio by up to 3.5 dB when it was first implemented<sup>7</sup> in 2011. That improvement has since increased<sup>14</sup> to as much as 6 dB. (Courtesy of Henning Vahlbruch.)

for the first time. Astronomy based on electromagnetic radiation can look back a maximum of around 380 000 years after the Big Bang, but in earlier times, the universe was opaque to electromagnetic radiation. Observations of the gravitational-wave background offer the unique possibility to gain information about the first tiny fraction of a second after the Big Bang.

### Quantum-correlation technology

Advances in optical measurement technology for gravitational-wave astronomy can also be applied to similar technology for industry and medicine. If light output can no longer be easily increased to improve a device's sensitivity, using quantum-correlated light is an alternative as long as the measuring method allows enough quantum-correlated light to be captured. Light output may be difficult to increase for many reasons. If it is above the eye-safe range, for example, costs for laser protection arise. Light sensitivity is also often a problem in the use of lasers to probe medical and biological samples. With squeezed light one could achieve higher measuring sensitivities with lower light output to avoid cell damage.

Many scientists and governments are expecting a so-called second quantum revolution. The first quantum revolution was driven by, among other things, the development of the laser, which is now a part of many everyday devices. The second quantum revolution could be broader. The best-known development would be the quantum computer, which is based on quantum-correlated building blocks. (See, for example, the article by Lieven Vandersypen and Mark Eriksson, PHYSICS TODAY, August 2019, page 38.) Another example is secure communication and quantum cryptography. Approaches with quantum correlations make it possible to secure not only the

communication channel but also the laser devices and measuring equipment. (See the article by Marcos Curty, Koji Azuma, and Hoi-Kwong Lo, PHYSICS TODAY, March 2021, page 36.)

Quantum technologies can rely on quantum physics with or without quantum correlations. But those that do use correlated systems are now enabling advances that could be appropriately dubbed quantum-correlation technologies. Although squeezed light has so far been developed into an end-user product in gravitational-wave observatories, its potential uses in industry and medicine could lead to one of the first commercial quantum-correlation devices.

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The Hubble eXtreme Deep Field, an image of a region of space in the constellation Fornax, reveals galaxies that existed about 13.2 billion years ago.

## A series of paradigm shifts

When asked to name a book for a general readership that would answer questions about the understanding of matter, time, the Big Bang, and more, the celebrated theoretical physicist Michael Dine couldn't recommend one. So he decided to write his own, and *This Way to the Universe: A Theoretical Physicist's Journey to the Edge of Reality* is the culmination of that effort.

Dine has made important contributions to the fields of supersymmetry, string theory, and baryogenesis—an explanation for the imbalance of matter over antimatter in the early universe (see the article by Helen Quinn, PHYSICS TODAY, February 2003, page 30). After completing a PhD at Yale University in 1978 and postdoctoral work at SLAC at Stanford University and the Institute for Advanced

Study in Princeton, New Jersey, he became a professor, first at the City College of New York and since 1990 at the University of California, Santa Cruz.

Taking the work of Isaac Newton as the start of modern physics, Dine takes the reader on a journey through the most eminent breakthroughs in theoretical physics. The story is built up in four parts, which Dine terms steps: The first two describe the well-established science of classical mechanics, quantum mechanics, and relativity. In the third part, titled "The Next Steps," he addresses currently open problems and proposed solutions; the fourth, "And Stepping into the Unstable," is about modern developments, mostly focused on string theory.

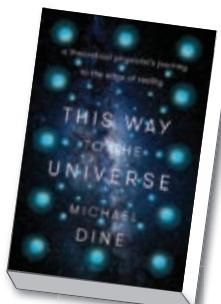
The book indeed covers a substantial amount of ground compared with most

### This Way to the Universe

**A Theoretical Physicist's Journey to the Edge of Reality**

**Michael Dine**

Dutton, 2022. \$28.00



other popular-science books. It is playfully written and reads as if the author is telling a story around a campfire. Although Dine's knowledgeable account of the history of science is mostly chronological, he does get sidetracked here and there. Given the density of information, it is impressive that the tone of the story remains light.

In steps 1 and 2, Dine describes the history of physics through a series of remarkable paradigm shifts. Newton proposed that nature was ruled by laws—the absolute and unchanging truths we seek

as theoretical physicists. Michael Faraday and James Clerk Maxwell introduced us to fields, a concept that formed the bedrock for Albert Einstein's theory of relativity and thereby the version of relativistic quantum mechanics that physicists use today.

In the later chapters, Dine switches to discussing developments in theoretical physics from his own vantage point. Memorable conversations, seminars he attended, and his own scientific collaborations form the common thread as the journey proceeds through two superstring revolutions to the current state of the field. Dine gives modest descriptions of theorems that bear his name, such as Affleck–Dine baryogenesis and the Dine–Seiberg problem in string theory, as well as anecdotes about colleagues. Notably absent, how-

ever, is Dine's seminal work with Ann Nelson, for which they shared the prestigious J. J. Sakurai Prize for Theoretical Particle Physics in 2018.

Woven through the book is a so-called journey through powers of 10, from the tiny scales at which the quantum nature of matter cannot be ignored to the vast scales ruled by Einstein's gravity. Even though the author provides examples to help readers imagine the enormous differences in scale, it might have been helpful if Dine had included illustrations in those sections.

The book occasionally touches on the sociology of science and the unfair exclusion of women and minorities from the academy. When Richard Feynman is first introduced, for example, a brief description of his career is accompanied by a

footnote that refers to the current understanding of his misogyny. Although descriptions of early woman pioneers mention the hardships they faced, those remarks remain largely parenthetical. In short, the question of who gets to do science and at what cost is not a central theme in the book.

*This Way to the Universe* is an accessible and impressively complete account of the history and current state of research in theoretical physics. Dine's infectious enthusiasm about the quest for nature's underlying truths is obvious on every page. Fellow science enthusiasts will enjoy this book and its unusual peek into the journey of a theoretical physicist.

Djuna Croon  
Durham University  
Durham, UK



Starlings flock in the sky above the Otmoor wetlands in Oxfordshire, England.

## Quantifying and mimicking life

When does matter become alive? Can the laws of physics describe living systems? To answer those vexing questions, early natural philosophers invoked notions of vitalism. But now we know better. Describing the living state is as much a physical problem as a biological one, and the modern tools of condensed-matter and nonequilibrium

physics are two of the microscopes of choice for attacking it.

At the end of the 20th century, the field of active matter emerged as scientists increasingly and successfully treated living systems as materials. Broadly put, active matter refers to a large class of self-driven systems, each composed of many interacting entities that can inde-

pendently and locally convert ambient free energy into sustained work or motion. In his latest book, *Active Matter Within and Around Us: From Self-Propelled Particles to Flocks and Living Forms*, the well-known author and complex-systems scientist Len Pismen provides a bird's-eye view of the young but rapidly growing field.

As the book's title suggests, active matter is pervasive throughout the natural world. It ranges in scale from the

thermally buffeted motions of motor proteins in a cell to the mesmerizing swirls formed by large flocks of birds. In the past decade and a half, researchers have developed synthetic and artificial active systems that use such inanimate components as colloids, grains, or robots to ingeniously mimic lifelike behavior.

The science underlying active matter spans physics, biology, and materials science, and covering it all in a 200-page book is a difficult task. But it's one that Pismen takes up admirably. *Active Matter Within and Around Us* presents a curated display of recent developments in the field of active matter from the vantage point of an experienced surveyor.

The book's eight chapters can be roughly grouped into three parts. The first is devoted to large-scale and continuum models of active fluids that display polar and nematic orientational order. Well-known models of flocking physics and active liquid crystals are described alongside their basic phenomenology and some experimental realizations. Phase separation caused by crowding makes a brief appearance, and the dynamic role played by topological defects that are often present in active fluids is appropriately emphasized.

Although some open theoretical issues are highlighted, they are often quite technical and at times inaccurate or misleading. For instance, the book claims that the Toner-Tu equations—which are used to describe flocks as a continuum fluid—rely on momentum conservation, Galilean invariance, and an equation of state for pressure. But those assumptions were explicitly broken in the model's formulation.

The focus shifts in the second part to microscopic active agents, both synthetic and biological. Mechanisms for propelling colloids and drops through viscous fluids are discussed, as are the particles' interactions and collective effects in suspensions. Chapter 4 dives straight into the movements of microorganisms and their mechanisms, including swarming, biofilm formation, and flagellar and ciliary motility. It also covers how the synchronization of flagella and cilia affects bacterial swimming.

Eukaryotes are covered next in a lightning-fast review of the cytoskeletal components and architecture, the dynamics and patterns present within a cell, and the role those factors play in cellular

## Active Matter Within and Around Us From Self-Propelled Particles to Flocks and Living Forms

Len Pismen

Springer, 2021. \$89.99



locomotion. That background motivates coarse-grained active-gel models that permit theoretical descriptions of mechanics and dynamics at both the single-cell and tissue levels. A brief excursion into how shape change emerges from growth and plasticity seems a bit tangential, but it perhaps portends the final two chapters.

The third part delves deeper into biology by covering such topics as tumor invasion; the dynamics of collective cell migration; and the spreading, jamming, folding, and shaping of tissues. Fundamental ideas of morphogenesis are highlighted—including positional information, symmetry breaking, morphogen gradients, and mechanical feedback—but the discussion remains brief. I appreciate the inclusion of sections on plant tissues. The book concludes, perhaps a bit abruptly, with a short digression into biomimetic systems and soft robotics.

Overall, *Active Matter Within and Around Us* manages to fulfill its promise of emphasizing the physical, biological, and technological aspects of active matter—at least to the extent that can be expected in 200 pages. Nonetheless, it is not a casual read, nor is it a pedagogical introduction to active matter. For the latter, the many extensive review articles that have been written on the subject remain the best option.

Because of the book's brisk pace, its heavy bias toward theory, and its often-impressionistic descriptions of phenomena without equations, it is unlikely to be useful to beginners except perhaps to whet their appetites for further study. But for attentive and motivated readers who are willing to dive into the literature, *Active Matter Within and Around Us* hints at many open questions and problems that are waiting to be solved.

Suraj Shankar  
Harvard University  
Cambridge, Massachusetts

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## NEW BOOKS &amp; MEDIA

**The Scientist's Guide to Writing**

How to Write More Easily and Effectively Throughout Your Scientific Career

**Stephen B. Heard**

Princeton U. Press, 2022 (2nd ed.). \$110.00

Although scientific knowledge is primarily communicated through the written word, students rarely focus on building writing skills. *The Scientist's Guide to Writing*, now in its second edition, aims to address that gap. Authored by the biologist Stephen Heard, the roughly 300-page book covers the ins and outs of writing, including strategies for overcoming procrastination, constructing a scientific paper, and dealing with peer reviewers. Each chapter comes with a concise, bullet-pointed summary and helpful writing exercises for students. Although he emphasizes that clarity should always be the primary goal in scientific writing, Heard encourages young scientists to include "touches of whimsy, humor, and beauty" in their writing, even if curmudgeonly reviewers eventually insist on their removal.

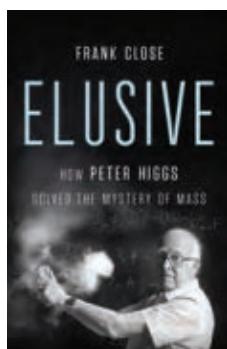
—RD

**The  
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Stephen B. Heard

**Elusive**

How Peter Higgs Solved the Mystery of Mass

**Frank Close**

Basic Books, 2022. \$30.00

What's it like to be the namesake of the legendary Higgs boson? As Frank Close demonstrates in his new book, *Elusive*, scientific fame was a disorienting experience for the theoretical physicist Peter Higgs, who was unaccustomed to the spotlight. Making matters even more bizarre was the fact that, as Higgs himself admits, he has had almost no involvement in the development of particle physics since the mid 1960s. Nevertheless, as the public became increasingly interested in the quest for the so-called God particle in the 1990s and 2000s, the reclusive physicist became the poster child for the search for the boson. *Elusive* demonstrates that in the scientific world, too, fame is both a blessing and a curse. —RD

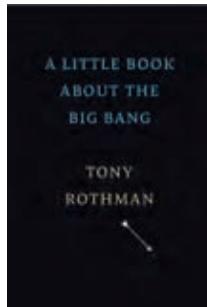
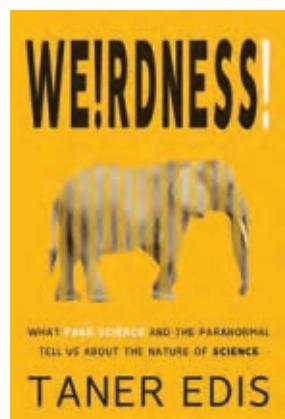
**Weirdness!**

What Fake Science and the Paranormal Tell Us About the Nature of Science

**Taner Edis**

Pitchstone, 2021. \$16.95 (paper)

Paranormal claims, fringe science beliefs, and conspiracy theories are the focus of *Weirdness!* by Taner Edis, a professor of physics. Fascinated by the odd and the controversial, Edis puts such notions to use as teaching tools for exploring the nature of science and the scientific method. Touching on topics like spiritualism, superstition, and psychic phenomena, Edis discusses the checklists and diagnostic criteria that can help people distinguish fake science from real science. Moreover, he points out that even proposals based on science can be wrong. In a time when anti-vaxxers, climate change deniers, and creationists appear to be running rampant, *Weirdness!* serves as a timely reminder to carefully weigh all arguments and exercise caution when deciding what to believe and whom to trust. —CC

**A Little Book About the Big Bang**

**Tony Rothman**

Belknap Press, 2022. \$24.95

Aimed at readers with minimal knowledge of science or math, *A Little Book About the Big Bang* discusses the structure and evolution of the universe with as few equations and graphs as possible. Tony Rothman, a physicist who specializes in general relativity and cosmology, has written several science books and articles for the general public. Using analogies rather than equations, he addresses fundamental questions asked by laypeople who are curious about science: How does relativity describe the entire universe? What has been left out of special relativity? What is so important about the cosmic microwave background radiation? True to its title, the book packs a lot of information into a small package. —CC

# NEW PRODUCTS

## Focus on software, data acquisition, and instrumentation

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

**Andreas Mandelis**

### Magnetic test and measurement instrument

Lake Shore Cryotronics has added a live plotting feature and other enhancements to its F41 (single-axis) and F71 (multiaxis) teslameters. They are easy to operate and provide fast, highly accurate field measurements. Live plotting of the magnetic field makes it easier to see fields changing over time; it can also be used to capture field measurement sweeps and save the data to a USB flash drive. Other improvements include the addition of maximum peak holding for high-speed pulse detection; fully configurable digital low-, high-, and band-pass filters that can be applied to an rms reading when the teslameters are operating in high-frequency mode; and a qualifier feature for pass-fail classifications of field values. Improvements have been made to the onboard TruZero technology's algorithm to further reduce residual offsets. TruZero, a time-saving feature, eliminates the need to re-zero the probe. *Lake Shore Cryotronics Inc, 575 McCorkle Blvd, Westerville, OH 43082, [www.lakeshore.com](http://www.lakeshore.com)*

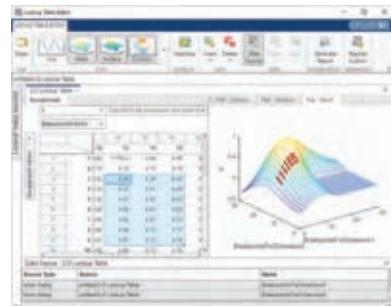


### Photon-counting system

The AuraTek-PCS from Photek, an all-in-one multichannel photon-counting system, enables parallel readout with precise timing and high event-rate capabilities. Its 256 independent channels, each with 60 ps timing resolution, can simultaneously register single-photon events with count rates of up to 480 kcps. Customizable features include detector gating. A range of photocathodes are available, including versions with high UV sensitivity and very low dark counts. A gigabit Ethernet connection and specially designed software allow for fast, easy data acquisition. According to the company, the PCS may potentially unlock new possibilities in wide-field fluorescence-lifetime measurements, lidar, quantum information systems, and other applications. *Photek Ltd, 26 Castleham Rd, St Leonards-on-Sea, East Sussex TN38 9NS, UK, [www.photek.com](http://www.photek.com)*

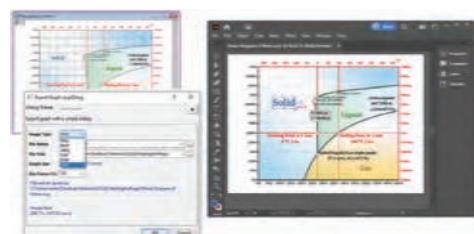
### Data analysis and graphing software

Version 2022b of Origin and OriginPro, OriginLab's data analysis and graphing software, adds new features, apps, and improvements. Graphs and layouts can now be exported in SVG (Scalable Vector Graphics) format, which allows for easy editing of the exported file in applications such as Adobe Illustrator. New workbook window buttons allow users to add sheets or toggle the organizer panel on and off. A new dialog box for arranging, tiling, and sorting windows makes it easier to manage large projects. Users can now define multiple regions of interest on GeoTIFF images and extract them for further analysis or create graphs such as a 3D surface plot. New graph types include a bar map for placing bar or column plots on a map base, a spiral bar chart (with Colormap for customizing the bar colors), and right- and equilateral-triangle ternary plots. Among the new apps are GeoTIFF Export, Color Spectrum Plot, and Matrix Analysis. *OriginLab Corporation, One Roundhouse Plaza, Ste 303, Northampton, MA 01060, [www.originlab.com](http://www.originlab.com)*



### Mathematical programming software

MathWorks now offers Release 2022a (R2022a) of its MATLAB and Simulink software. New capabilities in MATLAB include new apps and App Designer functions, graphics enhancements, and customizable Live Editor tasks. Simulink updates let users streamline masking workflows with a new mask editor and accelerate simulation using a model-reference local solver. New products in R2022a include the Bluetooth Toolbox, which provides standard-based tools to design, simulate, and verify Bluetooth communications systems; the DSP HDL Toolbox, which offers Simulink blocks and subsystems for developing wireless, radar, audio, sensor, and other signal-processing applications; and the Road-Runner Scenario interactive editor, which can simulate and test automated driving systems. R2022a includes major updates to MATLAB Compiler SDK and Production Server, Simulink Real-Time, and other products in the areas of signal processing, computational finance, and verification, validation, and testing. *The MathWorks Inc, 1 Apple Hill Dr, Natick, MA 01760-2098, [www.mathworks.com](http://www.mathworks.com)*



### Highly precise nanopositioning stages

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# OBITUARIES

## Eugene Newman Parker

Eugene Newman Parker, the leading figure in heliospheric physics for the past half century, died of complications of Parkinson's disease on 15 March 2022 in Chicago. Among other distinctions, he was the first individual to be honored by having a NASA mission—the *Parker Solar Probe*—named after him while he was still living.

Parker was born on 10 June 1927 in Houghton, Michigan, in the Upper Peninsula. By the time he was seven, he and his family were living in suburban Detroit. As a teen, Parker bought a tax-delinquent property in the woods of Cheboygan County, 300 miles north of Detroit. For three summers he and his younger brother commuted by bicycle and camped out while they built a log cabin, which the family still uses. That captures the spirit of the man who was our colleague for so many decades.

Parker earned his undergraduate degree in physics from Michigan State University in 1948 and his PhD in physics in 1951 from Caltech. In the abstract of his thesis, done under the supervision of Howard Robertson and Leverett Davis, Parker wrote, "From the inadequacies of this non-magnetic theory, one concludes that magnetic fields must play a very significant role in the dynamics of the interstellar medium." That prescient sentence foreshadowed a career devoted to studying magnetic phenomena throughout the universe. His thesis was one of the very few of his papers we could find that did not have Maxwell's equations in it.

From Caltech, Parker moved to the University of Utah, where he was an instructor and then an assistant professor. Walter Elsasser, a trailblazer of dynamo theory for Earth's magnetic field, had brought Parker to Utah, but with his many connections, he also brought Parker to the attention of John Simpson, a pioneer of space cosmic-ray physics, who recruited Parker to the University of Chicago in 1955.

By 1962 Parker was a full professor at Chicago, where he spent the rest of his career, retiring in 1995 as the Chandrasekhar Distinguished Service Professor. Along the way he chaired the physics department (1970–72) and the

department of astronomy and astrophysics (1972–78), the latter during a rebuilding phase when he mentored David Schramm, who followed him as chair. Parker also provided both of us with wise counsel when we were chairs of that same department. We best remember his admonition to spend as little time as possible in the chair's office.

Most of the more than 400 papers Parker wrote were single authored. His most famous was a 1958 *Astrophysical Journal* paper that predicted the solar wind and the spiral nature of the interplanetary magnetic field. The paper was revolutionary, and it was greeted that way. The first reviewer said, "Well I would suggest that Parker go to the library and read up on the subject before he tries to write a paper about it, because this is utter nonsense." The second reviewer wasn't any more positive.

Although the journal's editor and Parker's lifelong colleague Subrahmanyam Chandrasekhar was also unconvinced by the idea, he couldn't find a flaw with Parker's math, so he overrode the reviewers and published the paper. A year later the Soviet Union's *Luna 1* detected solar-wind particles, and that detection was confirmed by NASA's *Mariner 2* in 1962. The evidence for Parker's basic picture was completed in 2012 when *Voyager 1* left the bubble created by the Sun's wind—the heliosphere.

That experience likely led to the advice Parker often gave young researchers: "If you do something new or innovative, expect trouble. But think critically about it because if you're wrong, you want to be the first one to know that." Parker never coauthored a paper with his students, instead urging them to be independent.

Parker's seminal ideas on the origin of cosmical—his favorite term—magnetic fields and of fast plasma outflows, the rapid dissipation of magnetic field energy, the structure of magnetized shock waves, and diffusion of high-energy charged particles known as cosmic rays have permeated our understanding of astrophysical magnetism for more than 60 years.

Parker was humble, straightforward, and wise. His humility was illustrated by our email exchange with his son Eric, who said, "My sister Joyce and I didn't

COURTESY OF ERIC PARKER



Eugene Newman Parker

get a real feel for what a 'big dog' our dad was in the field." They got an even better sense when a month after Parker's death, they traveled to Lund, Sweden, to accept on his behalf the Crafoord Prize in Astronomy awarded in 2020. Other major honors included the National Medal of Science in 1989, the Gold Medal of the Royal Astronomical Society in 1992, and the Kyoto Prize in 2003.

It is fitting that the *Parker Solar Probe*, a mission "to touch the Sun" and to better understand the million-degree solar corona, was named in his honor. In the words of Thomas Zurbuchen, NASA's associate administrator for the Science Mission Directorate, "The field of heliophysics exists in large part because of Dr. Eugene Parker." He and his family attended the launch on 12 August 2018 from Cape Canaveral, Florida, and shortly before he died, NASA scientists shared some of the early results with him.

**Robert Rosner**  
University of Chicago  
Chicago, Illinois

**Michael S. Turner**  
The Kavli Foundation  
Los Angeles, California  
University of Chicago  
Chicago, Illinois

## William Frank Vinen

William Frank "Joe" Vinen, a pioneer in low-temperature physics, died in Birmingham, UK, on 8 June 2022. He was born on 15 February 1930 in Watford, an English town some 15 miles northwest of London. Vinen earned his undergraduate and graduate degrees from Cambridge University in 1953 and 1956, respectively. Superfluid helium, to which he was introduced by his PhD supervisor, Donald Osborne, became a lifelong passion. When Osborne left Cambridge, Vinen's new supervisor, David Schoenberg, let him continue his work independently. After receiving his doctorate, Vinen remained at Cambridge until the University of Birmingham offered him a chair in 1962. There he set up a strong low-temperature-physics group, held the prestigious Poynting Chair from 1973, led the School of Physics and Astronomy from 1973 until 1981, and retired in 1997.

In the years following his retirement, Vinen was a frequent and warmly welcomed traveler to the main low-temperature-physics laboratories in Prague, Czech Republic; Osaka, Japan; Manchester, Lancaster, and Newcastle, UK; and Gainesville and Tallahassee, Florida. He motivated scientists at each of those places to investigate aspects of quantum turbulence, such as visualization via excimer helium molecules; generation, dissipation, and decay in the zero-temperature limit and two-fluid states; and Kelvin wave cascades. No retirement was more productive scientifically!

Osborne had shown that rotating helium acquires a parabolic surface, like an ordinary liquid, in apparent disagreement with the two-fluid theory of Lev Landau and Laszlo Tisza. To solve that puzzle, Lars Onsager and then Richard Feynman had proposed that the circulation of the superfluid velocity is quantized in units of  $h/m$ , where  $h$  is Planck's constant and  $m$  is the mass of one helium atom. That constrains the superfluid vorticity to vortex lines of quantized strength. Henry Hall and Vinen's second-sound experiments in rotating helium and Vinen's experiments on helium heat currents in the 1950s provided the first indirect evidence for the quantization. They also revealed a mutual friction between superfluid and normal-fluid components. Vinen demonstrated its importance for helium flows and modeled its effects with great care and physical intuition.



William Frank Vinen

In 1961 Vinen directly measured the quantum of circulation, confirming the Onsager-Feynman conjecture and vindicating Fritz London's 1938 intuition that the superfluid is governed by a macroscopic wavefunction. The measurement, in which Vinen observed the change of the precessional frequency of a vibrating wire as one or more vortex lines encompassed it, was brilliant in its simplicity. That observation of the quantum character of a macroscopic body predates the related observations of flux quantization in superconductors. The vibrating-wire technique has been applied to many experiments since.

At Birmingham, Vinen led an intense program on type II superconductors with former students Colin Gough and Edward Forgan; they pursued the analogy between magnetic field in superconductors and rotation in superfluids both theoretically (with Philippe Nozières) and experimentally. But Vinen's interest in helium did not wane—he was attracted by the extraordinary purity achievable in helium compared with other materials.

Vinen performed light-scattering measurements near the lambda transition with Michael Vaughan and worked on the nucleation of a vortex ring by a moving ion. Ions allow studies of the nucleation process free of complications from remnant vortices produced in crossing the lambda transition. Vinen was aware that vortex nucleation requires an energy barrier to be overcome, and, with Chris Muirhead and Russell Donnelly, he calculated the barrier as a function of the geometry

of the nascent vortex. Their finding, that the vortex ring starts as a "handle" attached to the spherical ion, was confirmed experimentally at Lancaster University.

That success led Vinen to further nucleation experiments on oscillating ions trapped below the helium surface by electrostatic potentials. The trapped ions form an ideal two-dimensional system, and Vinen showed that they can form a Coulomb crystal. He did more studies of magnetoplasma resonances and ripplons while also working on cuprate superconductors.

It was Vinen's early experiments that suggested that a superflow breaks into turbulent vortex lines, as proposed by Feynman in 1955. Vinen's end-of-career work answered the natural question of how that "superfluid" or "quantum" turbulence is related to ordinary (classical) turbulence. In 1993, with Donnelly, he found that turbulence created by towing a grid in helium at rest displays classical scaling behavior over an unprecedented range of length scales. The experiment stimulated work that revealed surprising similarities between quantum and classical turbulence, described in his and Joseph Niemela's widely cited review in the *Journal of Low Temperature Physics*.

In the superfluid literature, Vinen's name is attached to three concepts: the Vinen equation, describing the evolution of the vortex-line density; the Hall-Vinen-Bekharevich-Khalatnikov equation, which generalizes the two-fluid equations by incorporating vortex lines; and Vinen turbulence, which is a state of turbulence that is devoid of the energy cascade found in classical turbulence. In recognition of his work, Vinen was awarded the Simon Memorial Prize (with Hall) in 1963, the Fernand Holweck Medal and Prize in 1978, the Rumford Medal in 1980, and the Guthrie Medal and Prize in 2005. He will be missed by his many friends across several generations.

**Carlo Barenghi**

*Newcastle University  
Newcastle, UK*

**Peter McClintock**

*Lancaster University  
Lancaster, UK*

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**Philippe Bourrienne** is an associate research scholar in the department of mechanical and aerospace engineering at Princeton University in New Jersey. **Gareth McKinley** is a professor in the department of mechanical engineering at MIT in Cambridge, Massachusetts.



## When fizzy water levitates

Philippe Bourrienne and Gareth H. McKinley

Carbonated droplets deposited on a superhydrophobic surface float on a self-generated cushion of gas.

Liquids are defined by their ability to flow. In a river, water moves freely under the influence of even a tiny incline. At smaller scales, however, droplets can resist gravity and remain attached to a solid substrate—for example, when raindrops cling to window glass. That common observation emphasizes the important role that surface tension and three-phase contact lines at a liquid–solid interface (see the Quick Study by Laurent Courbin and Howard A. Stone, PHYSICS TODAY, February 2007, page 84) play in overcoming the weight of a millimeter-scale droplet.

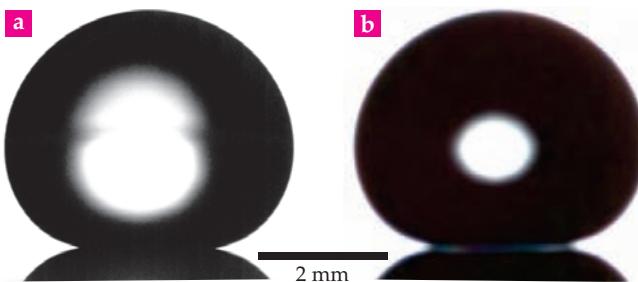
The main strategy for reducing liquid–solid adhesion is minimizing the contact area between a droplet and its substrate. In 1944 A. B. D. Cassie and S. Baxter, working at the Wool Industries Research Association in the UK, predicted a regime in which a water drop would sit above a textured and sufficiently hydrophobic solid. With its surface contact limited to a tiny fraction of the total basal area, a liquid in the so-called Cassie–Baxter regime adopts a quasi-spherical shape that is just slightly perturbed by the effects of gravity and appears to be predominantly surrounded by air, as displayed in figure 1a.

A droplet in the Cassie–Baxter state doesn't quite sit entirely above the surface. It still has small, localized contact points that lead to residual adhesion. More importantly, the surface repellency is fragile. An external perturbation can force the liquid to invade the textured surface's hydrophobic pores, thereby causing a dramatic increase in the contact area and, correspondingly, the adhesion. Ideal nonadhesion thus requires a droplet to levitate over a substrate, thereby avoiding any liquid–solid contact.

### Leidenfrost droplets

The first levitating droplets were reported in 1756 by Johann Gottlob Leidenfrost, a German physician who described the rounded shape and extreme mobility of water drops deposited on a glowing-hot iron spoon. The volatile liquid was levitating on a thin cushion of its own vapor—the so-called Leidenfrost phenomenon observable in your own kitchen when liquid water droplets skitter across a sufficiently hot pan.

A droplet in the Leidenfrost regime experiences near-perfect insulation from the hot substrate below it. The insulation prevents boiling and enables zero adhesion and high mobility, and a droplet's motion can then be directed by, for example, surfaces with millimeter-scale textures (see PHYSICS TODAY, June 2006, page 17). Still, the properties and applications of the levitating drops are limited by the high energetic cost of super-



**FIGURE 1. LEVITATION** on a textured superhydrophobic solid. (a) A 30  $\mu\text{L}$  drop of still water sits flush against the surface. (b) A thin ray of light passing between a 30  $\mu\text{L}$  drop of carbonated water and its reflection on the solid indicates that the drop is levitating on a micrometer-scale gas cushion.

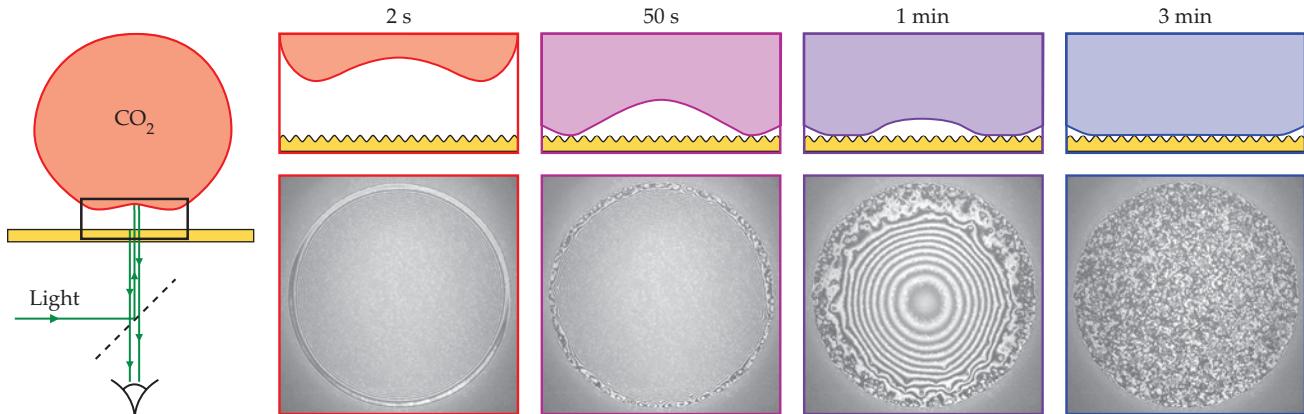
heating the solid far above the liquid's boiling point. For water, the so-called Leidenfrost temperature above which droplets levitate is around 200 °C on common smooth solids, and it can be even higher for rough hydrophilic solids.

Recent studies have tried to lower the critical temperature above which droplets levitate. In 2012 Ivan Vakarelski and collaborators demonstrated that the use of a microtextured hydrophobic solid could extend the Leidenfrost regime all the way down to the boiling point of the liquid. The water-repellent solid stabilizes the vapor cushion, even as the temperature difference between the droplet and the solid shrinks and makes the cushion thinner. But that extension of the Leidenfrost domain still requires a substantial temperature difference between the liquid and the solid to maintain evaporation-driven levitation.

### Fizzy droplets

Levitating a droplet at a temperature below its boiling point requires another strategy. A liquid that releases gas through a mechanism other than evaporation—for example, through a chemical reaction—can sustain its own cushion at ambient temperature in the absence of any external field. Here we illustrate the strategy using carbonated water made by pressurizing a bottle of deionized water with carbon dioxide gas.

The water-repellent solid in figure 1 features a so-called Glaco coating that consists of microscopic hydrophobic silica particles. It therefore combines hydrophobicity with submicrometrical roughness. Although similar hydrophobic surfaces can be readily made in the lab, the commercial Glaco



**FIGURE 2. LIFE AND DEATH** of a levitating fizzy water drop. In the experiment, a drop of sparkling water is placed on a transparent superhydrophobic substrate, and its basal area is imaged using interferometric microscopy with monochromatic light. Two seconds after deposition, the drop's base exhibits circular interference fringes, indicating the drop is entirely levitating over a thin gap of carbon dioxide gas. After 50 seconds, the first contacts between the solid and the liquid appear at the drop's edge. A central air bubble remains in the center. One minute into the experiment, the liquid–solid contacts spread inward as the central  $\text{CO}_2$  bubble shrinks because gas is escaping through the porous solid. After three minutes, the remaining  $\text{CO}_2$  concentration is too low to maintain levitation. The drop returns to a Cassie–Baxter regime, in which the liquid sits on the peaks of the surface's microtexture. (Note that the sketches in the upper row are not drawn to scale.)

coating developed by the Japanese company Soft99 has the added benefits of being mechanically robust and optically transparent.

After depositing a drop of carbonated water on the textured superhydrophobic surface, we indeed observed a subtle difference between it and a drop of still water. Although the drops' quasi-spherical shapes are roughly the same, a thin gap appears between the carbonated drop and the superhydrophobic substrate (figure 1b), thus indicating that the drop levitates at ambient temperature because of the continuous release of  $\text{CO}_2$  gas under the drop and into the porous solid. A pressure difference builds up under the drop as the emitted gas is forced radially outward from under the drop's base.

Figure 2 shows interferometric microscopy images of a sparkling droplet's levitation. We imaged the drop's base from below through the transparent superhydrophobic solid. The monochromatic light used for imaging produced fringes as it interfered with the reflected light coming from the base of the liquid, and those fringes allowed us to reconstruct the topography of the liquid interface at the base of the drop.

When a drop of sparkling water is first deposited on the water-repellent solid, it produces axisymmetric fringes characteristic of a levitating liquid droplet. The dimpled liquid–air interface hovers a few microns above the solid. As the initially dissolved gas is progressively released, however, the gas-release rate decreases. After about 50 seconds, the gas-release rate is insufficient to generate enough of a pressure difference to sustain the drop's total levitation. Some liquid–solid contacts appear at the perimeter of the drop base. The drop enters a regime of partial levitation with a central bubble, or blister, trapped underneath. The contact patches spread progressively inward. Eventually, the liquid comes to rest on the random local peaks, or asperities, of the porous hydrophobic surface. The myriad dark and bright spots in the last image serve to emphasize the heterogeneous local nature of the Cassie–Baxter wetting regime.

The time between when the droplet is deposited and when it no longer retains sufficient  $\text{CO}_2$  for levitation is just a few

minutes. Despite that loss of levitation, carbonated water drops enjoy a better fate than their thermal equivalent: Leidenfrost drops eventually vanish because of their complete evaporation, whereas decarbonated fizzy water drops remain in the superhydrophobic regime. Similar levitation at ambient temperature can also be achieved with other liquids. For example, the same principle applies to a droplet of two mixed liquid chemicals whose reaction generates a gas. The procedure also paves the way for the levitation of nonvolatile liquids such as oils.

Fizzy levitating drops demonstrate that all the desired transport properties of Leidenfrost drops, including their high mobility, are now accessible at ambient temperature. They exhibit a reduced friction when sliding on a superhydrophobic solid and can be propelled by millimeter-scale textures. (See the online version of this article for videos of those behaviors.) Larger volumes of fizzy liquids also retain similar dynamic features: When poured into a superhydrophobic-coated glass, the bubbles in fizzy beverages can't cling to the inside of the glass and produce their usual sparkle. Instead, the liquid becomes encased in a thin continuous gas film that could cause bewilderment, and maybe disappointment, to an admirer of bubbly drinks.

*We would like to acknowledge important contributions to this work by our collaborators Divya Panchanathan, Philippe Nicollier, Abhijatmedhi Chottratanapituk, and Kripa K. Varanasi.*

## Additional resources

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- I. U. Vakarelski et al., "Stabilization of Leidenfrost vapour layer by textured superhydrophobic surfaces," *Nature* **489**, 274 (2012).
- D. Panchanathan et al., "Levitation of fizzy drops," *Sci. Adv.* **7**, eabf0888 (2021).
- P. Agrawal, G. McHale, "Leidenfrost Effect and Surface Wettability," in *The Surface Wettability Effect on Phase Change*, M. Marengo, J. De Coninck, eds., Springer (2022), p. 189.

# BACK SCATTER



## Role-playing the life of a scientist

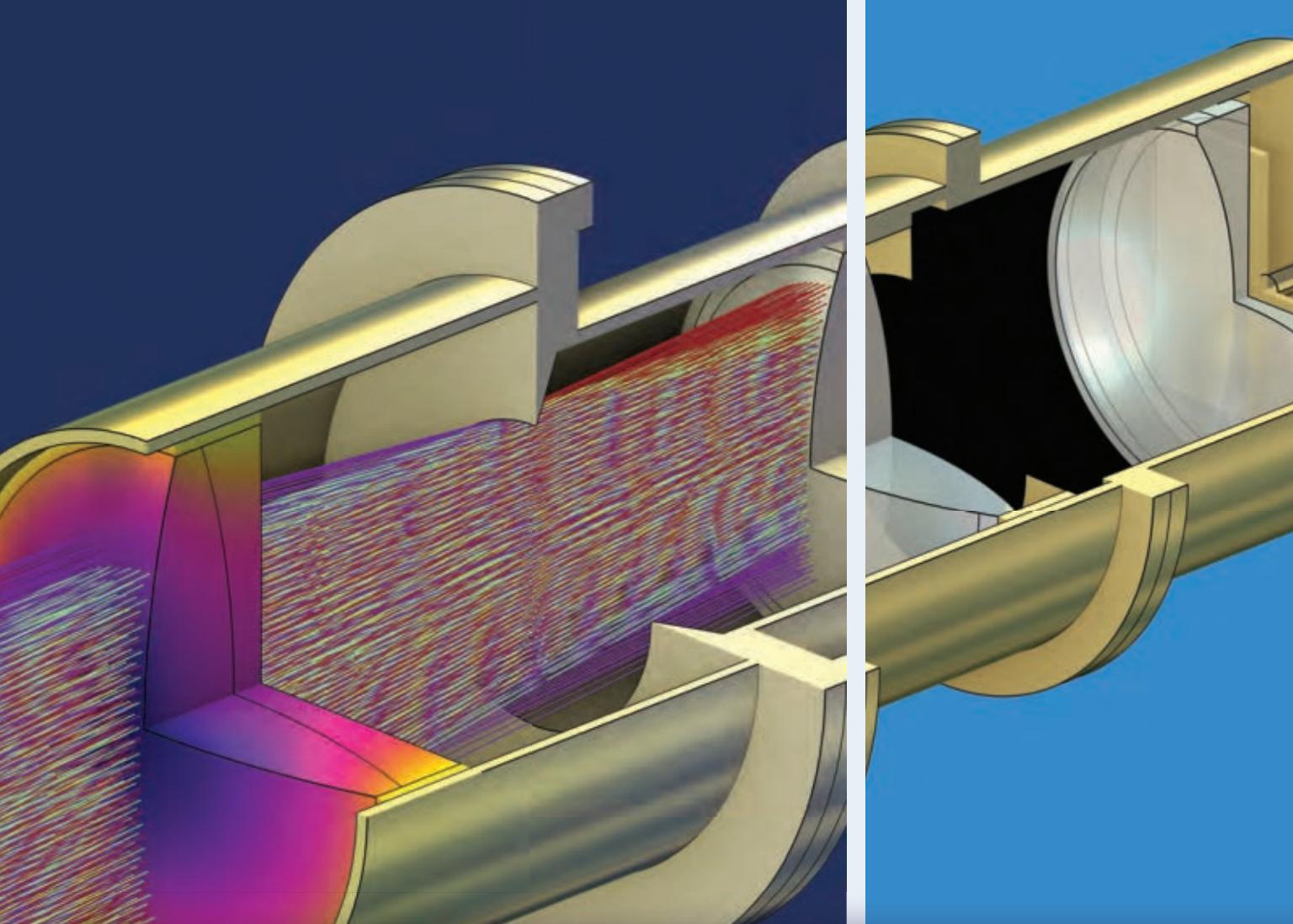
Over the past decade, board games have become increasingly popular as a method to marry educational content with play. To teach complex scientific concepts and to highlight the many careers in STEM (science, technology, engineering, and mathematics) that students can pursue, Claire Murray (left), Mark Basham (center), Matthew Dunstan (right), and their colleagues designed an educational board game, primarily for secondary school students. The board is based on the floor plan at the Diamond Light Source, the UK's national synchrotron facility, where Murray and Basham work as research scientists. Dunstan is a chemistry postdoc at the University of Cambridge and designs board games in his spare time.

To win, players—in the role of scientists—must complete projects,

which they do by moving from one beamline to another and conducting experiments. The various cards that players draw affect the success of experiments, and players who work together can gain advantages over their competitors. The initial play testing of the board game by 222 students revealed a change in many of the participants' perceptions of what it means to be a scientist. Before playing, many students described scientists as being "smart" and "successful." Afterward, however, many of them also associated "collaboration" and "failure" as features of scientists' careers. And of the 82 students who said that they would not like to be a scientist or engineer, 22 changed their minds after playing the game. (C. Murray et al., *Res. All.*, 2022, doi:10.14324/RFA.06.1.14; image courtesy of the Diamond Light Source.)

—AL

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