PHYSICS TODAY

February 2025 • volume 78, number 2

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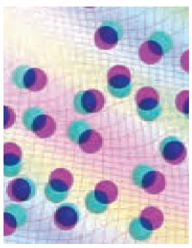
FEATURES



ON THE COVER: As students of electromagnetism and quantum mechanics learn, different configurations of unobservable fields can give rise to exactly the same observable physics. Perhaps surprisingly, the same holds true in statistical mechanics, where the "unobservable fields" are the positions and momenta in ensembles of real particles. To learn more, turn to the story on **page 11.** (Image courtesy of Florian Sammüller.)

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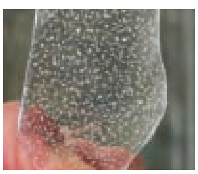

BEN RIDDELL-YOUNG

Ice-age fires

An analysis of trapped methane in polar ice cores has enabled researchers to uncover evidence of wildfire activity during parts of the last ice age. The results indicate heightened activity during some of the instances of abrupt climate change that took place between 15 000 and 50 000 years ago.

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CTK/ALAMY STOCK PHOTO

Frédéric Joliot-Curie

Often known for his research on radioactivity, Frédéric Joliot-Curie also led the development of France's first nuclear reactor after World War II and advocated for nuclear disarmament. Bill Sweet profiles the French physicist and explains how his life story parallels J. Robert Oppenheimer's.

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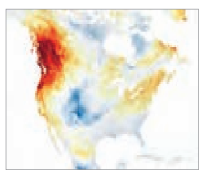

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Atmospheric rivers

Narrow bands of water vapor in the atmosphere are known for the torrential rains that they deliver to places such as the northwestern US. New research shows that those atmospheric rivers also transport vast amounts of heat, which can result in surface temperatures that are several degrees above average.

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Physics Today (ISSN 0031-9228, coden PHTOAD) volume 78, number 2. 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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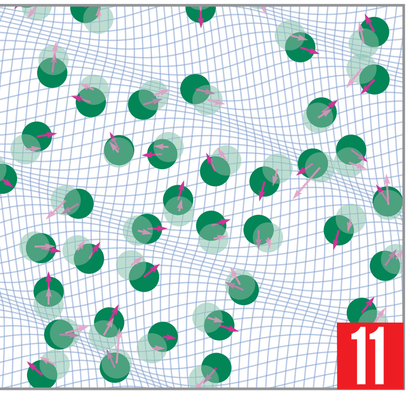

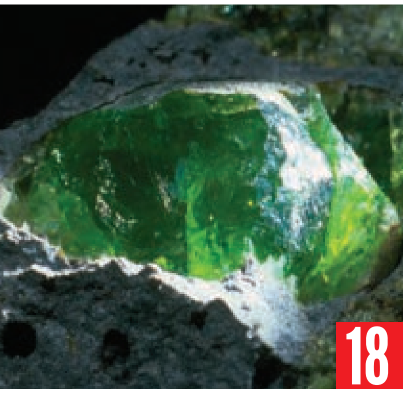

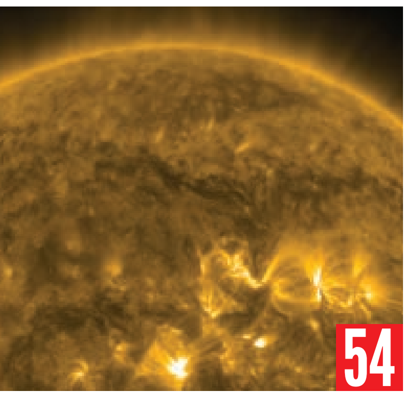

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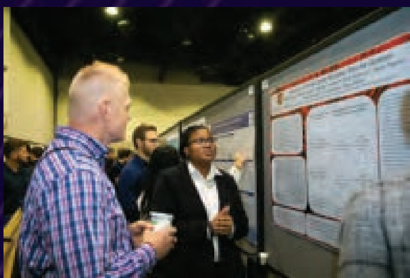
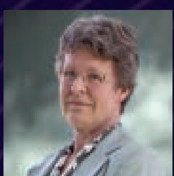


Plenary Speakers



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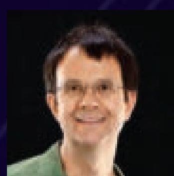

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Physicists' role in modern life: Reflections from the Lindau Nobel Laureate Meeting

At the end of June 2024, 37 Nobel Prize recipients and hundreds of young scientists studying physics or adjacent fields descended on the tiny, idyllic island of Lindau, Germany, on Lake Constance, for the year's Lindau Nobel Laureate Meeting. The first of these meetings, which hosted seven Nobel laureates and 400 scientists, was held in 1951 in an effort to reintegrate Germany into the global scientific community following World War II. In 1953, young scientists—students and postdocs—were invited to attend as well. The tradition of bringing together Nobel laureates and young scientists has continued every summer since, with the meeting topic switching between the various Nobel Prize categories.

On the itinerary for last year's week-long meeting were so-called Agora Talks by one or two Nobel laureates who fielded questions from the audience, short presentations by young scientists, and panel discussions featuring the laureates, the meeting's industry and academic partners, and young scientists. In addition to the conference-style talks, dinners (some themed) gave the students and postdocs more time to mingle with the laureates and among themselves. During a dinner hosted by Texas A&M University, attendees could try their hand at riding a mechanical bull. There were also opportunities for the up-and-coming scientists to go on a

THE LINDAU HARBOR in Germany.

science walk with laureates or to attend a lunch at a restaurant with a Nobelist. The week was capped by the traditional boat trip to the island of Mainau, where the meeting's host, Bettina Bernadotte, countess of Wisborg, welcomed the group to the sprawling gardens and palace lawn for the week's concluding events.

The meeting program walked a line between a traditional conference and a quirky and unique celebration of science and scientists. And although lots of fun activities were scheduled throughout the week, serious topics, such as climate change and nuclear proliferation, dominated the talks and conversations. On those important topics, the scientists in attendance seemed divided on the appropriate role of physicists in society.

On one hand, we listened to Nobel laureates declare that funding agencies should allow physicists to pursue fundamental research without any justifying application—a statement that was greeted with enthusiastic applause from the audience. And we heard speakers urge the young attendees to focus their efforts on so-called "useless" physics and work on the science that they find fascinating, regardless of the broader applications and implications that the research might have.

On the other hand, sessions included the unambiguously titled "Physics-Based Solutions to the Energy Challenge" and "The Role of Physics in Solving Global Problems of the 21st Century." And many of the panels, Agora Talks, and events hosted by governmental, academic, and business partners were centered around discussions of practical applications of physics.

That action-minded stance on the role of scientists was demonstrated on the last day of the meeting, when we witnessed the Nobel laureates in attendance sign the Mainau Declaration 2024 on Nuclear Weapons. The document implores that "all nations must commit to ensuring that nuclear weapons never be used again." It echoes a plea signed on Mainau Island in 1955 by many of the scientists whose work had made such weapons possible and who sought to limit their discoveries' devastating effects on humanity. A similar declaration on climate change was signed in 2015, warning about the need for research and action.

The two of us departed this year's Lindau meeting with more questions than clarity on a fundamental and pressing matter: What responsibility do scientists have both to engage in research aimed at addressing global challenges and to participate in the ongoing conversations surrounding how the work will be used to shape our global community in the coming decades?

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Demands on early-career faculty

In his article "Early-career faculty face many challenges" (Physics Today, October 2024, page 40), Alex Lopatka effectively points out some of the barriers to building a research program. But his discussion of teaching and teaching-related duties is brief, and when he does discuss them, he states, "Teaching pressures are common and add to faculty members' already busy schedules." The phrasing seems to imply that teaching is in competition with and of lower value than research. And notably, of the six questions Physics Today asked early-career faculty members for this article, none mention teaching.

The article's treatment of teaching is surprising to me. Fellow early-career faculty, at both large research universities and primarily undergraduate institutions, have told me that teaching and engaging students is a major challenge of theirs. The popularity of resources such as the Faculty Teaching Institute, which at least 2 of the 10 questionnaire respondents said they attended, speaks to this challenge.

Many academic institutions place a disproportionately low weight on teaching in their tenure evaluations,[1] and the article's heavy bias toward research perpetuates that disproportion. But the undervaluation of teaching by some does not change the fact that it's inherently a high-value activity and worth doing well.

Finally, despite having a section titled "Finding students," the article misses an opportunity to point out that teaching can be a great way to scout for research talent and recruit students. I personally try to approach my tenure requirements by looking for synergies—for example, between teaching and research, between grant writing and service, and between outreach and parenting my kids. That not only makes being an early-career faculty member more manageable—it makes it more fun.

Reference

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I very much enjoyed Alex Lopatka's article "Early-career faculty face many challenges" (Physics Today, October 2024, page 40). In particular, when I read that "at a small liberal arts school, the pressures of research may be less, but the teaching load is likely larger" and then looked at the hypothetical daily schedule for an "academic" (page 43), I laughed out loud! Whatever will our "academic" faculty members do? They have a three-hour teaching load—how shocking!

I have been blessed to have a career spent in positions in colleges and universities that have a primary emphasis on teaching and a lower level of research expectation. In 29 years as a professor, my lightest teaching load for any
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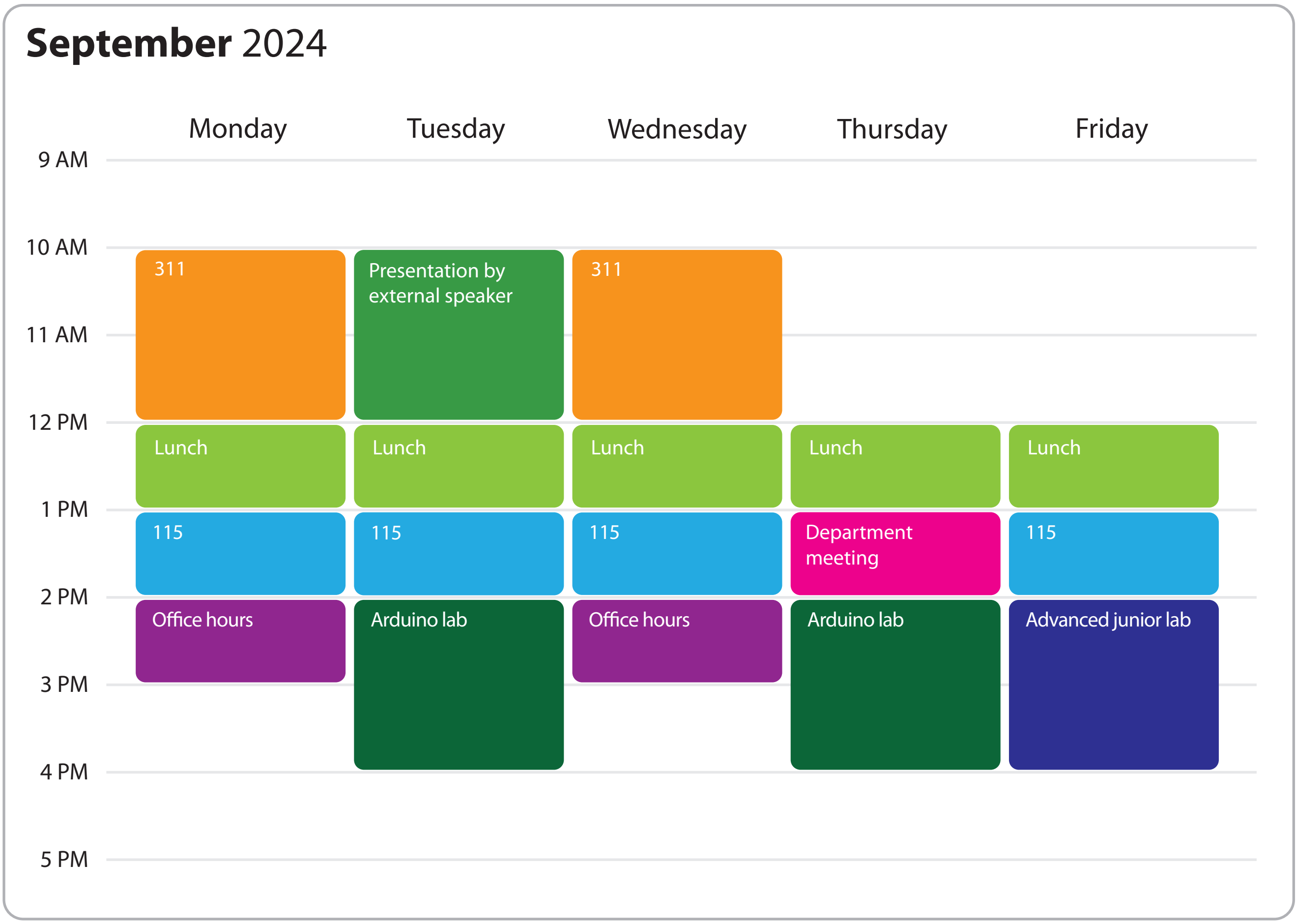

THE AUTHOR'S SCHEDULE last semester. (Illustration by Freddie Pagani.)

semester was eight hours, and that was during my first year in a tenure-track position. I had that "reduced" teaching load because I was also serving a one-year term as the interim chair of the department. Last semester, my teaching load was 11 hours. And I have done all of the grading in all of my courses—I've never had a graduate teaching assistant.

That isn't to say the research component of the job is easy. There are about 2600 four-year degree-granting postsecondary institutions in the US, but only about 150 of those are classified as R1 institutions (doctoral universities with "very high research activity") by the Carnegie Classification of Institutions of Higher Education. The academic positions at non-R1 schools, which make up the majority, will have reduced research expectations compared with academic positions at R1s, but they are still stringent. Such expectations include publishing at a certain rate and obtaining external funding.

To do the latter, you must convince an agency to fund projects that are based on research you have done—which may not be much if you have a high teaching load—using the equipment you hopefully already have. Keep in mind that if you aren't at an R1, your startup package as an experimentalist will not be $1 million, as is described on page 42 (again, I laughed out loud). A startup package of $40 000 would be much more typical. In my department, in order to have a successful grant application for any major equipment, my colleagues have needed to describe to the agencies how that equipment will be used in upper-level courses. In my experience, research gets done half as fast with undergraduates helping and twice as fast with graduate students helping—and the funding agencies know this too. Undergraduates might be on your team for only three years or less, so you'll be constantly building a new team of members with diverse academic backgrounds.

I am not writing because I am jealous of the hypothetical teaching schedule shown, and I am aware of the greater research requirements imposed on faculty at large PhD-granting universities. I have had my schedule because I love teaching and doing research with undergraduates. I definitely do not want to trade places with someone with the schedule on page 43, which is hopefully someone who loves doing research and interacting with graduate students. I hope that I have been preparing my students sufficiently so that you enjoy working with them as graduate students as much as I have loved working with them all these years. I am just suggesting that it would have been helpful to include a second, alternate version of the teaching schedule for an academic position in physics.

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Gauge invariance applies to statistical mechanics too

Mathematical tools from the abstract world of quantum fields have surprising relevance to the seemingly more concrete realm of particles in boxes.

To the uninitiated, the standard model of particle physics can seem like a random hodgepodge of particles and forces: quarks and gluons, charged leptons and neutrinos, W and Z bosons, each with its own idiosyncratic properties and behaviors. To paraphrase I. I. Rabi's remark about the muon, "Who ordered that … or that … or that?"

But a deeper dive into the theory reveals a method to the madness. Far from being arbitrary, many features of the model follow mathematically from the symmetries of the universe. Once the symmetries are known, much of the rest follows inevitably.

The theoretical workhorse for deriving physical laws from symmetries is the gauge transformation. Roughly speaking, you start with a quantity, such as the phase of a quantum mechanical wavefunction, that doesn't affect any physical observables, and you write it as a local function that takes different values at different points in space. Turn the mathematical crank, and out pops a physical law—in this case, a description of the existence and behavior of photons.

Now, Matthias Schmidt and colleagues at the University of Bayreuth in Germany have shown that gauge transformations can also be fruitful in a seemingly disparate area of physics: statistical mechanics.[1] They're still exploring all the consequences of their discovery, but they've already uncovered a plethora of mathematical structure, equations that can help to characterize soft-matter systems, and questions about what statistical mechanical averages really mean.

Mindset shift

It all started with an offhand remark in 2019. Schmidt was working with Sophie Hermann, a new PhD student in his group, to explore the effect of a mathematical manipulation that he called "shifting." "Sophie is a very clear and

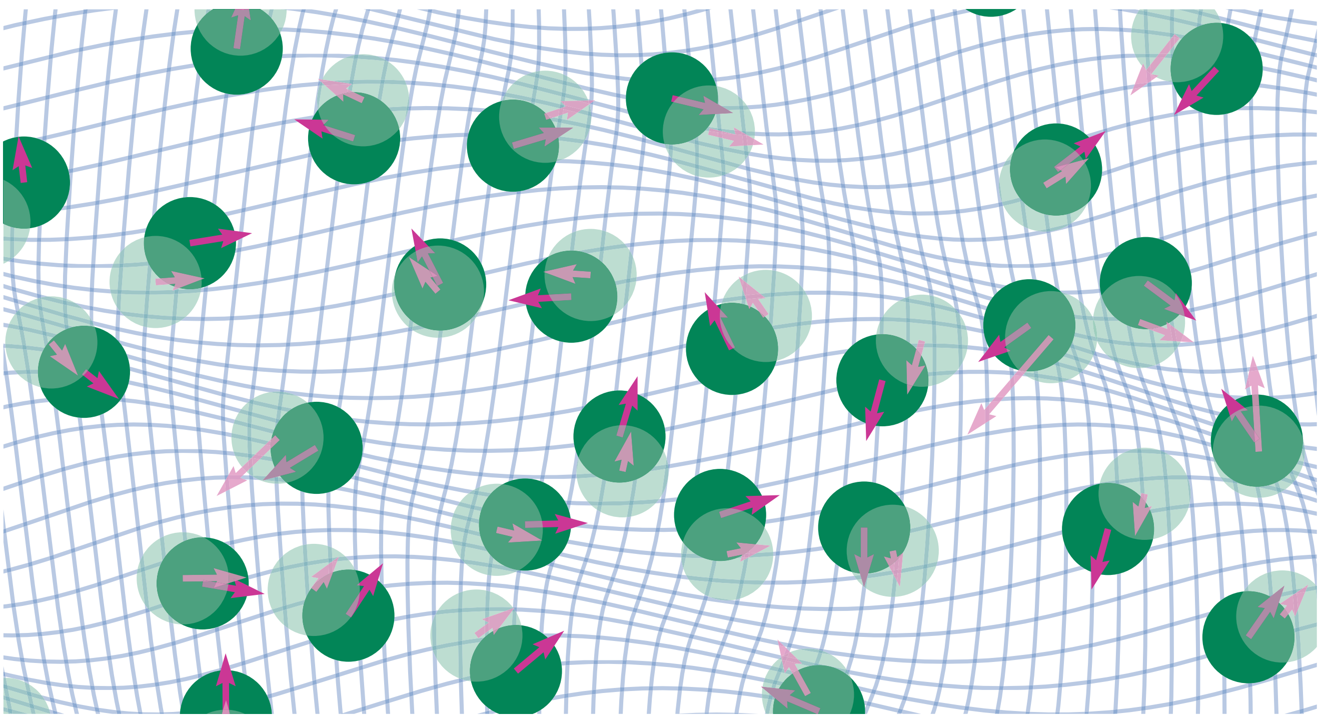

FIGURE 1. A SHIFTY TRANSFORMATION. In a statistical mechanical ensemble at equilibrium, when the position **r** of each particle (solid circles) is shifted to a new position (transparent circles) by a smooth vector field $\boldsymbol{\varepsilon}(\mathbf{r})$ and the momenta are adjusted in a corresponding way (solid and transparent arrows), the values of all observable quantities remain unchanged. The realization that the shift is a symmetry of the system—a gauge transformation—can be used to derive new equations about how the particles behave. (Figure courtesy of Florian Sammüller.)

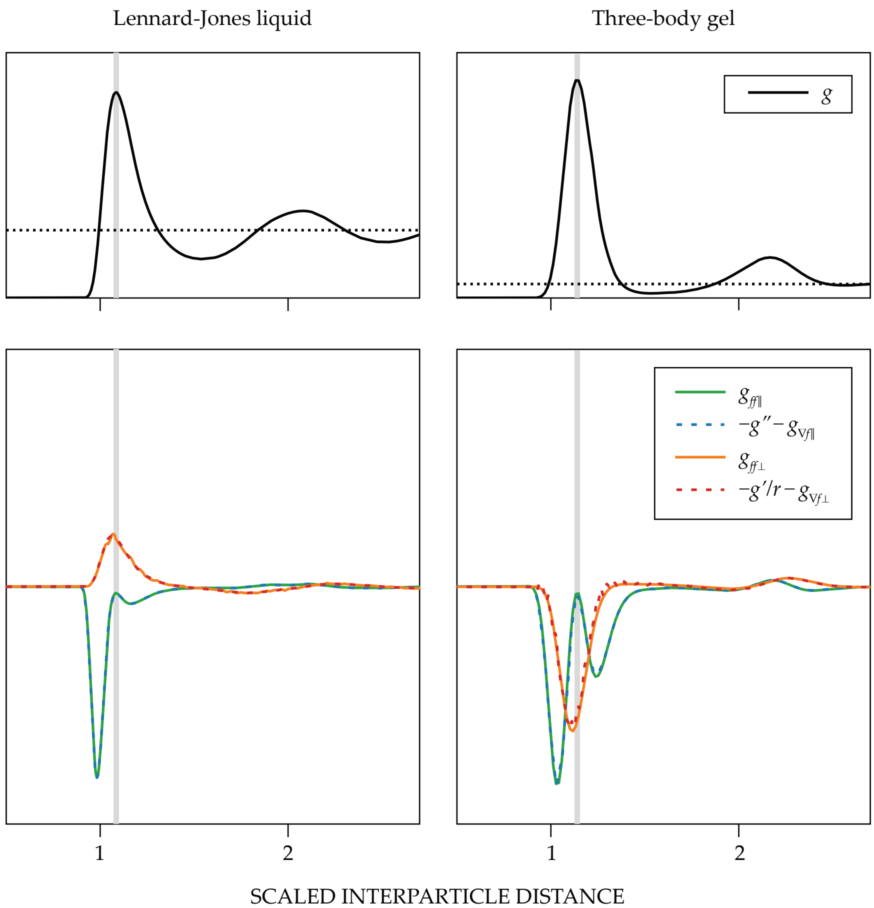

FIGURE 2. LIQUID OR GEL—HOW TO TELL? The position correlation function g can be qualitatively similar for different forms of soft matter, including common models of a liquid and a gel, as shown by the black curves in the upper two panels. But the gauge transformation from figure 1 generates equations involving other correlations among forces (g_{ff}) and force gradients ($g_{\nabla f}$) that can be more sensitive to a system's macroscale mechanical properties. Gauge invariance implies that the quantities shown by the solid and dashed lines in the lower panels should be equal; the plots, derived from numerical simulations, show that the theoretical predictions are correct. (Adapted from ref. 3.)

systematic thinker," says Schmidt, "and she kept insisting that it was unclear what 'shifting' actually implies."

Grasping for an answer, he appealed to a topic he'd covered in his undergraduate classical mechanics course, which Hermann had taken a few years previously: "Think of it like using Noether's theorem," he said. "Translational invariance in a given direction implies conservation of momentum in that direction."

Schmidt was referring to Emmy Noether, the foremother of modern thinking about the role of symmetry in physics. With her theorem, published in 1918, she proved that whenever a system is invariant under a continuous symmetry, it has a corresponding conserved quantity. Translational symmetry implies conservation of momentum, rotational symmetry implies conservation of angular momentum, and time-translation symmetry implies conservation of energy.

Those undergraduate-friendly examples might seem pedestrian and hardly worth mentioning, but the theorem's implications go far deeper. Noether herself was drawn to the problem by the desire to reconcile what physicists thought they knew about classical mechanics with the new theories of special and general relativity. A relativistic universe—especially if it's expanding—might not be translationally or time-translationally invariant, so it might not conserve momentum and energy. But it has other symmetries, and thus other conserved quantities. Noether laid the foundations for understanding it all.

"It was meant to be a throwaway comment," says Schmidt. "What I hadn't expected was that Sophie would go back to Noether's original paper, work through it, and come back with the conclusion that the idea actually has some real substance in it. Once that was clear, we just sat down and worked it out as clearly as we could."

To start with a simple example, they considered shifting the position $\mathbf{r}$ of each particle in an ensemble by a constant vector $\boldsymbol{\varepsilon}$. That's not inherently a symmetry of the underlying classical mechanical system, because they envisioned the particles moving in an external energy potential $V(\mathbf{r})$ that stays put under the shift. So when the particles' positions change, their energies do too. But when the researchers looked at the system as a statistical mechanical ensemble, something more subtle happened.[2]

The basic operation of equilibrium statistical mechanics is the computation of weighted averages by integrating over all possible arrangements of individual particles, with each arrangement, or "microstate," weighted by $e^{-E/kT}$, in which E is the total energy, T is the temperature, and k is Boltzmann's constant. The weighting reflects the fact that low-energy microstates always show up with the highest probability, but the higher-energy ones are not ruled out, especially at higher temperatures.

Shifting a microstate changes its energy and, therefore, its weight in the average. As a result, it turns out, the equilibrium average—of any observable quantity—is unaffected by the shift. Shifting by $\boldsymbol{\varepsilon}$ is not a symmetry under classical mechanics, but under statistical mechanics, it is.

Mathematically, the symmetry means that in thermal equilibrium, the derivative $dX/d\boldsymbol{\varepsilon} = 0$, no matter what X is. Hermann and Schmidt took X to be $\sum V$, the sum of the total potential energy of all particles—and the derivative of potential energy is just the force exerted by that potential. Ergo, in equilibrium, $\sum \mathbf{F}_{\text{ext}}$, the sum of external forces on the system, equals zero.

That might seem boringly obvious. If $\sum \mathbf{F}_{\text{ext}}$ were not zero, the system would start to move, which would mean it hadn't been in equilibrium after all. But as the researchers pointed out, $\sum \mathbf{F}_{\text{ext}} = 0$ is not true for most of the individual microstates. Rather, it's a nontrivial statement about the nature of thermal equilibrium—a so-called sum rule—and Noether's theorem offered a new way of proving it.

From global to local

With subsequent waves of group members over the past five years—including Florian Sammüller and Johanna Müller—Schmidt and Hermann continued to develop the theory. In particular, says Schmidt, "Noether's theorem comes in two flavors, local and global. We'd started with global shifts, but the real powerhouse is the local version."

Generalizing from global to local symmetry would mean changing $\boldsymbol{\varepsilon}$ from a single vector to a position-dependent function $\boldsymbol{\varepsilon}(\mathbf{r})$. In general, shifting by $\boldsymbol{\varepsilon}(\mathbf{r})$ is not a statistical mechanical symmetry: The shift spreads out some particles and moves others closer together. The distortion leaves the respective microstates either overrepresented or underrepresented in the integral over all microstates.

But the thermal average is an integral over not just the particles' positions but also their momenta. So the Bayreuth researchers introduced a corresponding momentum transform, as shown in figure 1, that compensated for the effect of the position shift: Where $\boldsymbol{\varepsilon}(\mathbf{r})$ spread the positions apart, the momenta were correspondingly compressed, and vice versa. As a result, the position–momentum shift (still referred to as simply $\boldsymbol{\varepsilon}(\mathbf{r})$ for brevity) once again left the equilibrium averages of all observables unchanged.

Unraveling the consequences of the local symmetry follows similar lines. Now, $dX/d\boldsymbol{\varepsilon}(\mathbf{r})$ is what's called a functional derivative—a derivative with respect to a function—but just like an ordinary derivative with respect to a number, it can still be set to zero for any observable X. Moreover, one can study the second derivatives with respect to $\boldsymbol{\varepsilon}$ to generate higher-order sum rules that relate the spatial correlations among forces and other quantities.

"All these sum rules just say, 'Zero equals zero,' " says Schmidt, "or 'These two things add up to zero,' where one is an obvious everyday object, and the other is some strange correlation function that you'd never otherwise think of measuring. But it's really worth it to study them, because they can tell you a lot about the system you're looking at."

For example, for their first foray into exploring the consequences of the local symmetry, they looked at simulations of liquids and gels.[3] Those two forms of matter have obvious differences on the macroscale, but it can be tricky to relate their properties to what's happening on the microscale. "The natural thing to want to measure is the shell structure—how likely particles are to be some distance apart," says Sammüller. That quantity, plotted as g in the upper panels of figure 2, is qualitatively similar between model liquids and model gels.

But when the researchers differentiated energy twice with respect to $\boldsymbol{\varepsilon}(\mathbf{r})$, they got a sum rule relating derivatives of g to correlations of forces g_{ff} and force gradients $g_{\nabla f}$. The correlations would be hard to measure in real fluids, but they're certainly measurable in simulations and possibly even in experiments on micron-sized colloids. And as the bottom panels show, they're starkly different between liquids and gels, and the quantities that the sum rule predicts to be equal really are.

"These quantities that come out of the analysis can be very sensitive to various important physical mechanisms," says Sammüller. "They might even be useful for designing liquids with tailored properties."

Full circle

"We could have continued like this," says Schmidt, "with a new paper for every observable: 'Now we can do this for energy, now for kinetic energy,' and so on." But when Müller joined the group, she brought with her a master's degree in mathematics—and the tools to show just how general the shifting theory really was.[1]

The universe of all possible shifts $\boldsymbol{\varepsilon}(\mathbf{r})$, it turned out, forms a mathematical structure called a Lie algebra (named after Norwegian mathematician Sophus Lie—nothing to do with prevarication). Lie algebras turn up in many other areas of physics and mathematics, including in the gauge transformations from particle physics. "Dealing with gauge invariance and Lie algebras is such a standard thing in other areas," says Schmidt, "and it helps us to better understand, assess, and manage the implications of the mathematics."

In particular, the Lie algebra structure sets clear boundaries on the types of sum rules that the $\boldsymbol{\varepsilon}(\mathbf{r})$ shifts can generate. No matter what observable quantity the researchers start with or which functional derivatives they calculate, they'll end up with a sum rule involving correlations of forces and other specific force-like quantities. "These do form a hierarchy of increasing complexity, but the complexity is within the limits set by the Lie algebra," says Schmidt. "The sum rules don't proliferate into an uncontrolled, ever-increasing range of quantities that they relate to each other."

The implications of the $\boldsymbol{\varepsilon}(\mathbf{r})$ shifts were falling into place, but there remained the matter of Hermann's original question: What does the shift really mean? "Gauge invariance is a brutal thing somehow," says Schmidt, "because it says that all these things that one can reach with the gauge transformation are really the same." That is, the gauge transformation is more than a mere mathematical manipulation: The transformed and untransformed versions of the system are physically indistinguishable, which means they're also physically equivalent.

Other common targets of gauge transformations, such as quantum fields and electromagnetic potentials, are already such abstract entities that it's relatively easy to accept that one way of writing them down is no more physically real than any other. Statistical mechanics seems different in that regard, because classical intuition gives rise to mental movies of ensembles of particles zipping around in boxes. Those microstates might seem too concrete to exist as part of an $\boldsymbol{\varepsilon}(\mathbf{r})$-shifted equivalence class: Surely one set of positions and momenta must be the real one?

"It's absolutely weird that gauge invariance also applies in this context, and it's hard to get your head around," says Schmidt. "But it's the averages we're taking that are the abstract thing. The movies aren't real—they're just one very specific illustration. It's possible to look at a system too accurately."

Johanna L. Miller

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UPDATES

The gradual, then sudden, demise of an East Antarctic ice shelf

Decades of satellite imagery held previously unrecognized clues to the ice shelf's impending collapse—and could help researchers foresee the next one.

In March 2022, Catherine Walker, of the Woods Hole Oceanographic Institution in Massachusetts, and her colleagues were poring over the latest satellite images of part of the Antarctic coast, when they noticed something alarming. A 1200 km^2 ice shelf—not the one they were studying at the time, but one nearby—had abruptly shattered. Days later, it was all but gone.

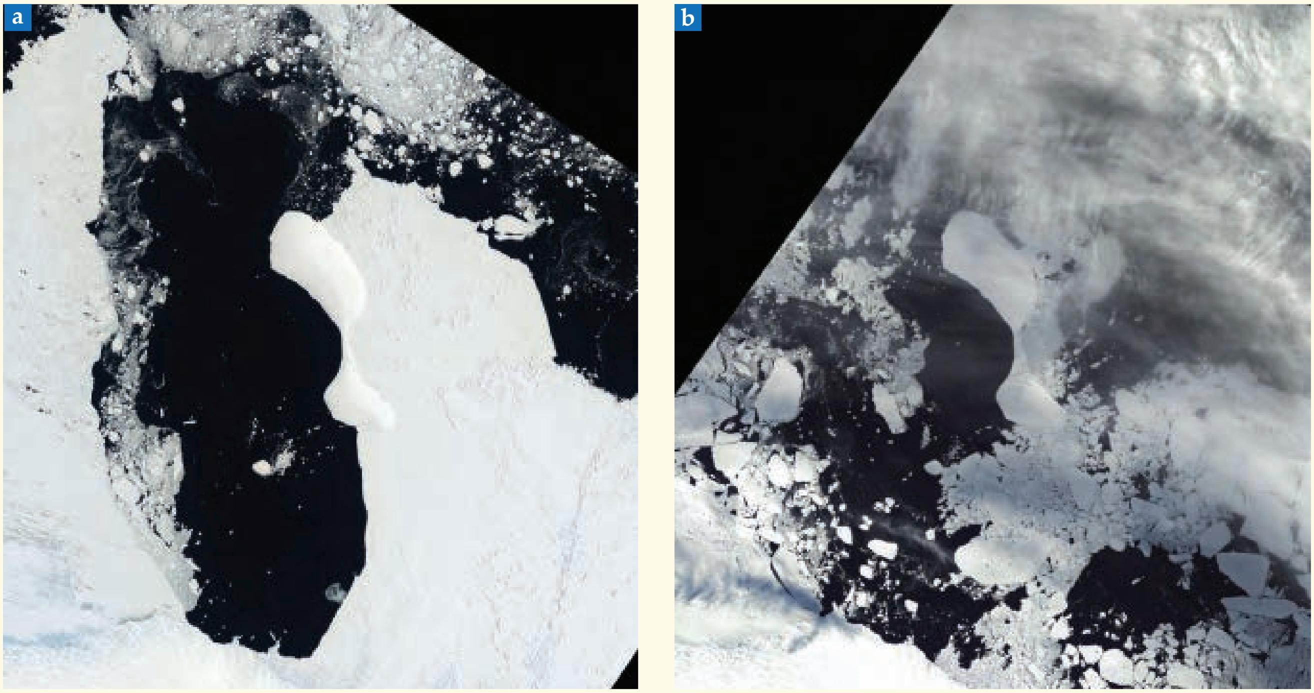
The loss of an ice shelf isn't an immediate threat. The ice is already afloat, so it doesn't raise sea levels when it detaches from the continent, although it can destabilize adjacent land-bound glaciers. Moreover, the lost ice shelf, known as Conger–Glenzer, was not especially large; the Rhode Island–sized Larsen B, which collapsed in 2002, was 2.5 times as big. What made Conger–Glenzer's demise concerning was its location. Larsen B was on the slender Antarctic Peninsula, where summer temperatures often rise above freezing. But Conger–Glenzer was in East Antarctica, a more reliably chilly region that also harbors the bulk of the continent's ice mass.

The obvious culprit was an atmospheric river that had struck East Antarctica that season. Similarly to how they've been affecting the continental US and other temperate regions, formerly rare atmospheric rivers have increasingly been afflicting Antarctica with stormy weather and vast amounts of unusually warm precipitation. Still, Conger–Glenzer showed no signs of surface melting in the weeks before its collapse. Instead, the destructive force was wind, which churned the surrounding sea and stressed the ice shelf to its breaking point.

But now Walker and colleagues have dug deeper into the satellite record, and they've concluded that Conger–Glenzer's demise wasn't solely the result of a freak event. Rather, the ice shelf had been on the decline for decades. Its thickness decreased from 200 m in the 1990s to 150 m in the late 2000s. And in the late 2010s, it started to rapidly accumulate a network of large surface fractures. Those changes, among others the researchers noticed, left the ice shelf vulnerable to breakup when the storm of 2022 hit.

The glaciers that the Conger–Glenzer Ice Shelf had been stabilizing already appear to be flowing slightly faster into the ocean. But with the ice moving at a literal glacial pace, it's far too soon to know what the long-term consequences will be. A better understanding of the signs that foreshadow an ice-shelf collapse could help researchers more accurately forecast Antarctica's future. "We don't actually have a good understanding of how ice breaks," says Walker. "We have models of fracturing and melting, but we're continually taken by surprise when these things happen." (C. C. Walker et al., *Nat. Geosci*. **17**, 1240, 2024.)

Johanna L. Miller



THE CONGER–GLENZER ICE SHELF, **(a)** although intact on 9 January 2022, **(b)** had shattered by 23 March 2022. The seemingly abrupt breakup was foreshadowed by a long period of ice thinning and crack formation. (Images by Lauren Dauphin/NASA Earth Observatory.)

Passive radiative cooling: Not such an off-the-wall idea

A growing class of materials can cool horizontal surfaces to below the ambient temperature with no power input. Now there's a material that works on vertical surfaces too.

The atmospheric greenhouse has a hole in it. Although carbon dioxide, methane, and other gases absorb radiation across much of the IR spectrum and reradiate it back toward Earth, they're nearly transparent between 8 μm and 13 μm, the wavelengths most strongly emitted by a blackbody at 300 K. When a material is engineered so that all, not just most, of its thermal radiation is concentrated in that window, it beams energy straight into outer space. Its temperature spontaneously drops several degrees below that of its surroundings. If spread over 1–2% of Earth's surface, it could even help cool the planet.

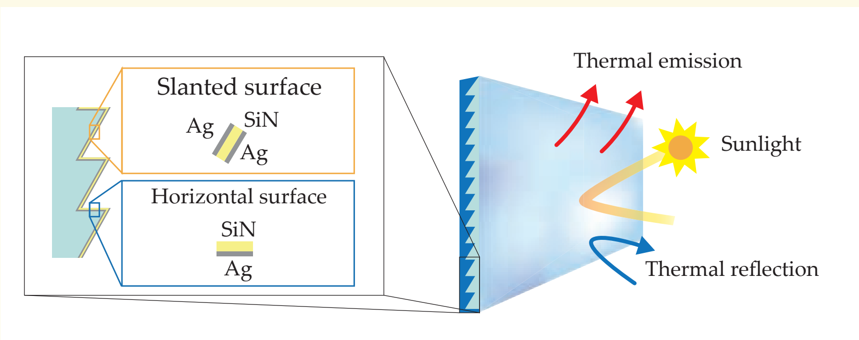
That may sound outlandish, but it's not. Over the past decade, researchers have developed several designs for cooling materials, typically based on substances with strong vibrational resonances in the 8–13 μm window, such as silicon dioxide (see Physics Today, April 2017, page 16). But there's a catch: The materials work only on rooftops and other upward-facing surfaces. If applied to a vertical wall, they'd exchange energy just as readily with the ground as with the sky. And because the ground is usually warmer than its surroundings, it negates the whole cooling effect.

Now an international team of researchers, led by Wei Li of the Chinese Academy of Sciences, Shanhui Fan of Stanford University, and Andrea Alù of the City University of New York, has developed a passive radiative cooling material that works on walls. As shown in the figure, the material has a sawtooth profile, with horizontal facets that face up and slanted facets that face down. The horizontal surfaces are coated with silicon nitride, which emits radiation in the 8–13 μm window. The slanted surfaces are coated with silver to reflect the thermal radiation from the ground.

The researchers tested the material on a hot, sunny day in Beijing. Although the air temperature peaked at 41 °C and the ground temperature reached a scorching 58 °C, the sawtooth cooling material remained below 38 °C. For comparison, a conventional radiative cooling material—designed for horizontal surfaces but deployed on a vertical surface—reached 42 °C, and ordinary white paint was heated to 46 °C.

The material probably won't replace power-hungry cooling technologies, like mechanical air conditioning, all by itself. But cooling an air conditioner's heat sink by just a few degrees can greatly increase its efficiency. And the researchers have their eye on a wide variety of applications, including not just the walls of buildings but also vehicles and clothing. (F. Xie et al., *Science* **386**, 788, 2024.)

Johanna L. Miller



TO COOL A WALL, a material must emit IR radiation toward the sky while reflecting the radiation coming at it from the ground. It can do that with a sawtooth pattern of facets, with the upward-facing surfaces made of IR-emitting silicon nitride and the downward-facing surfaces made of highly reflective silver. (Figure adapted from F. Xie et al., *Science* **386**, 788, 2024.)

A hybrid surface controls where frost forms

A textured honeycomb surface coated in graphene oxide remains frost-free for longer than other specialized materials.

An ephemeral layer of frost is a familiar sight for many of us on winter mornings. That frost doesn't form evenly on leaves: The concave veins often don't develop frost at all. In 2020, Kyoo-Chul Kenneth Park (Northwestern University) and collaborators reported that the geometry of the leaves' surface caused the smallest droplets in the valleys to evaporate and the veins to remain frost-free. Inspired by that discovery, they have now combined a textured surface with water-absorbing nanomaterials to passively prevent frosting.

Frost forms in cold, humid environments when water vapor in the air condenses onto a surface and creates liquid drops that then freeze into porous ice. Under harsh frosting conditions, the process usually occurs within 10 minutes. Research efforts to prevent frost tend to focus on either creating a hygroscopic surface to absorb the moisture that would eventually freeze or designing a textured surface that concentrates the frost in specific regions. But not all the techniques are easily scalable, and nearly all lose their efficacy when scratched or contaminated by air particulates.

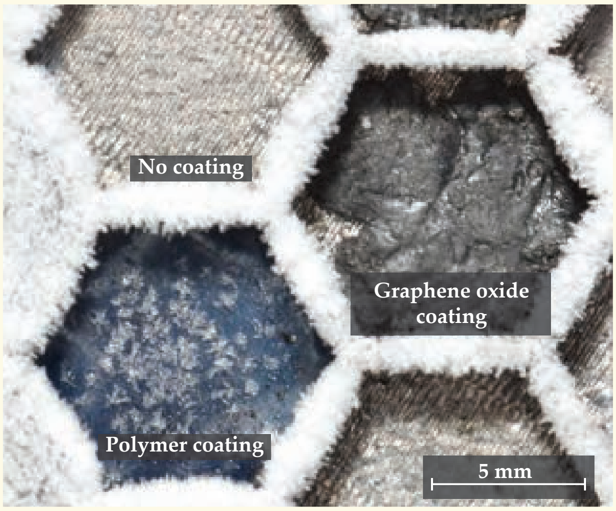
Park's group took a hybrid approach that combines a textured surface inspired by nature with a hygroscopic coating. The team's previous research had shown that convex regions of a surface are frosted more often than flat regions because water-vapor molecules are more likely to bump into the peaks and change to a liquid. Using a 3D printer, the researchers produced either polymer or aluminum walls with a honeycomb structure, on which frost will more naturally form. Like it does in the concave regions of a leaf, frost is slower to form in the flat regions of the textured surface.

A coating of graphene oxide on a surface already delays the onset of frost; frosting is even further delayed when confined by a macrotexture. The test surface was enclosed in an environmental chamber, set to high-humidity conditions and cooled to freezing temperatures, and it took a week for frost to form on the coated, flat regions surrounded by the 3 mm honeycomb walls. Unlike previous surface coatings, graphene oxide is resistant to scratches. Its nanoscale interstitial spaces confine adsorbed water molecules and prevent frost formation.

Park and colleagues are working on scaling the technique. The honeycomb structure is not restricted to a certain material, and the graphene oxide coating can be easily deposited. The group is already performing more tests to better understand how the design would work in real environments. Many industrial applications don't need materials to be 100% frost-free. In the future, a hybrid design may be used to reduce drag on airplane wings and to prevent power lines from collapsing under the weight of heavy frost accumulation. (C. Machado et al., *Sci. Adv.* **10**, eadq8525, 2024.)

Jennifer Sieben

FROST TENDS NOT TO FORM on the concave parts of leaves. Researchers have now replicated the geometry to manufacture a similar effect. (Photo by iStock.com/Anita Nicholson.)



THE FLAT REGION of a honeycomb surface texture (surrounded by 3-mm-tall walls) is less likely to form frost. After three hours, ice started to form on both the uncoated regions and those coated with a polymer. The region coated with graphene oxide remained frost-free for a week. (Image adapted from C. Machado et al., *Sci. Adv.* **10**, eadq8525, 2024.)

Office tape is an effective tool for making ultrathin diamond

The 1-μm-thick membrane is 5 cm wide, about an order of magnitude as large as diamond membranes produced by previous approaches.

Graphene's discovery in 2004 was made possible by an exceedingly simple technique: Andre Geim and Konstantin Novoselov used sticky tape to peel away atomically thin layers of carbon atoms from a graphite crystal. For that achievement and their subsequent study of the new 2D material, the two researchers were awarded the 2010 Nobel Prize in Physics (see Physics Today, December 2010, page 14).

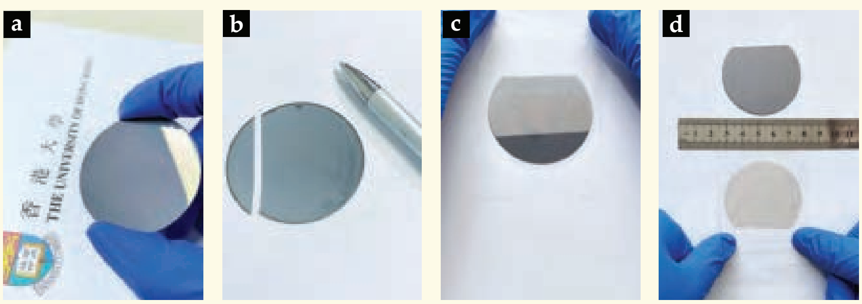
Even though diamond lacks the layered structure of graphite, a team of Chinese researchers found that tape can also separate an ultrathin diamond membrane from its growth substrate. The approach—developed by Peking University's Qi Wang, Southern University of Science and Technology's Kwai Hei Li, and the University of Hong Kong's Yuan Lin and Zhiqin Chu—could be helpful in the mass production of ultrathin diamond membranes. Unlike its bulky counterpart, ultrathin diamond has unique electrical and optical properties that make the material useful in fiber-optic cables, radar instruments, satellites, and other electronic and photonic devices (see Physics Today, March 2022, page 22).

There are a few ways to produce synthetic diamonds with submicron thicknesses. Bulk diamonds can be cut with a laser to produce monocrystalline membranes. Alternatively, thin films with a polycrystalline structure can be grown in a vacuum via chemical vapor deposition (CVD), in which methane and hydrogen react in the presence of an electric current and deposit carbon atoms on a growth substrate, often silicon. But those methods have issues: Laser constraints limit the size of the cut membrane, and until now, CVD diamonds have required time-consuming, multistep etching to separate them from the substrate.

With tape, Chu and colleagues isolated CVD-grown diamond membranes more quickly. The samples were grown on the silicon-wafer substrate shown in the figure below. By cutting across the wafer with a scribing pen, the researchers exposed the crucial diamond–silicon interface. With that access, they could then use the tape to peel the entire diamond membrane from the silicon substrate with limited cracks and deformations.

Polycrystalline diamond membranes tend to have fewer technological applications than their monocrystalline cousins. But the high-quality membranes grown by Chu and colleagues may have improved performance. The researchers' initial characterizations show that their diamond membranes have electrical, optical, and thermal properties similar to those of monocrystalline diamond thin films. (J. Jing et al., *Nature* **636**, 627, 2024.)

Alex Lopatka PT



AN ULTRATHIN DIAMOND MEMBRANE was grown on **(a)** a silicon-wafer substrate with chemical vapor deposition. **(b)** Researchers cut the substrate with a scribing pen, **(c, d)** and then they used sticky tape to peel the 1-μm-thick and 5-cm-wide membrane from the wafer substrate more quickly and effectively than other separation techniques. (Photos courtesy of Jixiang Jing.)

Vast amounts of hydrogen are likely hidden under our feet

Enough of the gas is trapped beneath our planet's surface to satisfy our energy needs for decades, a new study finds. The question is whether it's economically viable to use.

IRON-RICH ROCKS containing minerals such as the forsterite shown here can react with water at high temperatures to form hydrogen. (Photo from the Smithsonian National Museum of Natural History.)

Trillions of tons of hydrogen gas are likely trapped in Earth's subsurface, according to a new study. That's potentially more than enough to meet the projected hydrogen needed to achieve net-zero carbon emissions for about 200 years. Geoff Ellis, a petroleum geochemist at the US Geological Survey (USGS) who coauthored the 13 December paper in *Science Advances*, cautions that many of the hydrogen deposits may be too small or are located too deep or too far offshore to be economically practical for extraction. Nonetheless, he says, "it's a big enough number that if we could find a fraction of that hydrogen, it could still be a significant resource."

Ellis and his USGS colleague Sarah Gelman developed a model to predict global in-place hydrogen resources. It has significant uncertainty, with the estimated quantities ranging from thousands to billions of megatons, but the most likely value is about 5.6 million Mt. Global demand for molecular hydrogen, or H_2, reached 97 Mt in 2023 and is expected to increase to about 530 Mt by 2050.

Frieder Klein, a geochemist at the Woods Hole Oceanographic Institution in Massachusetts, says that the latest paper is "probably the most detailed statistical analysis of geologic hydrogen resources I have seen." He says that this study and others demonstrate "that there is a pressing need for basic research to better constrain the H_2 formation conditions and rates, as well as the potential to trap and exploit geologic H_2."

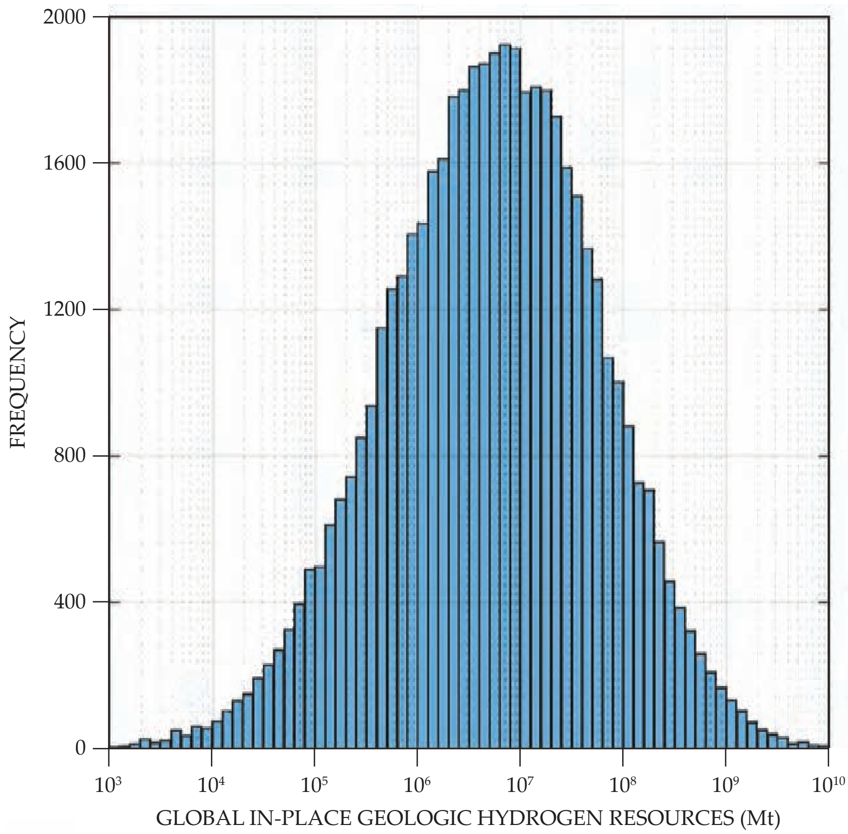
Today, H_2 is mainly used in industrial processes, such as refining petroleum and producing fertilizer and other chemicals. But hydrogen is a key energy source in plans to transition away from carbon-based sources. It has numerous potential clean-energy applications, such as using it as a replacement for carbon-rich natural gas, burning it to generate electricity, and using it in fuel cells, which run on hydrogen and produce water as a byproduct. The International Energy Agency estimates that hydrogen and hydrogen-based fuels could account for up to 30% of energy consumption in transportation by 2050.

Most commercially produced H_2 is a byproduct of fossil-fuel processing, which emits large quantities of carbon into the atmosphere. It is also possible to manufacture the gas by using renewable energy to split water molecules, producing what's referred to as green hydrogen; that method, however, is energy intensive and thus pricey (see PHYSICS TODAY, August 2022, page 22). Last year, the US government committed $7 billion to green hydrogen projects to spur innovation in the sector.

Naturally occurring hydrogen, known as white hydrogen or geologic hydrogen, circumvents many of the difficulties associated with the manufacture of the gas—mainly because it springs from the ground for free. Rocks generate hydrogen in several ways, such as serpentinization, in which iron-rich rocks interact with water, and radiolysis, in which radioactive decay splits water molecules. There are numerous sites in places such as Turkey, Oman, and the Alps where hydrogen gas seeps from the ground naturally.

Ellis, who has researched natural gas geochemistry for 30 years, says that conventional wisdom used to be that it was not worth trying to tap into whatever hydrogen gas was stored in Earth's subsurface. The gas, it was thought, would react with minerals in the soil, get consumed by microorganisms, or leak out and escape into the atmosphere before it could be extracted in large quantities.

A surprise 1987 discovery of a hydrogen deposit in Mali, however, ignited the possibility of large underground deposits of the gas and fired Ellis's curiosity about the potential of exploitable hydrogen gas resources underground. Recently, more discoveries have been made. In 2023, re-



THE RESEARCHERS' MODEL outputs a wide range of potential amounts of hydrogen that is trapped beneath Earth's surface. (Image from G. S. Ellis, S. E. Gelman, *Sci. Adv.* **10**, eado0955, 2024.)

searchers uncovered a massive deposit in the Lorraine region of France, and earlier this year, scientists described a giant geyser of hydrogen in Albania in a deep chromium mine (see "Geologic hydrogen is discovered in a chromite mine," Physics Today online, 8 February 2024).

In their paper, Ellis and Gelman provide estimates of annual geologic hydrogen generation and the extent to which the gas is absorbed by minerals and microorganisms, among other variables. Their models used data on how natural gas gets trapped underground to calculate the fraction of hydrogen that could accumulate and, with helium as an analogue, to investigate how long the hydrogen molecules would remain trapped. "We were able to calculate how much might be trapped in these accumulations," Ellis says, "and then how much might be leaking out to the surface every year."

Ellis underscores that the large quantities of subsurface hydrogen suggested in the model do not necessarily translate to a bountiful energy source. The International Energy Agency's 2023 *Global Hydrogen Review* warns that the resource may be "too scattered to be captured in a way that is economically viable."

Stuart Haszeldine, codirector of the Edinburgh Climate Change Institute, says none of the currently known deposits have reached the size to be produced profitably. To exploit a hydrogen reservoir, companies would have to drill multiple exploratory boreholes, build pipelines, and meet many safety criteria for the volatile gas. "There is a large overhead in producing that," he says.

Similar to natural gas, hydrogen would have to be transported. "You can do that by road tanker or railway, but hydrogen is much, much less dense than methane gas or oil," Haszeldine says. "You will need to compress it and cool it, which is really quite expensive in terms of the cost of energy."

The next step, according to Ellis, is to determine specific locations where hydrogen could potentially collect underground. "That's the big uncertainty," he says. "Is it down there in places we could get it out efficiently, and how do we do that?"

Sarah Wild

Yamilée Toussaint sparks girls' interest in STEM through dance

The engineer and dancer aims to increase the number of women of color in the sciences.

YAMILÉE TOUSSAINT is the CEO and founder of STEM From Dance, a nonprofit organization that aims to empower and encourage girls to pursue STEM careers. (Photo by CEO Portrait.)

When she was four years old, Yamilée Toussaint started taking ballet classes. While growing up on Long Island, New York, she continued to dance—adding tap, jazz, modern, and African hip-hop—while pursuing her other interest: math.

Toussaint has since combined those passions by founding and leading a program that helps girls, especially girls of color, become interested in the sciences through dance. Today, STEM From Dance hosts multiple free programs throughout the country.

Toussaint says that when she arrived at MIT in 2004 to study mechanical engineering, she noticed that she was one of the few women of color in her major. Later, as part of a service project, Toussaint and four classmates flew to New Delhi, India, to meet with college students to discuss how engineering could be used to tackle local sanitation issues. Seeing how engineering served people directly led Toussaint to think about a career with social impact.

After graduating with her bachelor's degree in 2008, Toussaint joined Teach for America, an organization that places teachers at schools where students face educational inequities resulting from poverty and systemic racism. While teaching algebra at a high school in Brooklyn, she learned that many students had negative views about math. "Students may not have had great teachers who inspired them or who made math feel relevant to the real world," she says. "If math was presented to me in a way that didn't feel exciting, then I probably wouldn't love it either." Toussaint began to wonder whether she could help improve perceptions about math and thereby increase the number of women in STEM.

That led to STEM From Dance, which she founded in Brooklyn in 2012. Through the organization, she aims to decrease gender and racial disparity in STEM by building the confidence of girls of color and increasing their exposure to career options. With a little more than $4000, Toussaint presented her first workshop. By 2016, her efforts had begun to gain national attention.

STEM From Dance programs include a network of three-week summer camps for girls ages 8–18. Each day, the participants learn about a specific topic and do group activities, such as coding, costume construction, music composition, and circuitry. They then incorporate those skills into dance routines that they choreograph and perform at the end of their camp session. "When you see the girls perform, you see the pride they have in their performance, not just because they get to dance, but because there's this technical aspect to it that they created," says Toussaint. The participants also go on field trips to places like Google, Amazon, and the American Ballet Theatre.

Last year, about 1500 girls participated in the dozens of after-school clubs that STEM from Dance has launched nationwide. School administrators, teachers, and independent community members can host a club. They receive training and materials to teach a STEM topic in a 10-week series of project-based lessons. One module intertwines Afrobeats and AI; another combines the physics of percussion with hoop dancing.

Many girls come in excited about dancing but skeptical about the STEM aspect, says Toussaint. She describes a participant who came to camp during high school eager to dance but wary

A DANCE PERFORMANCE at the end of a three-week STEM From Dance camp last year showcased the participants' knowledge of coding, circuitry, music composition, and more. The girls programmed the light-strip belts to change colors during the performance. (Photo by Jeremy Stanley.)

about learning coding and circuitry. The girl realized that she liked computer science and ended up coming back for two more years. She is now a junior at Georgia Tech studying computer engineering and is on the STEM From Dance board of directors.

Toussaint says that early on, skeptics warned her that her mission was too niche and that it would be hard to get funding. Yet STEM From Dance has received large grants and gifts from corporations and foundations, including a recent $2 million grant from Google's charitable arm to support AI learning.

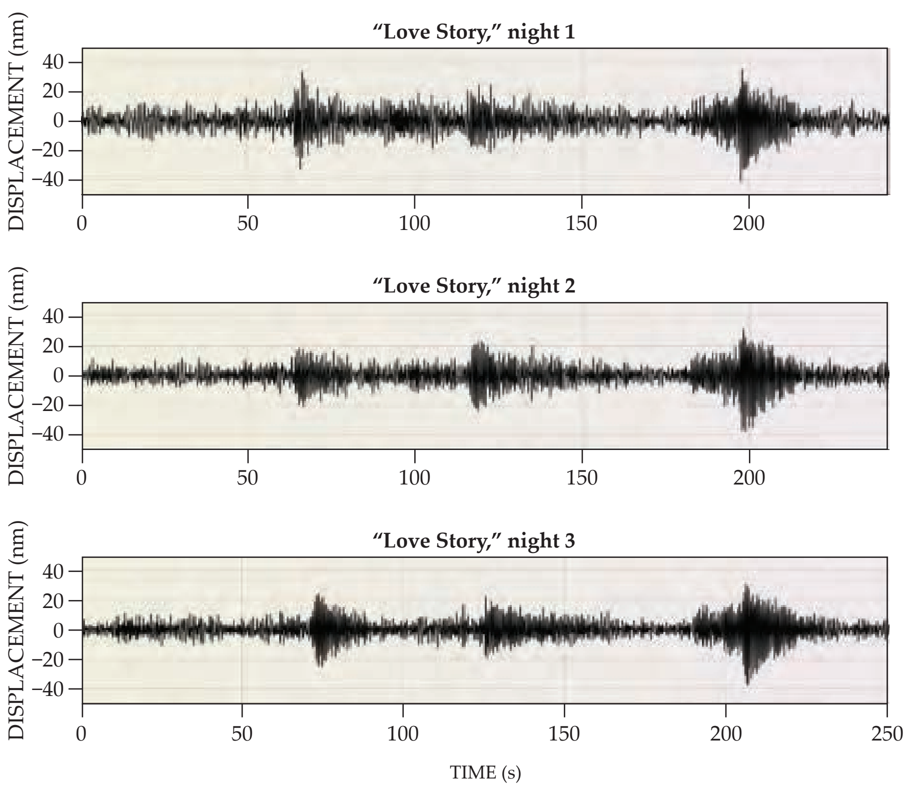
STEM From Dance has so far served more than 4000 girls nationwide. Toussaint says she hopes to meet the 1 million mark by 2032. To help reach that goal, the organization of 12 employees will soon offer resources, including mentorships and networking opportunities, to draw in high school participants entering college. Toussaint says that she wants girls of color "to know that they belong in the STEM community."

Hannah H. Means

A geophysicist uses Swifties' seismic activity for science outreach

Eleanor Dunn employs celebrity and crowdsourcing to spark the public's interest in science.

As many fans jumped and sang along with their idol at a Dublin concert at Aviva Stadium last June, one stayed outside the venue and quietly took data. Eleanor Dunn had set up 41 seismometers at 21 locations near the stadium where Taylor Swift would be performing for three nights. Residents let her put the seismometers inside their homes and underground on their property. Dubbed #SwiftQuakeDublin



FOR EACH OF TAYLOR SWIFT'S THREE DUBLIN CONCERTS in June 2024, the ballad "Love Story" produced the most seismic energy out of all the songs performed. A seismometer 53 meters from the stadium recorded peak activity during the chorus of the song. (Image courtesy of Eleanor Dunn.)

ELEANOR DUNN, a PhD candidate in geophysics and science communication at the Dublin Institute for Advanced Studies. (Photo courtesy of Eleanor Dunn.)

on social media, the research project by Dunn and her supervisor was designed to quantify the ground vibrations triggered by Swift's concerts and to educate the public on the diverse sources of seismic activity.

The fourth-year PhD candidate in geophysics at the Dublin Institute for Advanced Studies primarily researches the Sierra Negra, a volcano in the Galápagos Islands that experiences significant seismic activity before eruption. But Dunn is also interested in science communication and the influence of celebrities on piquing public interest in science. In July 2023, a Taylor Swift concert in Seattle, Washington, made news when seismologists announced that the crowd's movement registered activity equivalent to a magnitude 2.3 earthquake. As more concerts produced their own seismic activity, people online dubbed them Swift Quakes.

Leading up to the Dublin concerts, Dunn launched social media accounts on TikTok, Instagram, and X to promote her research. Dunn noticed that many people were worried about a potential earthquake because "Swift Quake" was in her project's hashtag. "People thought fans were encouraged to cause mass destruction," she says. But "seismic activity happens when you jump up and down in a room, and it doesn't cause damage." She aimed to show that seismic activity occurs every day, usually from sources such as transportation and construction but occasionally from major sporting and entertainment events, and even in places like Ireland that don't commonly experience earthquakes.

Every night during the three concerts, Dunn sat 25 meters away from the stadium and recorded the time each song began. Her subsequent analysis of the seismic data showed that all the songs were easily detectable from a seismic station 14 kilometers away. One song, "Shake It Off," registered 113 kilometers from the venue. It has a repetitive beat that is easy to dance to, Dunn says, which is likely why the song had such an impact. The popular ballad "Love Story" produced the most seismic energy during each of Swift's performances.

Dunn also wanted to elicit fans' interest in the research by involving them. She asked concert attendees to send her videos from the concert so she could compare stadium activity with the seismic data. She received 211 videos that covered almost every song.

Dunn plans to publish two papers: one based on the data and another about the science communication aspects of the campaign. "Social media is impossible to ignore now," she says. "You have to be on social media if you are a science communicator."

Science communication is all about "understanding who you are talking to and what they want to take away from the conversation," says Dunn. "It requires different tactics for different groups."

Hannah H. Means

SEISMOMETERS MEASURED THE GROUND VIBRATIONS produced from three Taylor Swift concerts in Dublin in June 2024. (Photo courtesy of Eleanor Dunn.)

UNESCO details the STEM gender gap and efforts to close it

Using two decades of data, a recent UNESCO report enumerates disparities between women and men in STEM in the G20 countries, considers the reasons for those disparities, and recommends measures to address them. Titled *Changing the Equation: Securing STEM Futures for Women*, it was published last November.

Women are underrepresented in STEM education and employment in all G20 countries, with no statistically discernible progress in the past decade, according to the report. In 2023, women in those countries made up about 35% of college graduates in STEM fields and 22% of the STEM workforce. South Africa and India had the highest proportion of women graduates in STEM, with 47% and 45%, respectively.

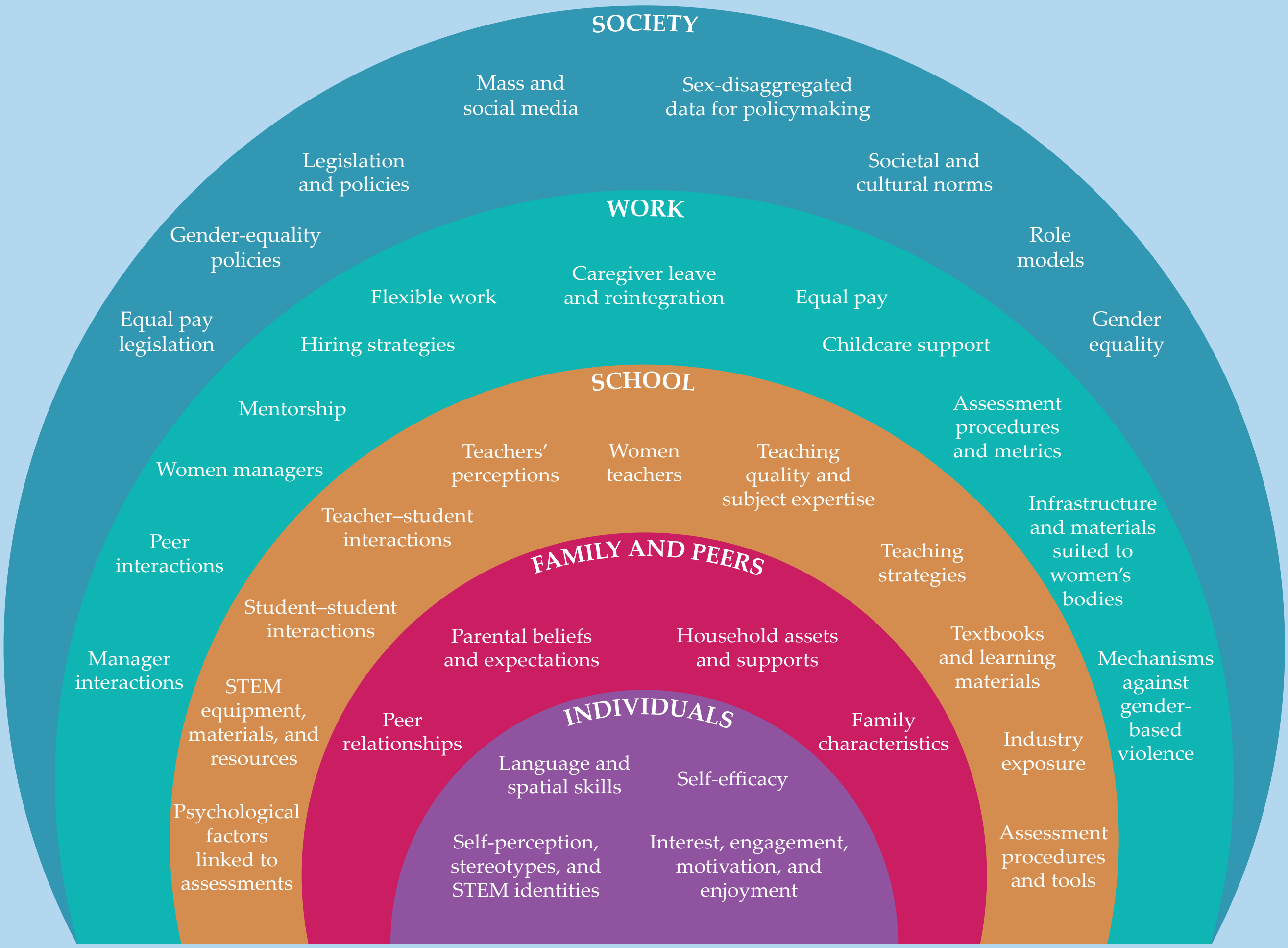
Factors that play into the persistent gender gap are shown in the accompanying figure. They include stereotypes, societal pressures, and cultural biases. Some 34% of women and 12% of men reported sexism, harassment, or gender-based violence as being a top challenge. The report data come from multiple sources, including a biennial survey targeted at students and professionals. The surveys provide a longitudinal view of themes and challenges that influence whether a student pursues a career in STEM.

Gender inequity continues in the STEM workforce. For the 10 countries for which earnings data were available, women in STEM fields were paid at most 88% as much as men; in the US, that number was 69% in 2023. At the faculty level, women's salaries in US STEM departments were 83% those of men. Furthermore, according to the report, women were less likely to receive research grants than men, and when they did, they received smaller amounts.

The report also details efforts around the world to bridge the gender gap. Suggested actions include ensuring equitable access to resources, creating mentorship and industry-partnered programs for girls and women, improving career guidance, ensuring fair and equal pay, and implementing policies for gender equality.

Since 2007, UNESCO has sought to reduce gender inequalities in STEM through its global Priority Gender Equality mandate. The organization argues that "achieving gender parity in STEM careers is not only a matter of social justice but also an economic imperative." More information on trends and UNESCO's work can be found in the report at https://unesdoc.unesco.org/ark:/48223/pf0000391384.

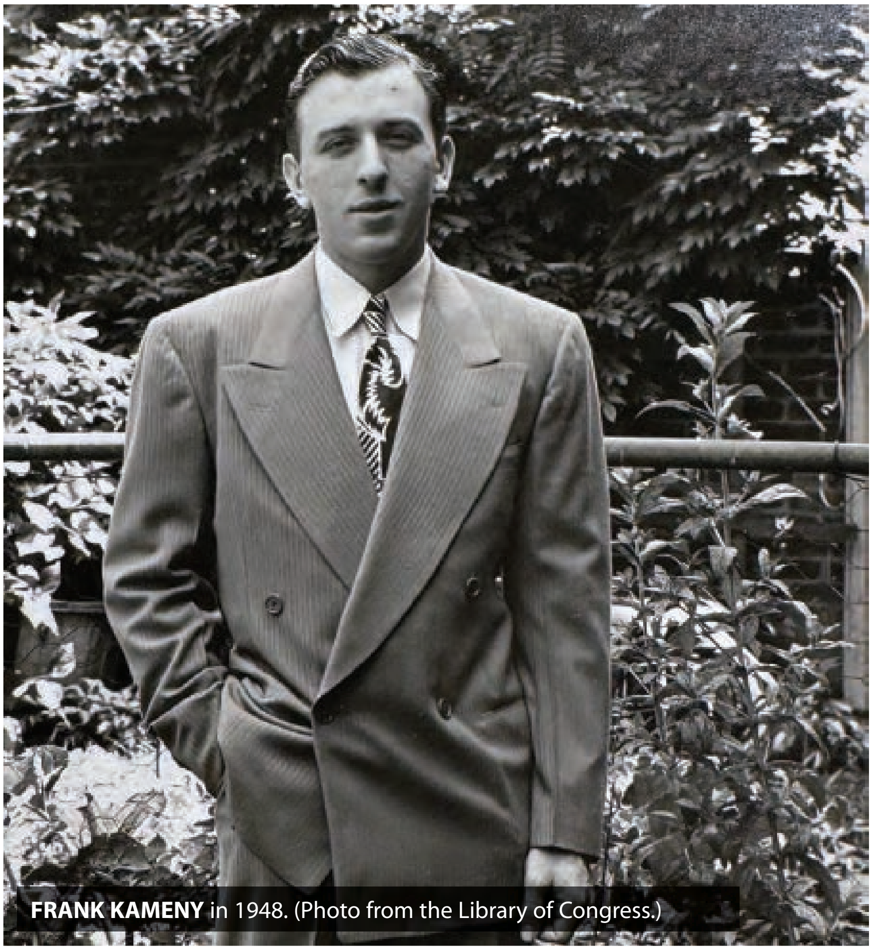
Tonya Gary



(Figure adapted from T. Straza, *Changing the Equation: Securing STEM Futures for Women*, UNESCO, 2024.)

Frank Kameny the astronomer

The famed gay rights leader and accomplished scientist was one of thousands of US government employees who lost their livelihoods during the Lavender Scare.



FRANK KAMENY in 1948. (Photo from the Library of Congress.)

The space race was a time of remarkable innovation and progress in US space science and exploration. Yet, even as the federal government was pouring money and resources into the natural sciences, it was also pushing out scientists, engineers, and other government employees that it deemed unfit. During the Lavender Scare of the mid 20th century, the US dismissed thousands of LGBTQ+ public servants, robbing them of their careers and their legacies.

One of them was Frank Kameny, often referred to as the grandfather of the gay rights movement. He became an activist after he was fired from his job as an astronomer at the Army Map Service.

Despite Kameny's renown in the gay rights movement, his work in astronomy is relatively unknown. In addition to previous interviews and biographical accounts, his papers in the Library of Congress offer perspective on his astronomical achievements. The story of Kameny and the science he only briefly got to pursue is a reminder of the importance of spotlighting those who were denied the opportunity to leave a mark on their fields.

An "unwavering" pursuit of astronomy

Franklin Edward Kameny was born on 21 May 1925 in Queens, New York, to a middle-class Jewish family. By age 4, Kameny knew he wanted to be a scientist, and by 7, he had decided on astronomy. He frequently visited the local planetarium and studied the night sky with his telescope, and he founded his high school's astronomy club.

In 1943, Kameny paused his physics studies at Queens College to enlist in the US Army Specialized Training Program, through which he studied mechanical engineering for a technical role in the military. But the program was soon cut, and Kameny went on to serve as a mortar crewman in Europe. After returning to Queens College, he received his bachelor's degree in physics in 1948 and left for Harvard University to pursue a doctorate. "My ambition to become an astronomer remained unwavering," he wrote in an unpublished memoir.

As a PhD student, Kameny dove into photoelectric photometry, an emerging field spurred by the new commercial availability of photomultiplier tubes. With their increased sensitivity compared with photographic plates, the tubes could detect photons from lower-flux astronomical objects and convert them into electric signals. For his thesis, Kameny measured the light curves of RV Tauri and yellow semiregular variable stars. His adviser, Cecilia Payne-Gaposchkin, was among the many prominent astronomers whom Kameny worked with during his time studying in Massachusetts, Arizona, and Northern Ireland.

Kameny also served as manager of George R. Agassiz Station, a Harvard observatory located about 50 kilometers west of the university. There, he and fellow student Harlan James Smith improved the high-vacuum aluminization process, a method for coating telescopic mirrors. They realized that if they depressurized the aluminizing chamber using vacuum equipment, a thin film of aluminum would coat the glass substrate evenly—a process known as vacuum metallization. After aluminizing the observatory's 61-inch reflector, they wrote an authoritative 171-page manual on the technique.

Lavender Scare

By the time Kameny had completed his doctoral thesis in 1956, he had realized his sexuality and dived into the underground gay scene: "I took to it like a duck to water," he said in the 1972 book *The Gay Crusaders*, "as if it were made for me or I for it!" At the time, sodomy was a crime in all 50 states and the

District of Columbia, and sodomy laws were used by authorities to arrest those deemed to be gay.

On 28 August 1956, after attending the closing banquet of an American Astronomical Society conference in Berkeley, California, Kameny traveled to San Francisco. That night, another man followed Kameny into a train station restroom—a popular gay cruising site—and "touched the private parts" of Kameny for some five seconds. Unbeknownst to them, the San Francisco Police Department had been observing Kameny for a half hour. Upon leaving, Kameny was arrested and charged with "lewd and indecent conduct." Kameny later recounted in a letter to a gay rights advocacy group that the engagement was nonconsensual.

KAMENY USES A TELESCOPE, most likely during his time as a Harvard graduate student, in an undated photo. (Photo from the Library of Congress.)

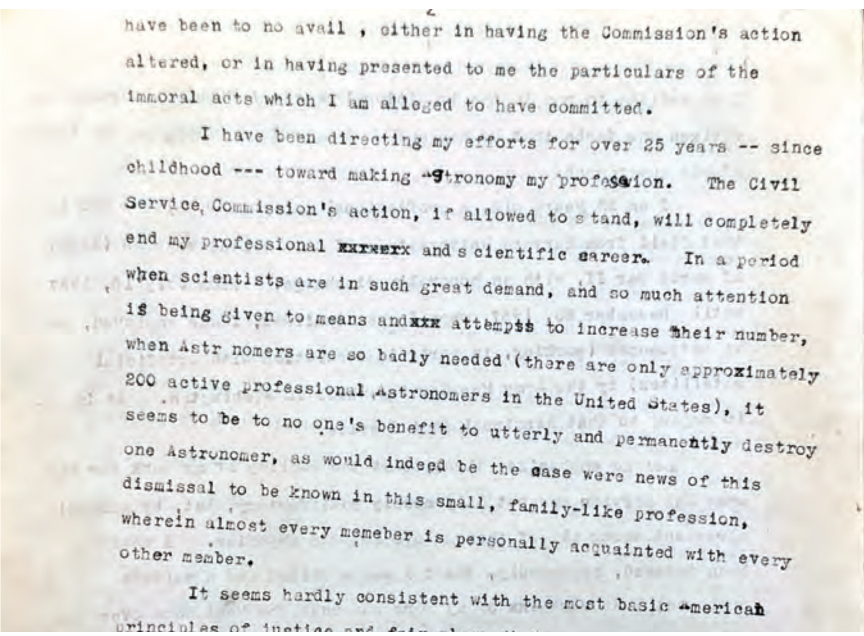
Because it was a minor charge, Kameny thought little of it and continued with his life. He was entering the workforce at a time when the US was competing with the USSR to launch the first satellite, and there were ample job opportunities for space scientists. Kameny relocated to Washington, DC, where he became a research associate at the Georgetown College Observatory and continued his work on photoelectric photometry. In 1957, Kameny took a job with the Army Map Service, where he supervised observing teams and assembled photoelectric observations of stellar occultations. His sky surveys would be used to determine precise distances between locations and to help guide missiles.

But on 24 October 1957, just 20 days after the Soviet launch of *Sputnik 1* sparked new urgency in the US space program, Kameny's career came crashing down. While conducting research in Hawaii, he received a summons from the Army Map Service. The federal government had learned of his 1956 arrest. Kameny was fired in December and, a month later, had his security clearance revoked.

During that time, LGBTQ+ individuals were broadly regarded as mentally ill and subject to blackmail, making them a security risk in the eyes of a government obsessed with preventing alleged subversion by communists. Following President Dwight Eisenhower's 1953 Executive Order 10450 explicitly barring people engaging in "sexual perversion" from federal employment, the Civil Service Commission began systematically dismissing government employees who were suspected to be gay.

Kameny was one of an estimated 5000–10 000 people who lost their jobs during a period that historian David K. Johnson termed the Lavender Scare. And, according to Johnson, because the federal government was becoming the leading employer of scientists and engineers, scientists were disproportionately targeted and impacted. Others dismissed include Benning Wentworth, a technical aide who held a security clearance at Bell Labs, and Clifford Norton, a budget analyst at NASA.

In the aftermath, Kameny struggled to find work in astronomy. Although scientists and other professionals praised his qualifications, including his "outstanding background and accomplishments," Kameny was rejected from institutions such as Johns Hopkins University and MIT. He managed to find temporary, menial jobs at optics laboratories and companies. Even as the government and its contractors were scrambling to reinforce the nation's scientific workforce to win the space race, they refused to hire Kameny because he was gay.



have been to no avail , either in having the Commission's action altered, or in having presented to me the particulars of the immoral acts which I am alleged to have committed.

I have been directing my efforts for over 25 years -- since childhood --- toward making Astronomy my profession. The Civil Service Commission's action, if allowed to stand, will completely end my professional xxxxxxx and scientific career. In a period when scientists are in such great demand, and so much attention is being given to means and xxx attempts to increase their number, when Astronomers are so badly needed (there are only approximately 200 active professional Astronomers in the United States), it seems to be to no one's benefit to utterly and permanently destroy one Astronomer, as would indeed be the case were news of this dismissal to be known in this small, family-like profession, wherein almost every memeber is personally acquainted with every other member.

It seems hardly consistent with the most basic American principles of

AN EXCERPT FROM KAMENY'S LETTER to President Dwight Eisenhower, circa 1958. (Image from the Library of Congress.)

Activism and advocacy

Rather than accepting the dismissal, Kameny fought the decision, becoming the first of those who were fired to challenge the government directly. Incensed by the loss of his scientific career, Kameny wrote to Eisenhower: "I have been directing my efforts for over 25 years—since childhood—toward making Astronomy my profession. The Civil Service Commission's action, if allowed to stand, will completely end my professional and scientific career." He ultimately appealed his case to the Supreme


KAMENY IS HONORED at the White House in 2009. (Photo by Pete Souza/White House.)

Court in 1960. Unable to find legal representation, Kameny drafted a 64-page petition requesting that the court hear his case. It refused to do so.

Nonetheless, Kameny continued his work advocating for gay rights and social justice. He led the Mattachine Society of Washington, DC, organized the first gay rights picket at the White House in 1965, petitioned Congress, and educated people across the country. When Wentworth, Norton, and others sought Kameny's help in regaining their security clearances, he served as their *de facto* lawyer in court. He eventually won pivotal cases, including the ones for Wentworth and Norton, and paved the way for broader inclusion of the LGBTQ+ community in government positions.

In 1969, Kameny turned his attention fully to advocacy. In 1971, he became the first openly gay candidate to run for Congress. The next year, he helped force the American Psychiatric Association to hold a panel at its annual meeting to discuss the classification of homosexuality as a mental illness. At the panel, he and other gay rights activists rebutted its classification, and at a later special session on homosexuality, Kameny served as the chief discussant. His actions played a pivotal role both in the association's 1973 decision to declassify homosexuality as a disorder and in the Civil Service Commission's reversal of Eisenhower's executive order two years later.

Until his death in 2011—on 11 October, National Coming Out Day—Kameny continued to influence public policy and advocate for equal rights. He became involved with local politics: serving on Washington, DC's Human Rights Commission, assisting in the repeal of the district's sodomy law, and becoming a staunch advocate for DC statehood.

Although progress has been made in the nearly 70 years since Kameny's dismissal from the Army Map Service, LGBTQ+ physicists today say they often feel excluded by the physics community (see "To retain and inspire LGBT+ physicists, welcome them," PHYSICS TODAY online, 2 June 2022). In a 2022 survey of 324 LGBTQ+ physicists, 36% had considered leaving their workplace in the previous year because of unwelcoming environments, and 22% reported experiencing discrimination firsthand. The discrimination figure reached 49% for transgender physicists.

As a community, physicists continue to fail their LGBTQ+ colleagues. Only by improving the communities we inhabit, particularly for those of marginalized backgrounds, can physics excel.

Kai Hostetter-Habib

A reference list can be found at **https://physicstoday.org/kameny**.

Q&A: Physicist Karen Hallberg is the new Pugwash secretary general

The organization relies on science diplomacy in seeking solutions to global threats.

In a time of nuclear escalation, including Russia hinting it might use nuclear weapons, says Karen Hallberg, "the situation is much riskier than anytime during the Cold War, except maybe the Cuban missile crisis." The threshold of nuclear confrontation is at an all-time low, says the theoretical physicist at the Balseiro Institute in San Carlos de Bariloche, Argentina. "The Doomsday Clock of the *Bulletin of the Atomic Scientists* is closer to midnight than ever. The situation is horrible." But, she continues, "There is so little public awareness. It's not on anyone's agenda."

It's certainly on hers. On 1 January, Hallberg took the mantle as secretary general of the Pugwash Conferences on Science and World Affairs. Established in 1957, Pugwash is focused on the elimination of weapons of mass destruction through science diplomacy. The organization shared the Nobel Peace Prize in 1995 with its cofounder Joseph Rotblat.

Hallberg previously served for two decades on the organization's governing board, the Pugwash Council. In her new role in the top leadership, she is responsible for organizing Pugwash activities and overseeing the group's international offices, financial transactions, and official correspondence. She works closely with Pugwash president Hussain Al-Shahristani. The nuclear chemist, she notes, was imprisoned in Abu Ghraib for 11 years because he refused to collaborate on a nuclear weapon for Iraq. His "courageous stance against nuclear weapons and his scientific approach to policymaking represent the core values of the Pugwash Conferences," says Hallberg.

Throughout her career, Hallberg says, she has been dedicated "both to science and to the ethical responsibilities of being a scientist." That has included participating in outreach for women and people from disadvantaged backgrounds, representing Argentina and, more broadly, Latin America in international scientific forums, and protesting funding cuts to Argentina's universities.

PT: How did you get interested in physics?

HALLBERG: I was always interested in science. When I was about 10, I had a science club with five or six girlfriends. We solved mysteries and did experiments. And we were very formal—with a president, a secretary, and someone who recorded the minutes of our meetings.

I was aware from an early age that there were not many women in science. I took that as a challenge. And when my dad told me about Einstein's theory of relativity, and that very few people in the world understood it, I took that as a challenge too.

I wanted to do something disruptive, especially as a woman.

PT: Why did you go into theoretical physics?

HALLBERG: As an undergraduate, I was measuring high-temperature superconductors in a low-temperature lab. It was 1986, right when high-temperature superconductors were discovered. The Bariloche Atomic Center had a good materials lab and was fast in synthesizing the new superconducting materials. We measured resistivity and critical magnetic fields. It was fascinating to be immersed in this crazy thing as a student.

PT: So why did you switch out of such a hot field?

HALLBERG: I got a bit scared about the level of demand in high-temperature superconductors. Even though they were extremely interesting times, I didn't think it was compatible with my idea of raising a family.

I spoke to a professor, who became my PhD adviser, and said, "I want to do theory." I told him I liked analytical calculations but that I did not want to have anything to do with computer calculations. Over time, another PhD student taught me how to do computer simulations for strongly correlated systems. By the time I was finishing my PhD in 1993, I was completely immersed in it.

KAREN HALLBERG. (Photo courtesy of Karen Hallberg.)

PT: How did you become involved with Pugwash?

HALLBERG: I used to engage in very interesting discussions on the social responsibility of scientists, nuclear weapons, and other related issues with my undergraduate professor of relativistic quantum physics, Luis Masperi. He was a member of the Pugwash Council, and he introduced me to the organization. I was invited to my first meeting, in Querétaro, Mexico, in 1998. I've been involved ever since.

We formed a local chapter of Pugwash in Argentina in 2000. It fizzled out, but two years ago, we formed a group again. And now that I am more devoted to Pugwash, we want to start doing local things again.

PT: What sorts of local things?

HALLBERG: Since the new government came to power in December 2023, science is in a dire situation in Argentina. Now we have science denialism, lack of funding, no journal access. Researchers do not get grants. Salaries have decreased by 30% in real value because of inflation. The universities are really suffering. This year was the first time we did not have any new PhD students at our institute. Not one. We are suffering a big brain drain.

In Pugwash, we work to convey to the general public the importance of science and how difficult it is to build up again after a period of lack of support. We want the public to realize that science is an important part of our culture and that it is important to bring knowledge to decision making.

PT: What is the nuclear situation in Argentina?

HALLBERG: Argentina has a strong peaceful nuclear program. We get about 7% of our power from nuclear energy. And a state-owned company exports small multipurpose nuclear reactors for research and for production of radioisotopes for medical, industrial, and environmental applications. They can also serve as a source of neutrons.

Argentina has signed many nuclear agreements, but it is the only country in Latin America that hasn't signed the Treaty on the Prohibition of Nuclear Weapons, although it is still considering doing so.

PT: You say the nuclear situation has become very risky today. Can you elaborate?

HALLBERG: Several nuclear treaties are becoming weaker. For example, the NPT—the Treaty on the Non-Proliferation of Nuclear Weapons—is being undermined, since the five original nuclear weapons states (the US, the UK, France, Russia, and China) are not abiding by their agreement to reduce their reliance on nuclear weapons and to aim at their elimination. On the contrary, they are increasing their nuclear stockpiles.

Also, in a year's time, in February 2026, the only remaining bilateral nuclear agreement between the US and Russia, New START, will expire. There are absolutely no conversations to renew it.

The wars in Ukraine and in Gaza have increased the risk even further. We are hearing explicit threats of use of nuclear weapons breaching the nuclear taboo. And the withdrawal of the US from the Iran nuclear deal several years ago was a serious step back in nuclear security. The whole system of nuclear agreements is crumbling.

PT: Where does Pugwash come in?

HALLBERG: In Pugwash, we try to bring people together who think in different and even opposite ways. We want to try to talk with governments.

It's not only about nuclear disarmament. We also have working groups on AI, biological and chemical weapons, and other topics.

There are many issues we want to tackle. We want to foster science diplomacy to help bring peace to conflicting regions, to build confidence, and to solve technical problems. And our networks are important.

We also think it's important to raise awareness among young people about the increased nuclear risk and to incentivize them to think of how science can help humanity. It's fundamental to bring in young people to participate in our meetings.

KAREN HALLBERG (left), secretary general of the Pugwash Conferences on Science and World Affairs, with Masako Wada, a nuclear bomb survivor and assistant secretary general of Nihon Hidankyo, the organization that won the 2024 Nobel Peace Prize. (Photo courtesy of Karen Hallberg.)

PT: How will Pugwash navigate the worsening nuclear environment?

HALLBERG: We will strengthen the scientific aspects, bringing knowledge to decision making. Following the tradition of Pugwash, we will hold consultations between conflicting sides, fostering dialogue and connections that are currently hindered or nonexistent.

We will also cooperate with kindred organizations. The current situation with increasing tensions and threats requires we all work together to halt escalation, reduce the nuclear threat, and aim toward nuclear disarmament.

PT: What are some of your recent or upcoming Pugwash activities?

HALLBERG: In December, I traveled to Oslo to represent Pugwash at the Nobel Peace Prize ceremony. The 2024 prize went to the Japanese organization Nihon Hidankyo, a grassroots movement of survivors of nuclear weapons. While there, I spoke on a panel about nuclear risks. And we are organizing a big meeting in Hiroshima next November for the 80th anniversary of the bombings, the 70th anniversary of the Russell–Einstein Manifesto—a call to world leaders to seek peaceful resolutions to conflicts—and the 30th anniversary of the Nobel Peace Prize to Pugwash.

PT: How do you use your physics in your Pugwash work?

HALLBERG: Of course, I bring my technical knowledge. But for science diplomacy, my scientific training is also helpful. People are used to having discussions where they stick with what they think and there is no exchange of ideas or elaboration based on scientific evidence. There is no listening. That happens a lot in politics. The mental training of a scientist is useful. The only way to counteract fake news is with critical thinking. That is how my training comes in.

Toni Feder

FYI SCIENCE POLICY BRIEFS

Review leaves US extremely large telescopes in limbo

The future of the proposed Giant Magellan Telescope in Chile and the Thirty Meter Telescope in Hawaii remains cloudy following the release late last year of a report evaluating whether NSF should progress either project to its final design phase. Written by a panel of external experts, the report concludes that receiving NSF funding is "critical to both projects" but warns that pursuing either project could dominate the agency's limited facilities budget and damage other research areas absent a significant and sustained budget increase from Congress.

Reacting to the report, Sethuraman Panchanathan, director of NSF, stated that the agency agrees that "the success of the U.S.-ELT [US Extremely Large Telescope] program hinges on securing the necessary resources from Congress." (The ELT program is the vehicle through which NSF would fund one or both of the telescopes.) Panchanathan had commissioned the report to help guide his decision on whether NSF should proceed with one project, both projects, or neither project. The report does not express a clear preference for one project over the other. Emphasizing the gravity of advancing either telescope to the final design phase, the report observes, "Entering FDP is not a commitment by NSF to fund construction; however, the community expectation and the past precedent is that no project has entered FDP without ultimately being built." —LM

US and China narrow scope of S&T cooperation agreement

In December, the US and China agreed to extend their bilateral science and technology cooperation agreement by five years but narrow it to only cover basic research. The agreement explicitly excludes work related to developing critical and emerging technologies and includes "new guardrails for implementing agencies to protect the safety and security of their researchers," said a State Department release. The agreement also includes "newly established and strengthened provisions on transparency and data reciprocity." (As Physics Today went to press, the text of the agreement was not yet public.)

The previous agreement lapsed in August 2023 amid a stalemate in negotiations and an increase in tensions between the two countries. Some Republican politicians criticized the negotiating posture of Joe Biden's administration and pushed to add new congressional oversight mechanisms to the process. Representative John Moolenaar (R-MI), chair of the House Select Committee on the Chinese Communist Party, and other Republican Congress members condemned the extension, calling it "a clear attempt to tie the hands of the incoming administration." —LM

DOE launches new research-security-risk review process

Late last year, the Department of Energy finalized a framework for mitigating research security risks across its grant projects and loans. The framework's effects are far reaching, introducing new protocols for the design of DOE funding solicitations, criteria for grant applications, and ongoing reviews of funded projects. Among the risk factors are connections to foreign entities subject to US export controls, Chinese military companies, and certain research institutions that pose risks of inappropriate technology transfer, according to the Department of Defense. DOE will consider past relationships with such entities but will take into account whether they started before the government began raising concerns about them.

The framework factors in the "technology considerations" of each project, demanding higher scrutiny of projects that involve critical and emerging technologies, access to critical infrastructure, or work near military installations. DOE may require the removal of individuals or vendors from proposed projects as a condition of receiving funding as well as less-consequential actions such as "certifications, tailored mitigation agreements, reporting, and special terms and conditions." —JT PT

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

AIP | FYI

SIMILAR TO BLUEBELLS, which bloom for just a few weeks in spring, some nuclei live for only short periods of time; their behaviors reveal interesting characteristics of the nuclear landscape. (Image by iStock.com/Olga Kaya.)

Witek Nazarewicz is a professor of physics at Michigan State University in East Lansing and the chief scientist at the US Department of Energy's Facility for Rare Isotope Beams, which is operated by the university. **Lee Sobotka** is a professor of chemistry and physics at Washington University in St. Louis.

The lessons learned from ephemeral nuclei

Witold Nazarewicz and Lee G. Sobotka

Recent experimental analyses of fleeting clusters of protons and neutrons put the very notion of the atomic nucleus in a new light.

Atomic nuclei can be divided into those that are stable and those that are not. The latter often are labeled radioactive. But this binary classification fails to capture the range of nuclear lifetimes, from those that last less time than it takes for light to cross atomic dimensions to those that dwarf the age of the universe.

The chart of the nuclides, shown in figure 1, displays the known assemblages of protons and neutrons, dubbed nucleons, that are glued together by the strong force and qualify as nuclei. They are grouped by the number of protons, or atomic number Z, and the number of neutrons N. Of the roughly 8000 isotopes with $Z < 120$ that are theorized to exist,[1] only about 300 can be found on Earth in more than trace quantities.[2,3] Those nuclei, indicated as black squares in figure 1, are usually characterized as either stable or practically stable because their half-lives are greater than Earth's age of 4.5 billion years, and they collectively define a valley of stability on the chart.

Most of the chart, however, comprises nuclei with short lifetimes. They are subject to various types of decay: Beta decay and electron capture are governed by the weak force; and alpha decay, spontaneous fission, and proton decay, by the strong and electromagnetic force. To achieve a broad understanding of atomic nuclei, the entire nuclear landscape must be studied.

The first lesson to learn about the nuclear landscape is that light, stable nuclei have about the same number of protons and neutrons, whereas heavier stable nuclei have more neutrons to compensate for the increasing electrostatic repulsion between protons. The valley of stability thus has a slightly concave curvature.

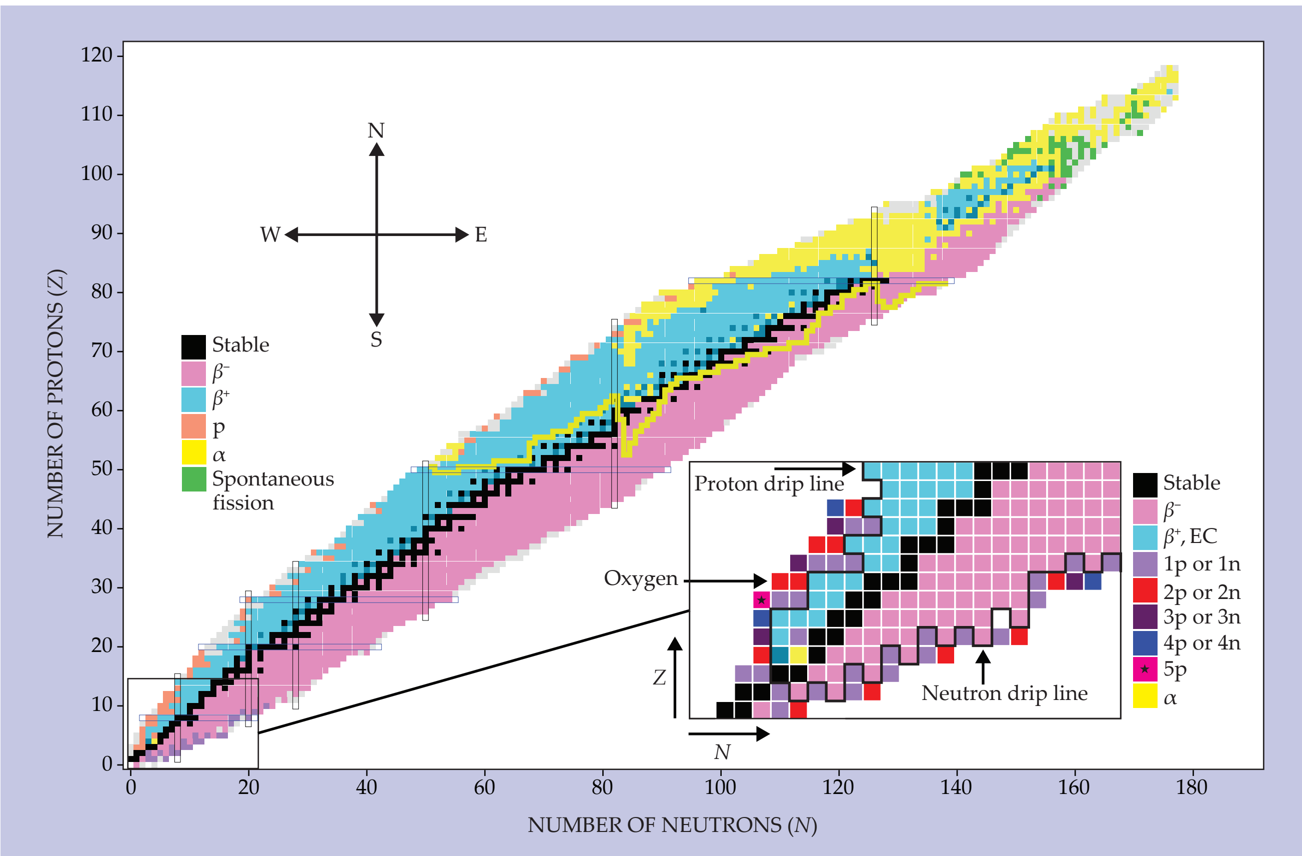


FIGURE 1. THE CHART OF THE NUCLIDES shows the main decay modes of the nuclear landscape. The yellow line corresponds to an alpha decay energy $Q_\alpha = 0$. Above the line, all nuclides are metastable to alpha-particle decay. The inset shows the region where all assemblages of nucleons that qualify as nuclei are known, with color-coded decays. The particle drip lines, indicated with a thick black line, mark the border between bound and unbound nuclei. All nuclides lying outside the drip lines can decay by emitting protons or neutrons. (Experimental data taken from ref. 2.)

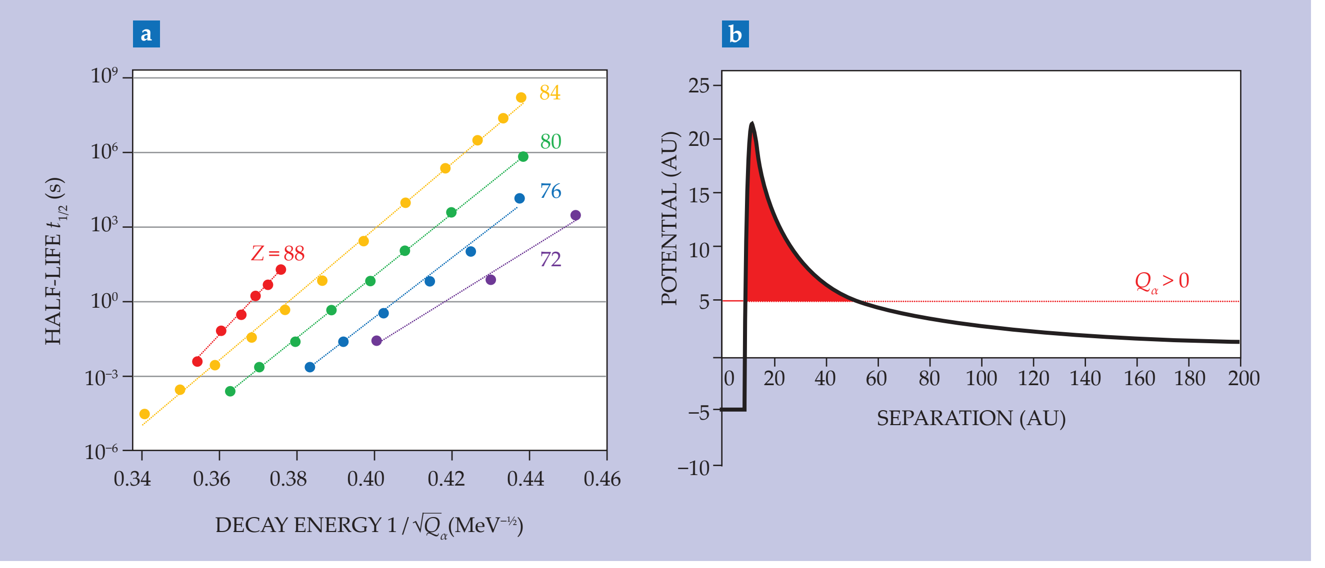


FIGURE 2. ALPHA DECAY. (a) The Geiger–Nuttall law states that alpha-decay half-lives (colored lines) increase exponentially with the inverse square root of the decay energy Q_α and with atomic number Z (labels). The data confirm that alpha particles can decay by tunneling through a potential energy barrier that behaves according to $1/r$ at large distances and that increases with Z, where r is the distance from the center of the nucleus. **(b)** For $Q_\alpha > 0$ (red horizontal line), which is different for each nucleus, the decay rate is determined by the size and range of the potential barrier (shaded region) and the detailed nuclear structure of the parent and daughter nuclides. (Experimental data taken from ref. 2.)

The next lesson is that the stability valley separates two regions of weak nuclear decays: Nuclei decay by β^- emission in the eastern region of the chart and β^+ emission and electron capture in the western region. In the extreme northeast region, where the superheavy elements are found, no long-lived, stable nuclei exist because of alpha-particle decay and spontaneous fission.

A pattern for the stable nuclei emerges when the focus is on isobars, which are defined by nuclides with a constant mass number $A = N + Z$. Usually, only one stable nuclide exists for odd-A systems. For even-A isobars, most often two stable nuclides exist, both of which have even numbers of protons and neutrons. Such observations are perhaps the clearest evidence that like nucleons tend to pair up—the phenomenon of nucleonic superconductivity—and the result is a more tightly bound nucleus.

The boundaries of the chart are more challenging to explain, and the study of nuclei at the boundaries is a subject of active investigations.[4] With enough excess protons or neutrons, the nuclear binding energy decreases to the point that the nucleus can decay by emitting the excess nucleons. The positions on the chart where nucleon emission becomes energetically favorable are called drip lines—the proton drip line to the west and the neutron drip line to the east. The drip lines do not, however, define the chart boundaries rigidly. On the proton-rich side, where the Coulomb repulsion is strongest, the drip line merely denotes a transition from a region that's energetically stable to proton emission to one that's metastable with respect to such emission.

That realization compels the question: When does an assemblage of nucleons constitute a nucleus? By studying ephemeral nuclei, we can begin to answer that question. Such nuclei can also be useful for understanding processes in nuclear astrophysics and various exotic environments.

What is a nucleus?

To answer the question of what constitutes a nucleus, it is helpful to consider the case of the long-known nuclear decay mode in which the nucleus emits an alpha particle. In 1912, Hans Geiger and John Mitchell Nuttall published a paper that showed that the half-lives $t_{1/2}$ of nuclides that emit helium-4 nuclei increase exponentially with the atomic number of the radioactive nucleus Z and with the inverse square root of the decay energy Q_α.[5] The latter is the difference between the energy of the parent atom and the summed energies of the daughter and helium atoms (see figure 2a). The Geiger–Nuttall law remained unexplained until the development of quantum mechanics more than a decade later.

A key element of the explanation was provided in 1928. An alpha particle, which can transiently form inside the parent nucleus because of the exceptionally strong binding of two protons and two neutrons, is subject to an average potential dominated at short distances by the attractive nuclear force and at long distances by the repulsive Coulomb force.[6,7] The competition between the short-range attraction and the long-range repulsion gives rise to a net effective potential with a barrier similar to what is schematically illustrated in figure 2b.

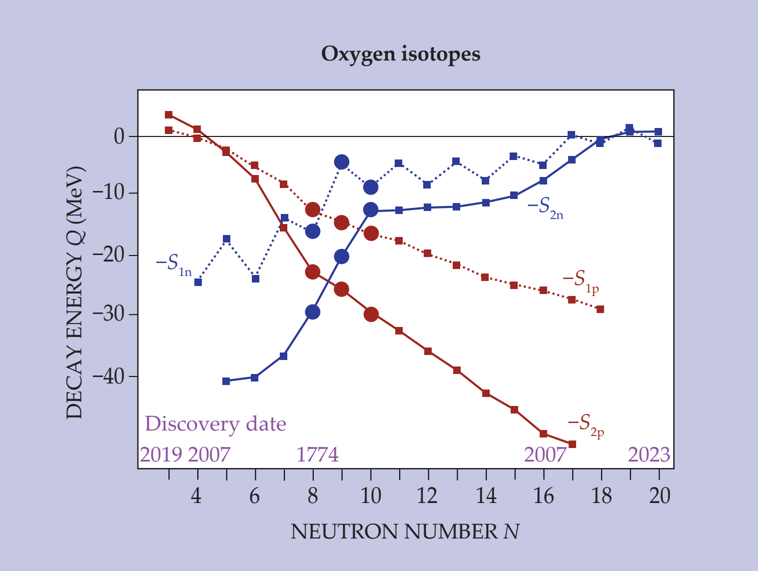


FIGURE 3. THE ENERGY REQUIRED to remove one (S_{1n}, S_{1p}) or two (S_{2n}, S_{2p}) nucleons for each of oxygen's isotopes. The nuclides ^{16}O, ^{17}O, and ^{18}O (largest dots) are the only truly stable isotopes of oxygen because they are also stable to the weak interaction. Oxygen isotopes at lower and higher neutron numbers are unstable to weak decays. On the neutron-deficient side (left), the isotopes ^{11}O and ^{12}O are unbound to 1p and 2p decay. Below the solid horizontal line, the nuclei are stable with respect to particle emission, and some energy—quantified by the Q value—is needed to remove a nucleon from the nucleus. On the neutron-rich side, without a Coulomb barrier, the nuclei beyond ^{24}O are ephemeral. Neutron-unstable ^{26}O and ^{28}O isotopes have small neutron separation energies and emit multiple neutrons. Only in recent years, with the discovery of ^{11}O, ^{12}O, and ^{28}O, have researchers begun to study the zone of nuclear ephemera. (Experimental data taken from ref. 2.)

According to classical theory, if the energy of the potential barrier is higher than that of the alpha particle, decay is impossible. But because of its wavelike behavior, an alpha particle can leave the nucleus by quantum mechanical tunneling. If the tunneling probability is low, then the nucleus is metastable to alpha decay. The fact that the experimental Geiger–Nuttall systematics were consistent with the picture of tunneling through a potential barrier constituted an early triumph of quantum mechanics.

Since the discovery of the Geiger–Nuttall law, nuclear scientists have mapped where alpha decay is the dominant decay mode. The territory is shown in yellow in figure 1. The number of nuclei for which alpha decay is energetically possible ($Q_\alpha > 0$), however, is much greater. (In figure 1, those nuclei lie above the yellow line.) If not for the robust alpha-decay barrier, the region of stable nuclei would end with atomic numbers in the low 60s. Using the same argument, one can conclude that all nuclides heavier than $A = 110$ are energetically unstable to the division into two lighter nuclei through fission. (Alpha decay can be viewed as an extremely asymmetric fission.) The elements in the upper half of the periodic table exist not because of their absolute stability against decay but because of an imposing barrier that prevents them from partitioning into smaller nuclei.

Thus, any reasonable answer to the question of what constitutes a nucleus must not come from whether an assembly of nucleons is energetically bound. Instead, the answer must be based on lifetime considerations. That applies to the light nuclei discussed in this article as well as the heaviest nuclei that define the upper northeast boundary of the chart. In the northeast territory, the nuclei can decay by both fission and alpha emission, but they can be studied as long as they possess an imposing barrier to decay. The situation for neutron-rich nuclei is a bit different than for proton-rich nuclei. Closer to the neutron drip line, beta decay times decrease until neutrons become unbound. Without the Coulomb contribution to the potential, and thus no imposing barrier inhibiting neutron emission, neutron-decay metastability is far more limited, and nuclei rapidly transition from particle-stable to unstable. The long-sought-after tetraneutron sits near that transition.[8]

Confronted with the reality that metastability presents a continuum of lifetimes that depends largely on the effective potential barrier, is there a sensible definition for a nucleus? One measure that makes physical sense is that an assemblage of nucleons possesses a mean lifetime $\tau = t_{1/2} / \ln(2)$, which is long enough for nucleons, moving with velocities characteristic of the internal kinetic energies of the weakest-bound nucleons, to traverse nuclear dimensions at least several times. The result is a characteristic single-particle time scale τ_{SP} of about 1.5×10^{-22} s.

Consequently, if a nuclear state lasts for a long time compared with τ_{SP}, it should be considered a nucleus. Fleeting nuclei that are barely kept together by a potential barrier are referred to as ephemeral. With that definition, a collection of nucleons—including some extremely neutron-poor oxygen isotopes and other light nuclei with an unusually high proton-to-neutron ratio—builds an effective average potential barrier like the one shown in figure 2b. For such nuclei, which are on the western side of the figure 1 inset, the barrier generates metastability similar in form to that which inhibits alpha decay and fission.

A family of nuclei

Oxygen isotopes ($Z = 8$) offer a complete set of possible collections of nucleons that satisfy any reasonable definition of a nucleus. Figure 3 shows the experimental mass difference between an oxygen parent nucleus and a daughter nucleus, with one or two nucleons removed, and the separated nucleons. The decay value Q is the negative of the energy required to separate one or two nucleons from the parent system.

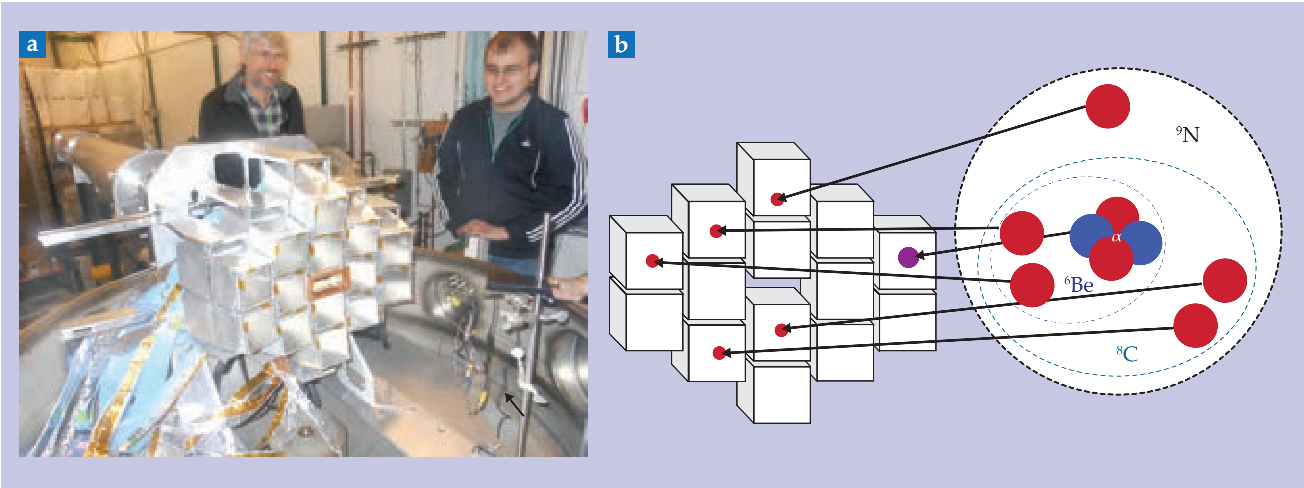


FIGURE 4. INVARIANT-MASS SPECTROSCOPY. (a) A high-resolution array is used by (from left) Robert Charity (Washington University in St. Louis) and Kyle Brown (Michigan State University) to detect the nitrogen-9 nucleus.[12] **(b)** The particle type (proton or alpha in this case), position, and energy of all the fragments from the decay of a ^{9}N parent nucleus are detected by the high-resolution array. Each of the 14 detector elements has multi-hit capability and 1024 location pixels. In the case of the ^{9}N decay, five protons (red) and one alpha particle (the cluster of two red and two blue dots) hit the detector simultaneously and are associated with one decay event. The total decay energy of a ^{9}N nucleus can be reconstructed from each alpha + 5p event, as can the decay energy of intermediates such as carbon-8 from the five possible alpha + 4p subevents. (Image by Jason Keisling.)

When a separation energy is positive (and when Q is negative), some energy is required to remove the designated number and type of nucleons from the nucleus. Hence, if all the nucleon separation energies are positive, the nucleus cannot emit nucleons. All the oxygen isotopes, at least in their ground states, also have positive alpha separation energies and are, therefore, stable to alpha decay. The same cannot be said of excited states, where alpha decay and the fission of oxygen-16 into two beryllium-8 nuclei have been observed.

The ^{16}O, ^{17}O, and ^{18}O nuclides are also stable to weak decays. They are, therefore, the only nonradioactive oxygen isotopes. The nuclei near the three stable oxygen isotopes cannot emit particles but are unstable to weak decays. When Q becomes positive—the uppermost region in figure 3—the oxygen nuclei are metastable.

On the proton-rich side, ^{11}O and ^{12}O are not only unstable to beta decay, they are also unbound to proton emission. For light nuclei, particle emission dominates over beta decay. But for the heavier elements—and deep in the proton metastable region, especially when Z is even—weak decays can prevail. On the neutron-rich side, nuclei heavier than ^{24}O ($N = 16$) strain the definition of a nucleus. Only the presence of finite angular momentum, which generates small potential barriers, and subtle many-body correlations among the nucleons can save the collections of nucleons from prompt disassembly.

Figure 3 shows two even–odd features. First, only the one-neutron separation energy S_{1n} shows even–odd staggering: More energy is required to remove a neutron when a neutron pair must be broken—a signature of neutron pairing. The second is that for the metastable neutron-deficient isotopes, less energy is needed to remove two protons than to remove one. Both ^{11}O and ^{12}O are simultaneous two-proton emitters.

In fact, throughout the proton-rich metastable region, one-proton emission dominates for odd-Z values and two-proton emission for even Z (see the figure 1 inset). The zigzag pattern of the proton drip line results from the relative ease with which elements with an odd number of protons shed one proton. Elements with even Z are relatively resilient—their primary particle decay mode is to shed two protons.[9]

A similar zigzag behavior is seen for the neutron drip line. Odd-N nuclei are often unbound, and their even-N neighbors are bound to neutron emission. Again, the phenomenon of neutron pairing is to blame. Only during the last decade have researchers discovered the extreme isotopes, which are unbound in their ground states to proton and neutron emission. The discoveries were made possible by advances in the production of radioactive beams, which are required to probe the outer reaches of the chart, and by advances in technology that simultaneously detect the many decay products of a metastable nucleus as it disassembles.

Unraveling complex decay sequences

As shown in the inset of figure 1, the proton metastable region has been probed deep enough to find cases for which up to five protons are emitted. The decays always seem to proceed sequentially in steps of one- and two-proton emission. Two-proton nuclear decay usually occurs when no energetically allowed one-proton emission is possible. The situation occurs regularly for even-Z elements because of the pairing energy.[10] If the atomic number of the parent nucleus is odd, the first emission step is always one-proton decay.

The ultra-exotic nucleus nitrogen-9 is a spectacular example of a nuclide that lies west of the proton drip line and approaches the point at which nuclear existence is questionable.[11] The ^{9}N nucleus decays initially by the emission of a single proton and then by two sequential steps of two-proton emission: $^{9}\mathrm{N} \rightarrow [^{8}\mathrm{C}] + \mathrm{p} \rightarrow [(^{6}\mathrm{Be}) + 2\mathrm{p}] + \mathrm{p} \rightarrow [(^{4}\mathrm{He} + 2\mathrm{p}) + 2\mathrm{p}] + \mathrm{p}$. The decay sequence may conjure an image of nested dolls, in which the disassembly of the parent generates a smaller, unstable daughter that eventually decays.

The complicated decay sequence can be unraveled with invariant-mass (IM) spectroscopy, a technique that is borrowed from high-energy physics but that has many refinements specific to the study of exotic nuclei. IM spectroscopy is applicable to situations with many particles in the decay sequence. The technique measures the mass of the decomposed parent relative to the stable, final decay products, each of which has a well-known mass. In IM spectroscopy, a beam composed of nuclei that are unstable to beta decay but are particle-bound is directed toward a target that's in front of a detector capable of identifying and measuring the energy of many particles at the same time. Figure 4a shows an example of an IM spectroscopy system.[12]

The ability to generate such beams is possible at only a few facilities, which use primary reactions to generate radioactive species that themselves can be made into usable beams. A second reaction produces the metastable nucleus that decays, and its progeny fly into the detector system, as seen in figure 4b. From the energies of all the progeny, researchers measure Q for multistep decays and the decay energies of all the subsystems, which represent possible intermediates in the decay sequence. State-of-the-art multiparticle IM spectroscopy can determine absolute masses of the decaying species, or any of the possible intermediates in the decay sequence, with uncertainties of about one part in a million for a nucleus of $A = 10$.

IM spectroscopy is the essential tool for dissecting the multistep decay of ^{9}N. To do so, a bootstrap search looks for the possible decay intermediates within the six particles found in the final state.[11,13] In the case of ^{9}N, if it's formed and ultimately decays to a ^{4}He nucleus and five protons, one must search for the intermediate ^{8}C resonance in the five possible $^{4}\mathrm{He} + 4\mathrm{p}$ subevents of the complete $^{4}\mathrm{He} + 5\mathrm{p}$ event. Similarly, the ^{6}Be resonances must be searched for in the six possible $^{4}\mathrm{He} + 2\mathrm{p}$ subevents of the $^{4}\mathrm{He} + 4\mathrm{p}$ subevents.

Beyond nuclear physics

In recent years, nuclear scientists have studied regions of the nuclear landscape beyond the limits of nucleon binding. Nuclei such as ^{11}O, ^{12}O, ^{25}O, ^{26}O, ^{27}O, ^{28}O, and ^{9}N live in an ephemeral region beyond the drip lines. To better understand the regions at the extreme border of the nuclear landscape, experiments are being planned at radioactive-ion-beam facilities, such as the Facility for Rare Isotope Beams at Michigan State University, the Radioactive Isotope Beam Factory at RIKEN in Japan, and the GSI Helmholtz Centre for Heavy Ion Research in Germany.

The goal of the experiments is to discover exotic nuclides with extreme neutron-to-proton ratios. The work will revolutionize our knowledge about nuclear science and nuclear astrophysics. Violent astrophysical events, such as neutron star mergers and supernovae, synthesize many nuclei via nuclear reaction sequences that proceed through particle-unbound regions and, in some cases, metastable regions of the chart of the nuclides. The methods developed to produce nuclei at the edge of the chart also improve the ability to create much longer lived unstable nuclei that lie closer to the valley of stability, which may have significant applications for society's benefits.[14]

The presence of unbound, very short lived states, which approach the nuclear ephemeral zone, poses fascinating challenges for nuclear theory. Such nuclei cannot be described by the quantum framework found in a textbook. Instead, an open quantum system description must be used that allows for the incorporation of scattering states into a coherent description of the full many-body system.[15,16] The situation parallels the need to include the electromagnetic field in a quantum description of unbound atoms or molecules. With that analogy in mind, researchers have predicted that the interaction between the bound states of a system and the scattering environment will give rise to effects such as superradiance, which enhances alpha decay and is caused by quantum many-body dynamics,[17] and nonexponential decays.[18]

The study of nuclei in the ephemeral zone is closely related to investigations of other small open quantum systems, whose properties are profoundly affected by the environment. In the nuclear context, experimental data, such as that of the ephemeral ^{9}N nucleus, are putting open quantum system treatments of nature to an exacting test. The lessons learned from the study of nuclei with fleeting lifetimes can be applied to atomic, molecular, and reduced-dimensionality open quantum systems.

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Engineers working on *Voyager 2* in 1977. (Image from NASA/JPL-Caltech.)

For more than 30 years, **David Cummings** was the executive director of the Universities Space Research Association in Washington, DC. **Louis Lanzerotti** is a Distinguished Research Professor of Physics at the Center for Solar–Terrestrial Research at the New Jersey Institute of Technology in Newark. This article is based on their book, *Scientific Debates in Space Science: Discoveries in the Early Space Era*, published by Springer in 2023.

Early debates in space science

W. David Cummings and Louis J. Lanzerotti

Does the Sun generate a wind or a breeze? Where do gamma-ray bursts originate? Here's how five of the biggest questions in the field were answered with the help of satellites.

As the space age dawned at the end of World War II, the list of open questions in space science was vast. What was the source of the charged particles that caused auroras? How were those charged particles able to penetrate Earth's magnetic field? What was the nature of the Moon's surface? Those were but a few of the mysteries that remained unresolved in part because observations up to then had all been made from Earth.

Starting in the 1960s and 1970s, probes launched by the US and the Soviet Union helped to bring about a sea change in our understanding of our solar system, galaxy, and universe. The new phenomena detected by those probes forced scientists to refine their astrophysical models or develop entirely new ones. As new data poured in, physicists and astronomers often spent extended periods of time engaged in spirited debate as to which explanatory model was correct.

This article examines five significant debates in the early history of space science that helped shape our current view of the universe.

The solar wind

Observations of comet tails led German astronomer Ludwig Biermann to hypothesize in 1951 that a continuous flow of particles emanated from the Sun. His work attracted the attention of Eugene Parker (see figure 1), who began investigating the topic after arriving at the University of Chicago in 1955. Parker suspected that the flowing plasma is generated in the solar corona, which is about a million degrees hotter than the Sun's surface. The result was a 1958 *Astrophysical Journal* paper—published over the objections of several reviewers—in which Parker proposed a phenomenon that he later termed the solar wind: a plasma made up largely of protons and electrons that flows hydrodynamically with a velocity of about 500 km/s.[1]

One of Parker's colleagues at the University of Chicago, Joseph Chamberlain, made an alternate proposal in 1960. He theorized that the flow of plasma from the Sun was due to the evaporation of ionized particles from the hot solar corona.[2] Chamberlain's mathematical model resulted in what he called a solar breeze, because the plasma would move considerably more slowly than Parker's proposed solar wind.

In subsequent papers addressing each other's hypotheses, Parker and Chamberlain modified their models. Parker generalized his to show that there was only one physically reasonable solution to his hydrodynamic flow equations, one that resulted in a high-velocity solar wind. Chamberlain, recognizing that his evaporation model could be "severely unrealistic,"[3] began investigating a hydrodynamic approach that incorporated thermodynamic principles that Parker had ignored. He maintained that measurements taken by space-

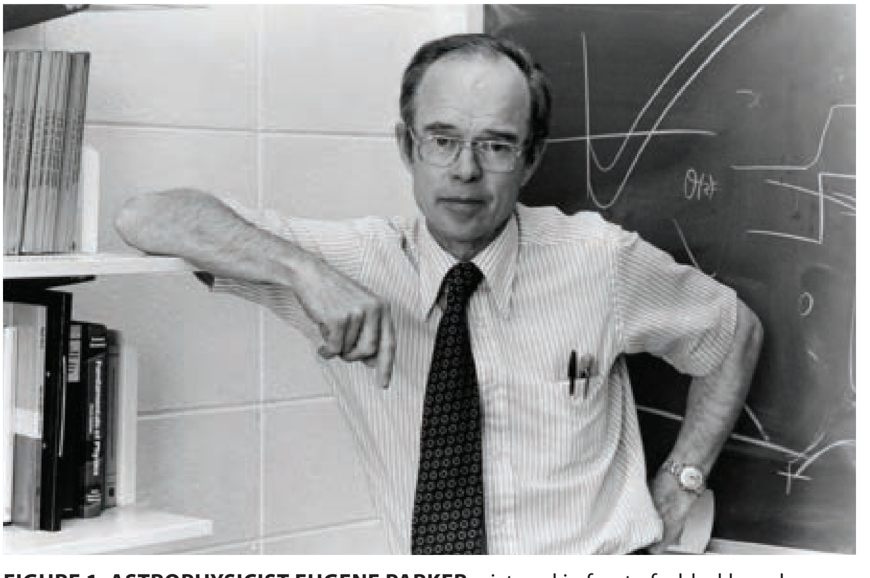

FIGURE 1. ASTROPHYSICIST EUGENE PARKER, pictured in front of a blackboard. (Photo from the University of Chicago Photographic Archive, apf1-11096, Hanna Holborn Gray Special Collections Research Center, University of Chicago Library.)

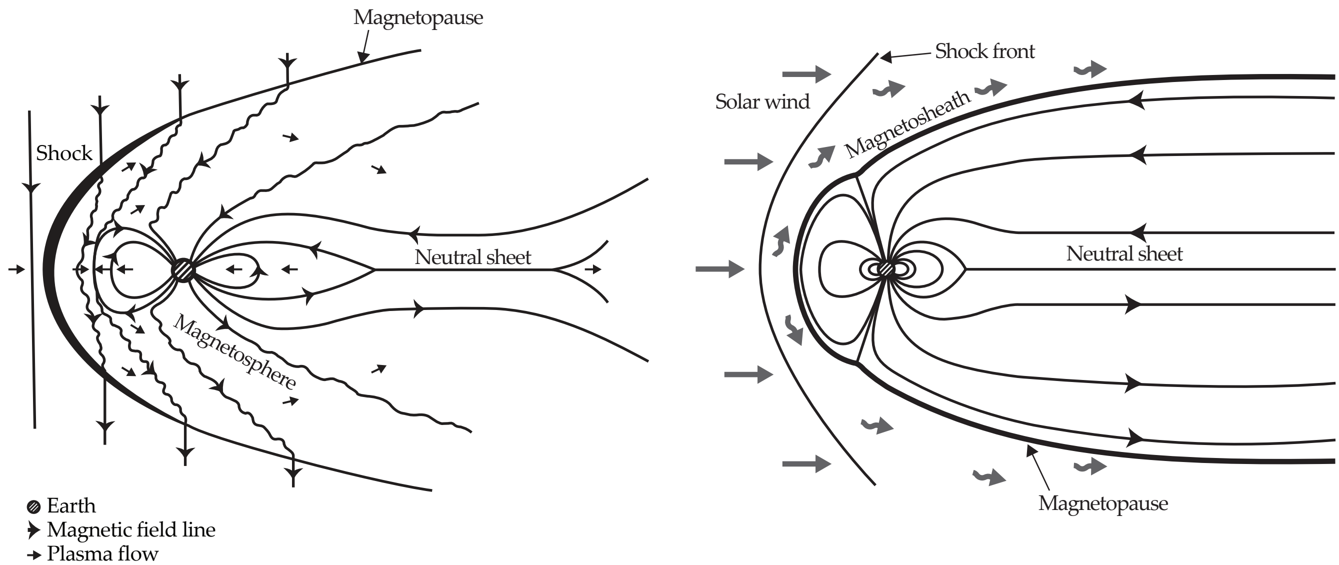

FIGURE 2. SCHEMATIC RENDERINGS of the open **(left)** and closed **(right)** models of Earth's magnetosphere developed, respectively, by James Dungey and Alexander Dessler. (Images courtesy of GreenPepper Media.)

craft would show outward flowing plasma speeds of about 18 km/s.

Launched in 1959, the Soviet Union's *Luna 1* and *Luna 2* probes put Parker's and Chamberlain's proposals to the test. As a team led by Russian physicist Konstantin Gringauz reported in a fall 1960 paper, the Luna particle detectors measured positively charged particles with energies exceeding 15 keV, which implied that proton speeds exceeded 50 km/s.[4] Unfortunately, the spacecraft were not equipped to determine the direction of particle flow. The debate was finally settled in Parker's favor two years later, when an instrument on the US *Mariner 2* spacecraft, operated by Marcia Neugebauer and Conway Snyder of the Jet Propulsion Laboratory, determined that the plasma was coming directly from the Sun at a velocity of about 400–700 km/s.[5] The solar wind is now an integral part of our understanding of the solar system.

Open or closed magnetosphere?

Space physicists soon realized that Earth's magnetic field would form an obstacle for the solar wind. But the extent to which it would do so was unclear. The big question was whether the space in which the motion of charged particles is determined by the terrestrial magnetic field—what is now termed the magnetosphere—is open or closed to the entry of solar wind particles. In the open model, magnetic field lines embedded in the solar wind merge with Earth's magnetic field, allowing the particles to enter the magnetosphere. That is not the case for the closed model.

The roots of that debate lay in the immediate postwar period, when physicist Ronald Giovanelli of the National Standards Laboratory in Sydney, Australia, noticed that solar flares seemed to be associated with the oppositely directed magnetic fields that are found near sunspots. In 1946, he speculated that those field lines might merge, energize plasma, and cause flares.[6] One of the external examiners for Giovanelli's PhD thesis was Fred Hoyle at the University of Cambridge. Hoyle soon suggested to another student, James Dungey, that he examine how magnetic field lines merge to determine if that process might explain the precipitation of charged particles into Earth's atmosphere and produce auroras. By 1953, Dungey had articulated a theory of what is now called magnetic reconnection, in which sheets of oppositely directed magnetic field lines merge, causing electrical discharges and the release of charged particles.[7]

The US *Pioneer 5* spacecraft, launched 11 March 1960, carried a magnetometer positioned so that it could measure the solar wind magnetic field perpendicular to the spin axis of the spacecraft, which was in the ecliptic plane. It found that the magnetic field often pointed out of the ecliptic plane, which in part led Dungey to develop an open model of Earth's magnetic field.[8]

But a colleague of Dungey's, space physicist Alexander Dessler of Rice University, saw the same data as evidence that Earth's magnetosphere was closed (see figure 2), and he developed a model in which the solar wind's magnetic field lines did not merge with Earth's. Aiming to preserve the concept of "frozen flux," in which the charged particles of the

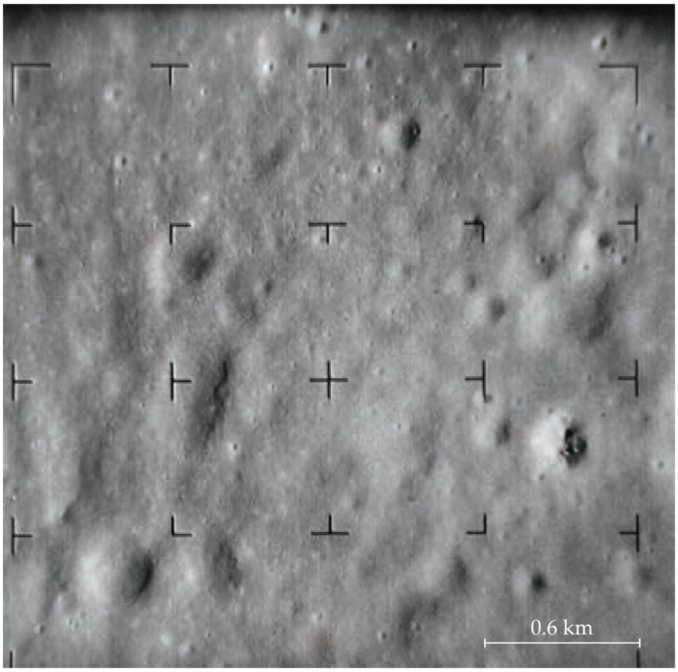

FIGURE 3. AN IMAGE OF THE LUNAR SURFACE, taken by the *Ranger 7* spacecraft in July 1964. (Image from NASA/Lunar and Planetary Institute.)

solar wind are always tied to its embedded magnetic field, Dessler argued that the wind simply flowed around the comet-shaped magnetosphere. Dungey, on the other hand, insisted that magnetic field merging was "not a consequence of the frozen field approximation, but of its breakdown."[9]

The debate continued for several decades. Spacecraft instruments gradually improved and became able to detect magnetic merging at small distance scales. Finally, in 2015, NASA launched the Magnetospheric Multiscale mission: four satellites that fly in formation in an orbit that encounters the nose of Earth's magnetosphere. Led by James Burch of Rice University, the mission took measurements definitively establishing that the magnetic reconnection process occurred on the electron scale, thereby demonstrating that the magnetosphere is open to solar particles.[10] Both field-line merging and the open magnetosphere model are now essential components of our understanding of the behavior of astrophysical plasma.

Lunar dust

In the 1960s, as NASA was planning to land humans on the Moon, space scientists were also turning their attention to Earth's natural satellite. The first crewed landings were to be on the large lunar basins, which many had long assumed were formed by ancient lava flows. But in 1955, Thomas Gold of Cornell University had proposed that the large basins were instead filled with fine dust that resulted from millions of years of bombardment by meteoroids.[11] Suggesting that the dust was "fluidized" either by hot gas generated during meteoroid impacts or by electric forces associated with the photoemission of electrons from the lunar surface, Gold warned in 1958 that the "top few feet [of the lunar surface] may well be extremely loose and more treacherous than quicksand."[12] His provocative claim set off a heated scientific debate among Gold and several distinguished scientists, including Harold Urey, Fred Whipple, Gerard Kuiper, and Eugene Shoemaker.

To reconnoiter the lunar surface prior to the first Apollo landing, NASA sent a series of spacecraft that took photos as they approached and ultimately collided with the Moon. The first images, which were returned in 1964, showed small craters with rounded edges that Urey termed "dimple craters" (see figure 3). The smooth edges of the dimples suggested to Gold that meteoroid impacts had created deep layers of dust on the Moon. He quickly published a paper in *Science* in which he also argued that "without any clear signs of firm rock the pictures must lead to more concern about sinkage on impact or dust blowing in rocket exhausts in future operations on the lunar surface."[13]

Subsequent landings by the Soviet *Luna 9* and the US Surveyor program allayed NASA's fears about the success of Apollo exploration of the Moon: The two spacecraft did not sink significantly into the lunar surface. In the end, although the Apollo astronauts had no trouble traversing the lunar surface, they did report the ubiquitous presence of dust that

FIGURE 4. A SIMULATION of the Sun's termination shock in a household sink.

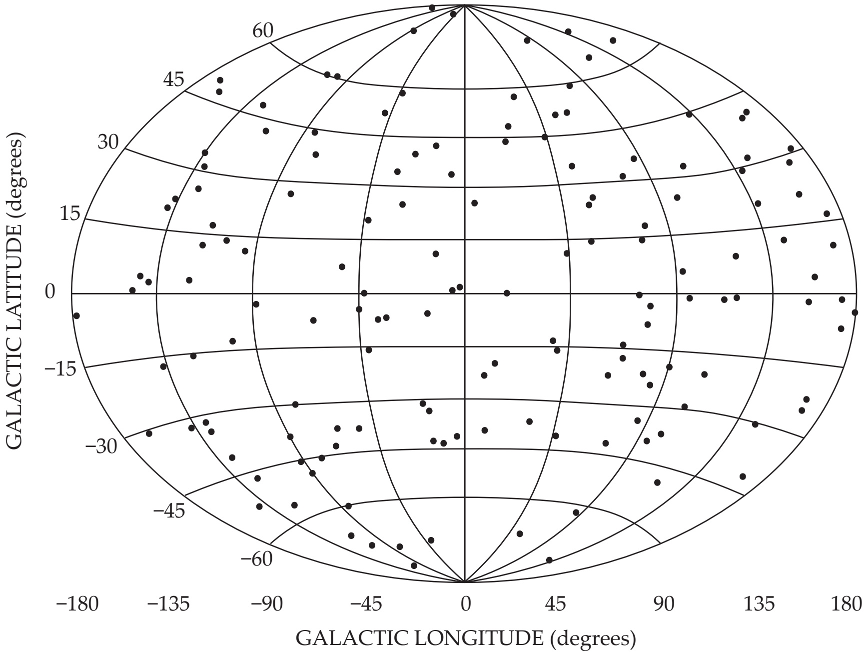

FIGURE 5. A PLOT OF THE 153 GAMMA-RAY BURSTS detected by the Burst and Transient Source Experiment, an instrument on the *Compton Gamma-Ray Observatory*, as of January 1992. The angular distribution of the bursts is isotropic across the entire cosmos. Subsequent observations have confirmed that isotropy. (Image adapted from C. A. Meegan et al., *Nature* **355**, 143, 1992.)

infiltrated equipment and space suits. Dust was blowing so strongly during the *Apollo 12* landing that pilot Pete Conrad could not see the surface and had to rely entirely on instruments for the landing.

Gold received a lot of criticism from lunar scientists during the debate about the Moon's surface. But, as Urey pointed out, "Like all proposals of this kind that any of us make, they are likely to be only partly right, and we ought to be immensely pleased if they are only partly right. I think Gold has made a great contribution in calling our attention to the possibility of dust on the surface of the moon."[14] Indeed, future crewed missions to the Moon will also need to contend with the hazard of blowing dust during landing.

Sizing up the heliosphere

The Biermann comet-tail paper that sparked Parker's initial interest in the solar wind also prompted the question as to the size of the cavity the plasma carved out of the surrounding interstellar medium. The first prediction of the size of what we now term the heliosphere in fact pre-dated Parker's work. Made in 1955 by Caltech physicist Leverett Davis Jr, it estimated the distance to the heliosphere's boundary—now called the heliopause—to be 2000 astronomical units (AU).[15] Davis's calculation was based on a rough estimate of the restraining pressure from the interstellar magnetic field.

At a 1960 symposium in Varenna, Italy, Francis Clauser of Johns Hopkins University pointed out that a standing shock wave would slow the solar wind to subsonic speeds—namely, speeds slower than those of hydromagnetic waves in magnetized plasma—at a distance from the Sun short of its boundary with the interstellar medium. Parker, who was also in attendance, then gave a rough estimate of 160 AU as the distance to the standing shock wave, now termed the termination shock. Figure 4 shows a simulation of the termination shock in a kitchen sink, an example used by Clauser at the Varenna symposium.

In more than four decades of speculation and cordial-but-spirited debate, estimates of the distance to the termination shock varied widely, from 2 AU to 100 AU. Theoretical and experimental information that formed the basis of the debates included such topics as the measured gradients of galactic cosmic rays in the inner solar system, the entry of interstellar neutral hydrogen into the solar system, the friction of cosmic rays with the solar wind, and planetary and heliospheric radio emissions.

Astronomers hoped that the instruments onboard *Voyager 1* and *Voyager 2*, which both launched in 1977, would be able to detect the termination shock and the heliopause. By 1989, with *Voyager 1* about 36 AU from the Sun, the termination shock had not yet been detected. That year, attendees at a space science conference at the University of New Hampshire were polled as to when they thought the probe would encounter it. The average response was 61 AU. *Voyager 1* would only cross the termination shock in 2004, when it was approximately 94 AU from the Sun. *Voyager 2* crossed the termination shock in 2007 at about 84 AU.

Although the debate on the distance to the termination shock was thus resolved, it prompted another significant debate as to the shape of the heliosphere. At least three contemporary models exist: one that is comet shaped, one that looks more like a croissant, and another that takes the form of a beach ball.[16] Space scientists express hope that NASA's *Interstellar Mapping and Acceleration Probe*, set to launch as soon as this year, will settle the debate.

Sources of gamma-ray bursts

Following the adoption of the 1963 Partial Test Ban Treaty, which banned nuclear weapons tests anywhere except underground, the US launched a set of orbiters designed to monitor the Soviet Union's compliance with the agreement. Known as the Vela satellites, they soon began detecting short-lived bursts of gamma rays, which researchers quickly realized did not come from nuclear explosions. So where did the

FIGURE 6. BUTTONS WORN BY ATTENDEES at the 22 April 1995 debate between Bohdan Paczyński and Donald Lamb about the origins of gamma-ray bursts. Those who believed that the bursts come from beyond our galaxy wore the red buttons; those who believed that they occur in our galaxy wore the blue ones. (Photo by Pflatau/Wikimedia Commons/CC BY-SA 3.0)

gamma rays come from? Nearby sources were quickly ruled out: In 1973, Ray Klebesadel, Ian Strong, and Roy Olson demonstrated that the measured gamma rays with bursts as short as 0.1 seconds and as long as 30 seconds could not come from Earth or the Sun.

Further investigations were made by Gerald Fishman and his colleagues at NASA's Marshall Space Flight Center, who took high-altitude balloon flight measurements in 1975 and 1977 and found no gamma-ray bursts. That led them to state that the sources of the bursts were unlikely to be at extragalactic distances and that they must be in the neighborhood of the Milky Way galaxy.

But unlikely is not the same as surely. So Fishman and his team proposed the Burst and Transient Source Experiment (BATSE), an instrument carried by the *Compton Gamma-Ray Observatory*, which was launched in 1991. Activated in April of that year, BATSE began to record gamma-ray bursts at a rate of about one per day. By 1992, it had demonstrated that the distribution of the bursts is isotropic across the celestial sphere (see figure 5). Because distant galaxies also follow an isotropic distribution, the BATSE results thus suggested to many astronomers that the sources of the bursts were outside the Milky Way. If that were the case, the BATSE results implied that gamma-ray bursts are some of the brightest, if not the brightest, explosions in the observable universe.

Some researchers at the time argued, however, that the gamma rays might come from a halo of neutron stars around the Milky Way. They suggested that some supernovae could impart high-velocity kicks sufficient to propel neutron stars out of the galaxy. Over time, those ejected neutron stars might form a nearly isotropic halo around the galaxy, which could theoretically produce the distribution of bursts measured by BATSE.

On 22 April 1995, the Smithsonian Institution's National Museum of Natural History hosted a debate between the two sides (see figure 6). Bohdan Paczyński of Princeton University presented the case that gamma-ray bursts come from beyond our galaxy. His argument was based solely on astronomical evidence: Other celestial bodies that follow an isotropic distribution, such as radio galaxies and quasars, are located far beyond our galaxy. Donald Lamb of the University of Chicago presented the case for the galactic neutron star halo theory. His argument was based on reasonable speculation about possible sources of the bursts.[17]

The 1995 debate did not resolve the dispute. A combination of space- and ground-based observations two years later did. In 1997, Jan van Paradijs, of the University of Amsterdam, and his students were able to associate a gamma-ray burst with a specific galaxy. Unfortunately, they were unable to measure the spectra of the emission lines in the host galaxy. Only a few months later, however, a group led by Mark Metzger of Caltech found an optical flash and a gamma-ray burst occurring simultaneously in the same galaxy. The flash contained emissions from elements within the galaxy, and the spectra of those emissions could be measured. The Doppler shift of the emission lines in the gas of the host galaxy established beyond doubt that the burst sources were outside our galaxy.[18] We now know that gamma-ray bursts are the most powerful phenomena in the universe. Studying them has helped astronomers further refine our understanding of the cosmos.

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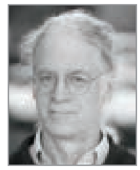
PT

Helping physics departments thrive

David Craig, Theodore Hodapp, and Michael Jackson

Capturing the wisdom of hundreds of individuals and departments, the Effective Practices for Physics Programs guide is a handbook for creating significant and sustainable change.

David Craig is the associate head of the physics department at Oregon State University in Corvallis. **Michael Jackson** is the provost and vice president of academic affairs at the New Mexico Institute of Mining and Technology in Socorro. Both were co-chairs of the EP3 task force. **Theodore Hodapp** is a program director at the Gordon and Betty Moore Foundation, based in Palo Alto, California. He previously served as the American Physical Society's director of education and diversity.



"I want to move our physics department to the next level. What are the five most important things to do in the next two years that will get us there quickly?"

That is the type of question posed by many department chairs and faculty members. Some want to see students be more engaged in their research labs and classes, some are seeing the culture change around them and are unsure how to proceed, and some are motivated by the threat of program dissolution. They love physics and are dedicating their professional lives to its study and to the education of the next generation of physics-informed individuals. What they need is a way to tap into the collective understanding of common issues and advice on taking the next steps for their department.

The American Physical Society (APS) Committee on Education had long wrestled with how to support departmental change. It received a steady stream of calls from members wanting support structures similar to those found in other organizations such as the American Chemical Society. Starting in the early 2010s, ABET, the accrediting organization for engineering, began to establish a framework for accrediting physics and other natural science programs, which caused some concern among physicists about who might have authority to regulate degrees.

An APS survey of physics department chairs in 2014 asked about initiating a national accreditation process. The results led the Committee on Education to propose the development of a comprehensive guide—now known as the Effective Practices for Physics Programs (EP3) guide[1]—that would lay out basic principles for improving undergraduate programs. Those principles included understanding ways in which significant and lasting change is advanced.[2] That understanding, which is woven throughout the EP3 guide, reflects a commitment by the individuals creating the guide to an ongoing cycle of experimentation, assessment, and reevaluation or redesign and a dedication to collective engagement.

The EP3 guide is built on the principle that departments can learn from other programs that have demonstrated positive outcomes from their own change efforts. Additionally, the guide emphasizes that strategies for change should be based on evidence and tailored to local context.

To create the guide, APS joined with the American Association of Physics Teachers (AAPT) in 2016 to assemble a task force, chaired by two of us (Craig and Jackson). The aim was to craft a process for soliciting effective practices, editing them into actionable formats, and vetting the collection with members of the community.

THE EP3 STORY IN NUMBERS

3	35	155	230+	3000+
years (2013–15) of extensive discussions in the APS Committee on Education	sections in the initial release	institutions involved in the development of the guide	contributors and reviewers	specific implementation strategies

The task force soon began recruiting numerous volunteers to begin compiling the collective wisdom of physics department leaders, education researchers, and program innovators. Existing reports[3,4] and studies[5,6] helped shape an understanding of leadership, education, and innovation that informed the guide's development (see also the article by Bob Hilborn and Ruth Howes, Physics Today, September 2003, page 38). In part through extensive conversations with faculty members and program leaders, the EP3 task force recognized that the most dynamic physics programs formed communities among educators and students that provided supportive environments for its members to teach, learn, conduct research, and grow professionally.

The leaders of those dynamic departments consider multiple facets of their program—the curriculum, undergraduate student retention, and the impact of outreach activities, for example—and then support what's working and improve what's not. The EP3 guide captures the wisdom of hundreds of programs and individuals and the work they have done to prepare the next generation of physics graduates for the careers and challenges that they will face moving forward. It also summarizes the scholarship on teaching and learning in ways that can help faculty members improve how their students digest information. And because highly functional departments are enabled by excellent leadership, numerous sections in the guide offer effective strategies for improving department leadership and management. The task force recently heard from one department chair, "The EP3 guide is the how-to guide I never knew I needed."

Effective departmental change

The EP3 guide's philosophy is deeply rooted in the idea that effective and sustainable change efforts are intentional. As it notes, successful physics departments engage in cyclic self-reflection on their processes and outcomes to guide decisions and actions, embrace shared action and ownership, engage appropriate stakeholders, and use data and a clear sense of departmental mission and identity to formulate plans.

Particularly central to the EP3 philosophy is the idea that effective and sustainable change efforts are driven by data. Too often, individuals and departments eager to tackle a perceived challenge make plans without investigating whether those changes actually address the specific underlying issues. For example, departments facing enrollment challenges often turn to aggressive recruitment efforts and new program development in the hopes of attracting new students. But what if the primary reason for a program's lack of physics majors is that it does not retain the students it already has?[7]

One department that the EP3 initiative worked with discovered through focus groups and exit interviews that its introductory course had a reputation for poor instruction. Another program's curriculum was structured primarily to prepare students for graduate programs, so students were getting the message that a physics major was only for those who wanted to become professors, even though that was not the career path that most of them wanted to follow. At those institutions, efforts to recruit more students rather than address the real reasons that students weren't persisting in the program would likely be wasted.

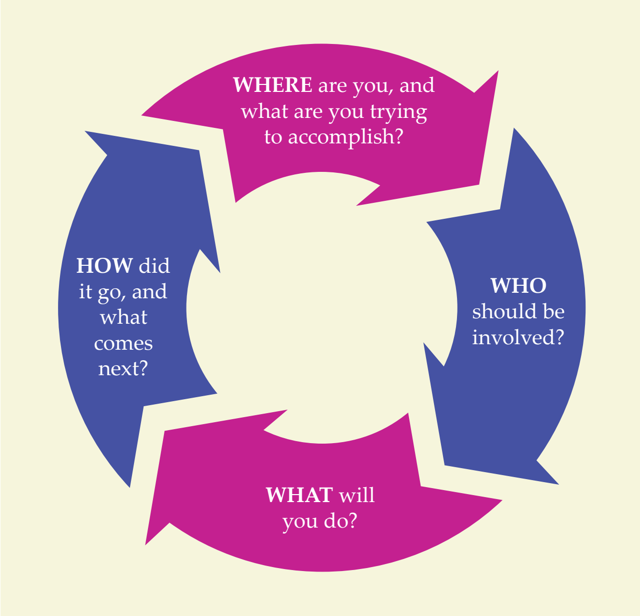
To know where change efforts need to be directed, individuals and departments need to gather data that are relevant to the proposed interventions and that will allow them to evaluate the impact of their efforts. Programs that the EP3 initiative has worked with have garnered important insights from focus groups, exit surveys, and other qualitative assessments to investigate the flow of students in and out of the program. That information was used to complement numerical data, such as course enrollments. Although numerical data are important, STEM faculty and administrators have a tendency to privilege numbers over qualitative data. Yet qualitative data can provide insights into what's going on in a department that numbers cannot.[8] The EP3 guide provides resources to help program administrators who want to collect their own qualitative data and learn from them.

Another related idea that shaped the EP3 guide is that local context matters. Every physics department has its own mission that frames its decisions and activities. Each one also has its own distinct set of conditions and circumstances: institutional, financial, political, and, of course, personal—that is, all the people involved, including students, staff, administrators, and faculty. That is why the guide is framed as a set of effective practices that departments can use to help address their own unique set of challenges rather than as a set of prescriptions that departments should follow. Although programs may have commonalities in possible approaches to challenges that they face, which practices make sense for them to implement depends strongly on local conditions.

For example, consider the task of overseeing the development and implementation of a new curriculum. A small institution, with few impacted programs and people, can often act quickly. But at a large university, the task may be charged to a small group of faculty members and will likely also involve gathering data, consulting a larger number of affected programs, and discussing resource needs with administrators. One large research-intensive department that the EP3 initiative worked with finally found success—after several previous failed attempts at curricular reform—by designing a process to build consensus among the faculty for the proposed transformation and its implementation. With regular communication and opportunities for feedback during the plan's development, the departmental committee guiding the reforms was able to make important adjustments that addressed concerns before making a final proposal.

Changes are most likely to be successful and sustainable if addressed at the department level. Individuals can adapt the EP3 guide's recommendations to help them advance a particular initiative. But for programmatic change to occur and evolve over time, all department members—faculty, staff, students—need to be engaged in the process. Often, efforts fail to take hold when the "hero" who leads it becomes discouraged by the lack of broader support from the program, runs out of time or energy, or changes positions or institutions. Without shared engagement and ownership by an appropriate subset of department members—and a deliberate plan in place for ongoing review and support—efforts to implement change and sustain successes that have been achieved are likely to dissipate over time.

The guide, we realize, is big. Really big. The aim of the EP3 task force was for the guide to be comprehensive, including giving options for programs at different stages of evolution. The guide emphasizes throughout that departments should choose to implement the easiest things first and then return to the guide for the next steps. The task force also wanted to make sure that every recommendation was directly actionable. The task force—and now, editorial board—and the guide's many contributors and reviewers have experienced the difficulties and complexities that departments currently face, and they are attempting to ensure that each effective practice can be done within the limitations that academic departments have.



THE CYCLE OF REFLECTION AND ACTION is a key component of the EP3 guide's philosophy. The guide includes many examples of what to do, but the cycle reminds users that sustainable improvements involve both action and reflection, which then lead to more change. (Courtesy of the EP3 initiative.)

The guide in action

The physics program at Lewis University was in an enviable position of growth, brought on by initiatives such as establishing dual-degree partnerships, adding concentrations to provide flexibility for students, and modernizing the major. Over a decade, the department went from graduating, on average, fewer than four physics majors per year (2007–12) to 15 per year (2017–22). Yet its physics teacher preparation program remained stagnant, averaging one graduate roughly every two years.

Department leaders recognized an opportunity. They applied for and received funding from the PhysTEC (Physics Teacher Education Coalition) initiative to determine the gaps in their departmental offerings and identify how best to measure the success of their work. Based on the data, they resolved to take specific actions to rewrite the story that students were hearing about teaching as a career path. They engaged faculty members and current students and agreed on strategies that could be undertaken, assessed, and improved.

Using established resources,[9] they implemented several strategies designed to help grow the teacher preparation element of their physics program. Along with developing marketing materials for the program, they gathered data on salary information and market demand to promote teaching as a viable career path to their students and other members of the physics department. Their efforts paid off when, in 2024, PhysTEC recognized them with an award for nondoctoral institutions that graduate at least five physics teachers within three academic years.

Lewis University embodied the cycle of reflection and action—a core principle during the EP3 guide's development and one of its recommended strategies—when improving its undergraduate program and advancing its teacher education initiative (see the cycle graphic above). Joseph Kozminski, chair of the Lewis physics department, said, "We realized there were things we could do that required a different way of thinking, a new mode of speaking to one another and students, both prospective and current, about our program. Focusing department conversations on

THE ORIGINAL TASK FORCE, shown here, was small, and the EP3 guide is a result of extensive collaboration with members of the physics community. The many voices who contributed and continue to contribute to the guide are what make the living document a success. In the back row, from left, are Michael Jackson, Stephanie Chasteen, Courtney Lannert, Gubbi Sudhakaran, David Craig, Kathryn Svinarich, Willie Rockward, and Theodore Hodapp; in the front row, from left, are Sam McKagan, Ramon Lopez, Carl Wieman, Robert Hilborn, Gay Stewart, and Lawrence Woolf. Noah Finkelstein is not pictured. (Photo by Sean Costello.)

creating opportunities for students, backed by data, was critical in developing buy-in that ultimately increased the number of students we could help become teachers."

How to use the guide

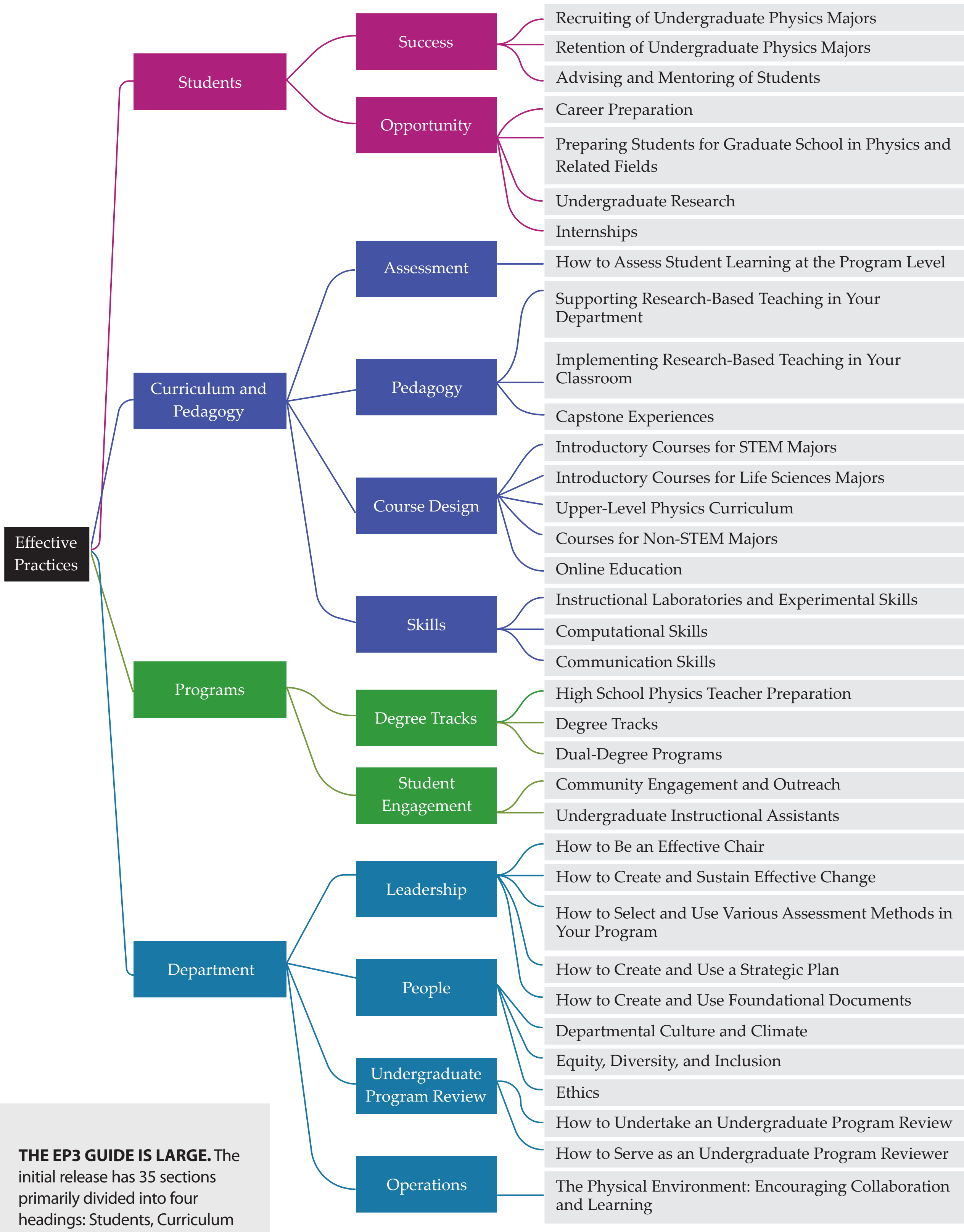
The EP3 guide is a living collection of knowledge and advice provided by the physics community of educators and researchers; it spans all aspects of the undergraduate student experience. The guide addresses topics such as recruitment and retention, pedagogy and assessment, and creation and sustainment of effective change.

Many individuals who enter leadership positions do not receive training in advance and must learn to lead on the job. To help address that critical need, the EP3 guide includes resources to support faculty members as they take on various leadership roles during their career. Sections include "How to Create and Use Foundational Documents," which can help set a common understanding of the department's mission, vision, and values among all members of the department, and "How to Be an Effective Chair."

Because the EP3 guide is not a prescriptive to-do list, it includes far more strategies and actions than any individual department can implement, and many departments are already doing some of what's recommended. Each section starts with a brief description to orient readers, followed by a set of effective practices, which are organized into thematic groupings with multiple actionable strategies for implementing each practice. Sections also include specific assessments and techniques that departments can use to evaluate whether they are achieving their desired outcomes. Nearly all sections end with a list of evidence-based, high-level resources that include deeper dives into the material and language that can help convince colleagues and administrators to implement changes.

For example, a new department chair may use the guide to find tips on how to manage difficult issues or to explore strategies on how to engage with their dean and advocate for resources. Similarly, a leader of a department with low enrollment may facilitate a retreat by asking one working group to report on ways of leveraging the institution's support structures for students (from the section "Retention of Undergraduate Physics Majors") and another working group to summarize key guidance on structuring introductory courses to meet department goals and students' needs within institutional constraints (from the section "Introductory Courses for STEM Majors").

Departmental reviews are another mechanism for implementing change. Most accreditation bodies require them at regular intervals, typically every five to eight years. Reviews are an opportunity for department members to discuss and evaluate what has been accomplished during the previous review period and assess their goals going forward. They can also be a time to clarify the department's strategic directions. Reviews offer opportunities for programs to engage their university leadership on how their activities and aspirational goals align with the institution's vision and mission, to reinforce their contributions to the institution, and to



THE EP3 GUIDE IS LARGE. The initial release has 35 sections primarily divided into four headings: Students, Curriculum and Pedagogy, Programs, and Department. (Chart courtesy of the EP3 initiative.)

We want to hear from you

What is missing? Where should the guide go next? Because it really is a resource developed by and for the physics community, the EP3 editorial board would love to hear from you. Let the board know how it should expand or improve the EP3 guide so you and your colleagues can do the hard work of putting principles and practices into action that will benefit your department and, most importantly, your students. If you are interested in contributing to future versions of the guide, we encourage you to contact the editorial board at ep3@aps.org.

advocate for continued (or increased) investments in the department. The EP3 guide provides templates and details on how department chairs can conduct an external review for their department and how faculty members can serve as a program reviewer for another department.

Moving forward

Having available resources and actually implementing recommended changes are separate things. Even in the early days of the EP3 initiative, the team knew that a living document was essential but wouldn't be enough to make a sustainable difference. There also needed to be active support for departments using the guide. Because of feedback from focus groups and surveys with physics department chairs, the EP3 initiative offers workshops to support use of the guide and is exploring partnerships with other organizations and change initiatives.

One major effort is the Departmental Action Leadership Institute (DALI). Developed and facilitated by one of us (Craig) and Joel Corbo, a senior research associate at the University of Colorado Boulder and a member of the EP3 research team, each DALI is a high-impact, yearlong development experience for physics program faculty to build leadership skills and learn how to create effective, sustainable, data-driven change and a robust culture of self-reflection and action. DALI participants report significant changes in departmental norms around the use of data in making important decisions. Their departments also demonstrate an increased recognition of the importance of involving a broad set of constituents and affected parties—including students—in major departmental initiatives.[10]

Since fall 2020, DALI has facilitated five cohorts of four to five departments each. Departments select two faculty members to be "change leaders" who participate in DALI activities, including an in-person kickoff workshop and around 30 hours of video conferences throughout one academic year. Within their institution, the change leaders create departmental action teams. DALI trains change leaders to better understand the situations that their programs face, engage in steps necessary for creating sustained change, and work with their action teams to achieve goals.[11] Participants report that the DALIs are an essential resource that enable them to become better change agents, and they come to appreciate that measured and intentional approaches to change indeed work.[12] DALI developers are continuing to explore partnerships with other change initiatives.

The EP3 guide was initially authorized by the APS council and its Committee on Education to be a living document rather than a static report whose value would decay over time. It is regularly reviewed for relevance and effectiveness, especially as the mission of physics departments morph under pressures from various economic, social, and scientific quarters. An independent editorial board is charged by APS and AAPT with that responsibility. Moving forward, the editorial board is already considering how it might expand the scope of the guide. New sections on graduate education are already under development because many departments are wrestling with such issues as recruitment, admissions, comprehensive exams, and fostering of high-performing research teams. Also under consideration are ways to interface with two-year colleges, given the critical role that they play in the educational ecosystem.

We thank the several hundred contributors and reviewers who provided their working knowledge of highly successful physics programs. We also thank the original members of the EP3 task force for the (collective) thousands of hours of work they put into creating the guide. We dedicate this article to the memory of our good friend and colleague Stephanie V. Chasteen, who provided significant insights into the development of EP3 in her role as external evaluator to the project. We also appreciate financial support from NSF (grant 1821372) and the American Physical Society.

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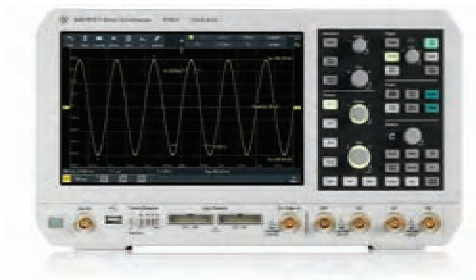
NEW PRODUCTS

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

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

Andreas Mandelis

Versatile entry-level oscilloscope



Rohde & Schwarz has presented its new R&S RTB 2 oscilloscope, an evolution of the company's R&S RTB2000 model. The entry-level oscilloscope now includes an integrated arbitrary waveform generator, which allows users to simulate circuit stimuli and emulate missing components. The waveform generator can produce signals up to 25 MHz and pattern speeds up to 50 Mbits/s. It supports imported waveforms from CSV files and oscilloscope captures and can add noise to simulate real-world conditions. Since the versatile instrument combines an oscilloscope, protocol analyzer, logic analyzer, waveform generator, and more, it is suitable for users, such as students and engineers, who work in limited-space environments and require compact solutions. Expanded memory capabilities allow up to 160 Mpoints in segmented mode, so users can capture more data for in-depth troubleshooting. The R&S RTB 2 oscilloscope delivers 10-bit resolution, comes in two- and four-channel models, and offers bandwidths of 70, 100, 200, and 300 MHz. The revised R&S RTB 2-PK1 optional software bundle offers a wider range of applications and enhanced performance. ***Rohde & Schwarz GmbH & Co KG**, Muehldorfstrasse 15, 81671 Munich, Germany, www.rohde-schwarz.com*

Automation to accelerate quantum computing

Zurich Instruments and QuantrolOx, based in Espoo, Finland, have partnered to integrate Zurich Instruments' Quantum Computing Control System (QCCS) into QuantrolOx's Quantum EDGE automation tool for bringing up, characterizing, tuning, and controlling different qubit systems. According to the companies, the software speeds up those steps by a factor of more than 100 times. The QCCS seamlessly unites RF signal generators, quantum analyzers, and qubit controllers. It offers advanced features such as more than 1 GHz instantaneous bandwidth for streamlined parallel qubit tune-up. The integration of the QCCS into the Quantum EDGE reduces complexity and enhances the performance of quantum computing experiments. Quantum EDGE users can now also harness the power of Zurich Instruments' recently developed SHF+ product line, which features technical specifications that enable high-fidelity gate operations. The integration has been facilitated by Zurich Instruments' LabOne Q open-source software framework. ***Zurich Instruments AG**, Technoparkstrasse 1, 8005 Zurich, Switzerland, www.zhinst.com* PT

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Cosmic extremes of luminosity

Donald C. Warren

What is the brightest object in the sky? The obvious answer is the Sun. But the difference between intrinsic brightness and perceived brightness complicates matters.

Even the smallest amount of the Sun's disk is bright enough to hurt your eyes if you stare at it. But the Sun is bright because it's so close to us. If you stand farther away from a light, it looks dimmer. Astronomers know the phenomenon as the difference between absolute magnitude and apparent magnitude. The former is a measure of intrinsic brightness, and the latter is how bright we perceive something to be from Earth.

Mathematically, it's the distinction between luminosity, which is how much energy an object produces per unit time, and flux, which is how much of that reaches us per unit area. If you have two objects with the same luminosity L, the one with a smaller distance D will have a higher observed brightness F. Alternately, if two objects have the same brightness, the one at greater distance is more luminous:

$$F = L / 4\pi D^2, \text{ or } L = F \cdot 4\pi D^2. \quad (1)$$

So, we could end the article right here. The Sun is the brightest thing we can see, 13 billion times as bright as Sirius, the second-brightest star in the sky. But let's rephrase the question: What is the most luminous object in the sky? If everything in the universe were placed at the same distance from Earth, what would shine the brightest? We'll focus on objects that shine steadily and leave transient sources like supernovae for some other time.

Stars

The Sun fuses more than half a billion tons of hydrogen every second to generate 4×10^{26} W of power (enough energy in one second to power modern civilization for 600 000 years at current energy consumption rates). As stars go, though, the Sun is nothing special. Betelgeuse, the red supergiant star in Orion's left shoulder (as seen from Earth), is 90 000 times as luminous as the Sun. But Betelgeuse isn't even the most intrinsically bright star in its own constellation: Alnilam, in the middle of Orion's belt, is more luminous still.

Deep in the largest stellar nurseries, colossal stars are born that dwarf the Sun, Betelgeuse, and even Alnilam. In our galactic neighbor the Large Magellanic Cloud, the star BAT99-98 clocks in at roughly 225 solar masses. Such large stars are never totally stable, but at present, BAT99-98's luminosity is fairly steady at 5 million times that of the Sun. If BAT99-98 replaced the Sun in the solar system, moonlit nights would be as bright as a cloudy day at high noon under the Sun. (Days would be rather less pleasant.) We know of no single star that is more luminous for extended periods of time.

Galaxies

Some 650 million light-years away from Earth, in the Centaurus constellation, lies the large elliptical galaxy ESO 383-76. It's 20 times as luminous as the Milky Way, or 4×10^{11} times as luminous as the Sun.

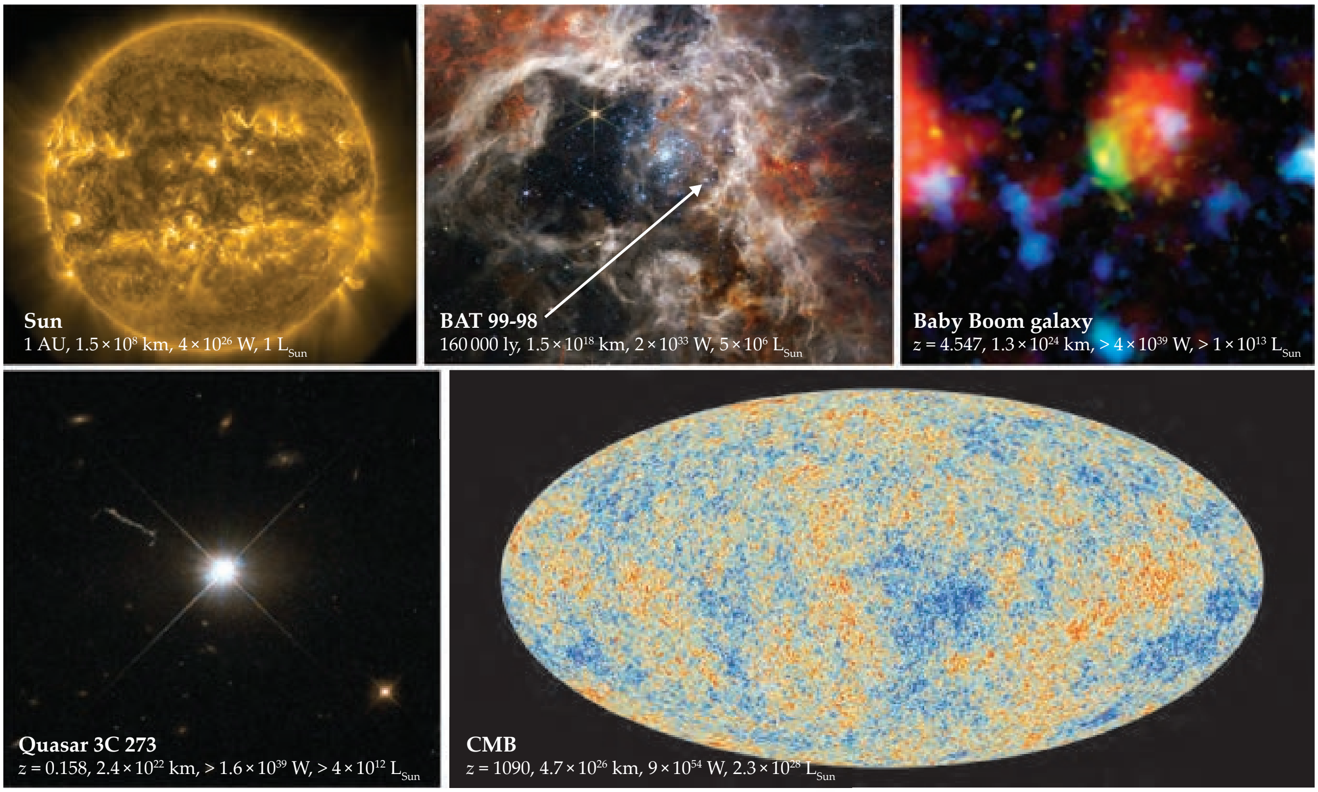
The current record holder among galaxies, though, is much farther away. The Baby Boom galaxy is so distant that we measure redshift ($z = 4.547$) and rely on models of the universe to convert that into distance. Telescope images of the galaxy are not impressive: just a small blob of IR light. But when you take the distance and use equation 1 to compute the luminosity, the galaxy is 10^{13} times as luminous in IR alone as the Sun's output at all wavelengths. The source of all that light, and the namesake of the galaxy, is a stupendous burst of star formation. Despite being just a fraction of our galaxy's size, the Baby Boom galaxy is churning out stars 400 times as fast as the Milky Way.

Quasars

In the 1950s, radio astronomers were looking for optical counterparts to newly identified radio sources in the sky. Deep searches with large telescopes turned up faint starlike objects on top of some sources. But those "stars" exhibited spectral lines that didn't correspond to any known element on Earth. They were called quasi-stellar radio sources, shortened to "quasars" (a term coined by Hong-Yee Chiu in Physics Today, May 1964, page 21).

In 1963, Maarten Schmidt showed that the mysterious spectral lines in the quasar 3C 273 could be explained as hydrogen, oxygen, and other familiar elements—but only if the object were moving away from Earth at a significant fraction of the speed of light. Because the universe is expanding, that meant 3C 273 had to be a distant object and thus far more luminous than an ordinary star: It releases 4 trillion times as much energy in visible light as the Sun does, and visible light is just a fraction of the total energy it radiates.

We know now that 3C 273 and other quasars are the cores of distant galaxies. In each of those cores, a supermassive black hole is accreting gas, dust, and stars at an extraordinary rate. The nucleus of 3C 273 releases so much energy that the core



THE PERCEIVED BRIGHTNESS OF CELESTIAL OBJECTS depends on their luminosity and distance from Earth. Distances are given in astronomical units (AU), light-years (ly), or redshift (z) and luminosity distance in kilometers (km). Luminosity values are given in watts (W) and solar luminosity (L_{Sun}). The cosmic microwave background (CMB) is both the most distant and the most luminous object in the sky. (Images of the Sun by NASA/SDO and the AIA, EVE, and HMI science teams; BAT99-98 by NASA, ESA, CSA, STScI, and the Webb ERO production team; Baby Boom galaxy by NASA/JPL-Caltech/Subaru/STScI/P. Capak, SSC-Caltech; 3C 273 by ESA/Hubble and NASA/CC BY 2.0; CMB by ESA and the Planck Collaboration.)

outshines the rest of the galaxy, and the galaxy appears as just a point in the sky.

Astronomers have now located more than a million quasars. The vast majority are less luminous than 3C 273. But the recently discovered J0529-4351 is devouring more than a Sun's worth of matter every day. Its black hole is 17 billion times as massive as the Sun, and it is radiating 2×10^{41} W, 500 trillion times the total power output of the Sun. If placed in the Large Magellanic Cloud next to BAT99-98, 160 000 light-years from Earth, you could read by its light at night.

The CMB

There's one more equation of relevance, the Stefan–Boltzmann law:

$$L = 4\pi\sigma R^2 T^4. \qquad (2)$$

A perfect blackbody with a radius R at an absolute temperature T radiates in proportion to its surface area and to the fourth power of its temperature, with the Stefan–Boltzmann constant σ controlling the proportionality. (Stars are not perfect blackbodies, but they're close enough.)

There is no more perfect blackbody than the universe itself, as evidenced by the cosmic microwave background (CMB). Predicted in 1948 as the cooling afterglow of the Big Bang, the CMB was discovered accidentally in 1964 by astronomers Arno Penzias and Robert Wilson after their radio antenna detected noise at certain frequencies no matter the direction or time of day. Those relic photons have been traveling almost uninterrupted since the universe was 380 000 years old. The very small departures from the CMB's near-perfect 2.726 K blackbody spectrum have revealed an astonishing amount about the history of the universe (see, for example, Physics Today, January 2023, page 14).

The emitting region of the CMB is a sphere of radius 4.7×10^{26} km that we're on the inside of. (Conveniently, equation 2 doesn't care whether we're on the inside or the outside of the blackbody, as long as the object is radiating equally in every direction.) The CMB is not very luminous per unit area. What it lacks in intensity, it makes up in size. Plugging in the temperature and the radius leads to a total luminosity of 9×10^{54} W, some 20 million times the total combined output of every star in the night sky.

It turns out that the most luminous steady source in the sky is the sky itself, which bathes us in a gentle sea of microwave radiation left over from the universe's fiery birth. You can't see it, but it's been there all along, just waiting for us to build the telescopes and learn about where we come from. If you're feeling warm and fuzzy right now, maybe that's the optimism for the future that astronomy tends to induce—or maybe it's the microwaves of the CMB.

Additional resources

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BACK SCATTER

Visualizing air disturbances

When a flame flickers, the resulting air disturbance is invisible to the naked eye. But it can be unveiled, as shown here, by observing fluctuations in the index of refraction. The use of background-oriented schlieren offers a conceptually simple method to do that. A pattern with high-contrast borders serves as the background. Changes in the index of refraction manifest as apparent displacements of the borders. Jaka Javh, a mechanical engineer and founder of Motion Scope in Slovenia, wrote software to visualize fluctuations in air density. The software converts the relative motion of the background pattern, measured to a resolution of 1 μm, into a color scale to represent the direction and amplitude of the fluctuations. Javh started with a simple checkered background. But to break up the periodicity and thus allow for visualization at different scales, he settled on an irregular pattern.

NASA has previously used the method on a macroscale: Speckles in the Sun or bushes against a desert served as the background to visualize supersonic shock waves and other air density gradients. Other potential applications of background-oriented schlieren include localizing gas leaks, calibrating pressure sensors, and designing face masks to minimize disease transmission. (Image courtesy of Motion Scope.) —TF